Real-time Condition Assessment of Power System Assets as a Vital Information Backbone for a Comprehensive Online Asset-Management System

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Abstract: In course of cost reduction efforts at electric utilities the budgeting for physical assets appears to be the most crucial planning instrument. The operational practice shows yet that the existing cost prediction tools are not sensitive enough for reflecting fast condition developments in the periodic maintenance budget plan. As a result, decision makers take financial consequences of assets degradation into consideration only with substantial time delay. This leads to sub-optimal management of interacting business processes and consequently to considerable losses in the entire organization. The present contribution will demonstrate an iterative technique for determination of asset degradation required for budget calculation. The approach combines financial and engineering information and it allows the decision makers to follow the technical and financial risks as a function of time. The article will also illustrate, that the assets amortization and the required maintenance budget might be calculated by deploying the Fuzzy-Logic in real time.

Key Words: Decision making, Power system monitoring, Risk analysis, Power transmission maintenance, Asset impairment, Strategic planning

INTRODUCTION

Despite the substantial effort made by utilities in course of implementing the condition-based **a**sset-**m**anagement (**AM**) paradigm the goal to enhance the profitability is still not achieved. The reasons for that are insufficient modeling the equipment aging phenomena and the lack of demand-oriented condition reporting to different functions of the organization. The AM-models applied till now fail to deal with the stochastic character of equipment condition development, because they either do not involve the condition relevant monitoring data on online basis or they are not able to process equipment related expert knowledge for condition assessment in a transparent simple manner.

Decision support at many utilities is till this day reliant on traditional disjointed financial systems and outmoded spreadsheet based data collection processes. As a result, the process cycle time for data collection, especially on higher management level, usually exceeds the developmental period of business critical events caused by assets degradation. The described situation is in particular crucial for management of expensive physical assets as power transformers (**TR**), whose failure modes may have development time in range of a week or even a couple of days. If an event starts to develop it should trigger the planning of several processes (procurement, funding, planning etc.) in order to initiate a comprehensive optimisation on the highest system level. Characteristic for the error-prone practice outlined above is excessive opportunity costs, which stand for incremental costs in comparison to those of the later described condition-based asset-management approach.

The overall objective of the online estimation of assets state is the real time cost and risk control of condition sensitive core processes (maintenance, procurement, financing, amortization etc.) having substantial influence on the business profitability.

This contribution describes an evaluation procedure for financial and operational risk exposures caused by condition deterioration of large power transformers. The contents of the paper are organized as follows:

After giving a short overview of the historical development of budgeting practice and its vital importance for asset-management the theoretical background and the shortcomings of traditional fixed assets depreciation for costs control will be outlined.

Next are objectives, relevant principles and the procedure of condition-based asset-management described.

Finally is presented a case study demonstrating the condition based risk evaluation and budgeting technique for three power transformers. The primary goal of the given example is to communicate a formalized procedure transforming condition relevant engineering data into time continuous control indicators by means of Fuzzy-Logic. In order to emphasize the shortcomings of imputed depreciation technique used traditionally the plots of equipment residual value after its depreciation will be demonstrated for both the traditional and the condition based approach in span of transformer operational lifetime. Closing the study we consolidate the assessment error of traditional method on transformer group level in order to show the enormous saving potential, which might be utilised by means of the new approach.

BUDGETING AND DEPRECIATION AS BACKBONE OF ASSET-MANAGEMENT

In broadest sense the assets budget charts the course and costs for planed actions on assets. In the narrower sense however it focuses on activities of condition driven business processes as equipment maintenance, financing and investment. The mentioned consolidating character of the budgeting process, its remarkable quantitative dependence on current assets condition and the fact, that budgeting activities of assets are inseparable part of financial processes point out its importance for asset-management.

Historical development of budgeting methods applied to fixed assets at utilities

Basically, there are three ways to plan a budget:

1. Incremental or baseline budgeting
2. Zero-based-budgeting
3. Combination of the baseline and zero-based types

In incremental budgeting the budget for the current year is the starting point for the next year budget. This costly approach disregarding the actual assets condition has been used by utilities till the liberalization of the energy market almost generally. The new market environment however pushed the utilities to introduce zero-based models for spending by breaking the habit of budgeting nonessential costs simply because they were incurred the prior year. The basic concept for zero-based budgeting corresponds to the condition-based asset-management. That is to start with zero and build the budget according to the current assets condition.

The cost saving potential of the zero based budgeting is particularly high for such assets categories like power transformers binding tremendous capital. In order to face the financial consequences caused by condition deterioration the maintenance budget should be readjusted in line with deterioration process concurrently. For that reason a computer supported online mapping of condition-expenditure dependency is necessary. The detailed description of the proposed model will be given in the 3rd paragraph and in the subsequent case study.

Accounting for depreciation of fixed assets

Depending on objectives there are two kinds of depreciation approaches regarding the fixed assets. The **f**inancial **d**epreciation (**FD**) is a process of assets amortization to spread the cost of acquiring long-term assets over their estimated useful life in order to make sure the nominal maintenance of capital. It will be carried out according to financial policies regardless of the actual assets condition and it serves for assets evaluation e.g. for balance sheet. Contrary to this, the **i**mputed **d**epreciation (**ID**) aims at the substantial maintenance of capital. It should account for actual equipment wear and provide the internal cost accounting with reports on costs induced by assets impairment. The purpose of this latter is to make the financial means available to annual assets maintenance and to assist the operation management in forecasting the breakdown probability of equipments. However, there is no prescribed method for this calculation. The method of strait **l**ine **a**mortization (**LA**) may be regarded as the most frequently applied approach.

The rate of **a**nnual **d**epreciation (**D$_a$**) for **LA** will be calculated according to the equation (1), the residual value of assets after linear amortization **LA** (**t**) as per equation (3).

$$D_a = \frac{RV - SV}{UL} \qquad (1)$$

$$RV_{UL} = PP \bullet \left(1 + \frac{IR}{100}\right)^{UL} \qquad (2)$$

UL = estimated useful life in years
$RV(t = UL)$ = replacement value at the end of UL
SV = estimated salvage value at the end of UL
PP = purchase price of TR at the begin of operation
IR = mean value of inflation rate p.a. in span of UL

$$LA(t) = RV_{UL} - \frac{RV_{UL} - SV}{UL} \bullet t \quad \text{where } t = 1,2,3......UL \qquad (3)$$

As regards the performance of **LA** for comprehensive asset management [1-2], disadvantages overwhelm the only advantage characterized by its simplicity.

Therefore, assets managers are looking for a depreciation model, which is in opposite to **LA** able to map the condition deterioration as a function of time. In the next paragraph, the proposed model called **c**ondition-based **a**mortization (**CA**) will be addressed in details.

CONDITION-BASED AMORTIZATION FOR POWER TRANSFORMERS IN TWO DIMENSIONS

In compliance with the underlying new concept the observation of transformer aging takes place in two separate dimensions. The reasons for that are various organizational functions having different time horizons for planning. While e.g. the long-term system planning is rather interested in information about estimated lifetime consumption on equipment level, functions for maintenance, operation management and annual budgeting need information about the development of critical failure modes on component level [1]. As a result of the mentioned different requirements two observation dimensions has been developed. The first one called **n**atural **a**ging dimension (**NA**) is designed for decision support in long term planning primarily, while the second dimension regarded as **f**ailure-based **a**ging (**FA**) provides information to limit operational and financial consequences of impairment rather in short term regard.

There is a difference concerning the subject of monitoring as well. In focus of **NA** supervision is the degradation of lifetime critical oil-paper insulation characterizing the aging process on equipment level by oneself. In case of failure-based dimension however all known failure modes of failure-prone transformer components are subjected to observation separately. It must be noticed yet, that the mentioned dimensions are not alternatives to each other, but rather complementary. This is supposed to be considered also by designing the reporting policy. As regards the report layout, displaying the two dimensions simultaneously seems to make sense, because it helps understand the discrepancies in different views on both the technical and financial sites.

Risk assessment by means of fuzzy-logic

As indicated in introduction, the present investigation aims at the quantification of technical and financial risks. Per definition, risk is described as expected losses [3]. It is calculated as the product of failure probability and the failure consequences. According to this definition, the task to be solved is to define the mentioned two variables at any time during the actual assets lifetime. Using the assumption that the (n-1) criterion for secure power supply is always granted and that a faulty transformer can be taken out of service without any collateral losses, the failure probability we are looking for might be described by simple fuzzy algorithms corresponding to human thinking [1]. This is valid for both the natural- and the failure-based observation models.

Assessment of transformer amortization caused by natural aging of lifetime critical oil-paper insulation

The objective of this observation dimension is to provide high quality information about remaining lifetime independent from whether distinctive failure modes of transformer are prevailing or not.

The lifetime of transformers depends on the lifetime of the cellulose providing the mechanical strength to withstand a short circuit. The lifetime of cellulose however depends on the insulation oil condition. The aging indicators used for assessment of the grade of natural degradation are listed in Table 1. Parameters marked with **N** have been applied in course of setting up the assessment rules for insulation degradation.

Table 1. Aging factors used as inputs for Fuzzy-Logic based assessment of the grad of natural aging.

<table>
<tr><th colspan="5">Natural Aging Factors (NAF)
for lifetime critical oil-paper insulation (CU₂)</th></tr>
<tr><th colspan="3">Initiators in oil (I)</th><th colspan="2">Accelerators (A)</th></tr>
<tr><td colspan="2">Oxygen</td><td>-</td><td colspan="2">Temperature</td></tr>
<tr><td colspan="2">Water</td><td>N</td><td colspan="2">Vibration</td></tr>
<tr><td colspan="2">Acid</td><td>N</td><td colspan="2">Overvoltage surges</td></tr>
<tr><td colspan="2">Particles</td><td>-</td><td colspan="2">Lack of antioxidants</td></tr>
<tr><td colspan="2">Ions (Cu,Ni)</td><td>-</td><td colspan="2">Overload</td></tr>
<tr><th colspan="5">Ageing indicators influenced by I & A</th></tr>
<tr><td rowspan="3">oil</td><td rowspan="5">insulation</td><td>Breakdown Voltage [kV/2,5 mm]</td><td>BV</td><td>N</td></tr>
<tr><td>Tan delta at 90 Grad Celsius</td><td>Tδ</td><td>N</td></tr>
<tr><td>Colour number (1,2,3,4,5,6)</td><td>CN</td><td>N</td></tr>
<tr><td rowspan="2">solid</td><td>2- Furaldehyde [ppm]</td><td>2-F</td><td>N</td></tr>
<tr><td>Ratio of CO₂ to CO</td><td>R</td><td>-</td></tr>
</table>

While according to the assumption above the current replacement value of transformer reduced by its salvage value accounts for the maximal loss, the probability of transformer breakdown due to natural aging has been assumed to be equal to the current grade of insulation degradation calculated by the related fuzzy module [1-4].

The equation (4) below stands for the time value of transformer after depreciation. For depreciation basis the replacement value at the end of estimated useful life has been chosen in order to provide the comparability to strait line amortization described in (1-3).

$$CA_n(t) = RV_{UL} - \frac{P_n(t)}{100} \bullet \left(RV(t) - SV(t)\right) \tag{4}$$

The second term of equation (4) accounts for the current expected loss characterizing both the current financial risk and the monetary expressed value of depreciation at the same time (cf. tables 5-7).

It must be noticed in place that in the case study below the time functions of depreciation based on natural (4) and failure-based aging (5) will be depicted in comparison to strait line amortization (**LA**) over operational lifetime (**OT**).

Amortization assessment based on distinctive failure modes of failure-prone transformer components

Contrary to the natural aging dimension aiming at the definition of lifetime consumption on equipment level, the failure-based dimension puts the emphasis on concurrent observation of all failure-prone transformer components. The priority purpose of this dimension is to deliver information about components degradation timely and to support the annual budgeting of maintenance activities on various process levels in the entire organization [1].

To calculate the expected value of maintenance budget for an equipment component its estimated breakdown probability and the related maintenance scenario must be quantified at any time. Should these are at disposal for all components the depreciation on equipment level can be calculated by aggregation of their product over all affected components. The second term of equation (5) accounts for the mentioned summation.

$$CA_f(t) = RV_{UL} - \sum_{k=1}^{n} \frac{P_k(t)}{100} \bullet C_{km}(t) \tag{5}$$

$P_k(t) =$ breakdown probability of the k^{th} component

$C_{km}(t) = m^{th}$ maitenance scenario of the k^{th} component

The estimated breakdown probability of the k^{th} component in (5) will be defined indirect by assigning to it the maximal grade of depreciation caused by its i^{th} failure mode (for more details see Fig. 1 and Table 5 of the case study).

The maximal financial loss, which must be borne by utility in case of maintenance, is characterized by the monetary value of related maintenance scenario. This scenario should be selected by asset manager according to the current value of breakdown probability of the monitored component, the financial means at his disposal and the risk strategy of the utility management. A monetary evaluated catalogue of component oriented corrective actions should always be available to asset managers. An example for building **m**aintenance **s**cenarios (**MS**) is given in Table 2.

Table 2. Assignment of evaluated maintenance activities to controlled units $\mathbf{CU}_{1\text{-}3}$ of $\mathbf{TR}_3$

Controlled units $\mathbf{CU}_k$ subjected to maintenance scenarios (**MS**)	Abbr. for **MS** $_{km}$	Place for the maintenance activities for $\mathbf{TR}_3$		Evaluation of the maintenance scenario	
		on site	in plant	Costs (1000$)	Process time month
Insulation oil CU $_1$	MS $_{11}$	Degassing (in operation)		5	6
	MS $_{12}$	vacuum filter (in operation)		10	18
	MS $_{13}$		replace	130	0,25
Solid insulation of HV windings CU $_2$	MS $_{21}$		replace	1800	7,5
Tap changer CU $_3$	MS $_{31}$	oil replacement		1,5	0,1
	MS $_{32}$	Diverter switch replacement		320	1
	MS $_{33}$		replace	550	3

The flowchart illustrated in Fig.1 shows the procedure for risk quantification and time continuous observation. It is a successive process making possible to adjust both the assessment rules for failure-mode oriented component depreciation and the proposed maintenance scenario as well. The adjustment has to be accomplished according to the historical development of failure modes and the current grade of component depreciation.

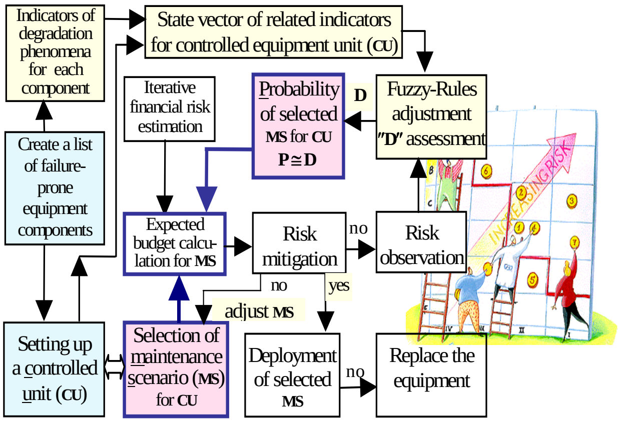

Fig. 1. Flowchart of iterative financial risk assessment using Fuzzy-Logic for depreciation estimation

CASE STUDY FOR TWO-DIMENSIONAL CONDITION-BASED AMORTIZATION

In this study we address a group of transformers subjected to the two-dimensional condition monitoring described above. The group consists of three power transformers, which are equipped with online gas-in-oil monitoring device. Additional to the online monitoring data, off-line condition data coming from laboratory analysis of insulation oil also have been applied. The underlying condition data for **NA** assessment are listed in Table 3.

Table 3. Set of measurement data and the calculated grade of depreciation for natural aging dimension.

Value of indicators used for the calculation of the grade of natural depreciation $\mathbf{A}_n$ in fuzzy reasoning on 08.08.2004					
indicators of natural aging			$\mathbf{TR}_1$	$\mathbf{TR}_2$	$\mathbf{TR}_3$
1.	for oil-paper insulation	Water in Oil [ppm] at T= 60 C	8,8	8,8	6,29
2.		Acid [mgKOH/g]	0,24	0,24	0,17
3.		Breakdown Voltage [KV/2,5 cm]	31,2	52,0	52.0
4.		Tan delta [%]	0,4	0,4	0,29
5.		Colour number	2,4	2,4	1,7
6.		2- Furaldehyde [ppm]	6,0	6,0	4,3
$\mathbf{A}_n$		Grade of natural depreciation [%]	**63,1**	**44,0**	**24,5**

The elaborated diagnostic tool for degradation quantification is a set of Simulink models incorporating fuzzy modules for each failure mode of a component. These fuzzy blocks process the failure-mode related condition data and provide the grade of depreciation as their output parameters. The structure of the mentioned module is depicted in Fig. 2. Details about the fuzzy model will not be given here; these are already published in [1,4].

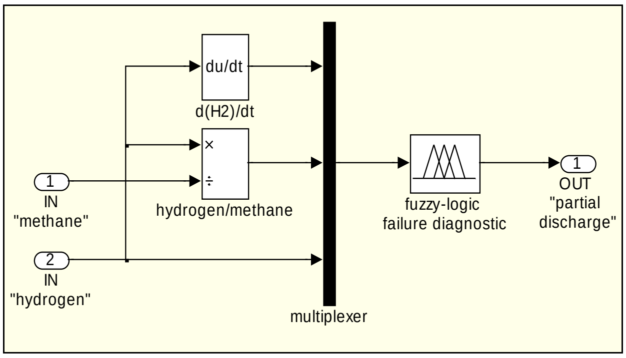

Fig. 2. Simulink-model for depreciation computation

Objectives of the present investigation

1. To compare the results of condition-based amortization modelling (**NA** and **FA**) to that of the condition independent strait line depreciation (**LA**).
2. To show a formalized way of condition-based budget calculation, which manages to link measurement data from the field with financial statements used by controlling.

Amortization of TR 1-3 due to natural aging

As a result of processing the relevant condition data for natural aging (cp. Table 1) the development of the grade of transformer depreciation ($\mathbf{A}_n$) and its residual value after depreciation ($\mathbf{CA}_n$) are depicted in context of strait-line amortization (**LA**) in Fig. 3-5.

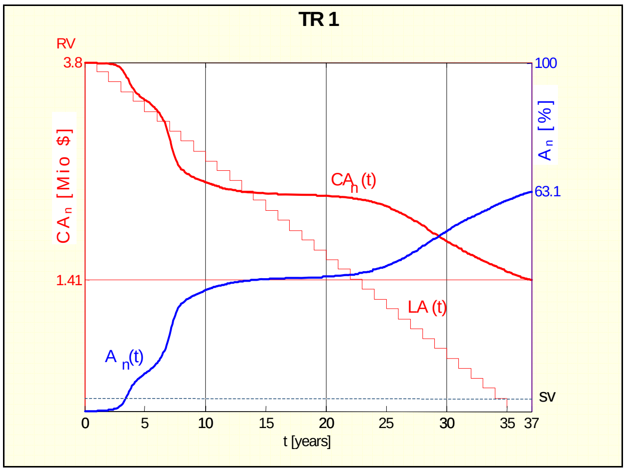

Fig. 3. Function of depreciation based on natural aging

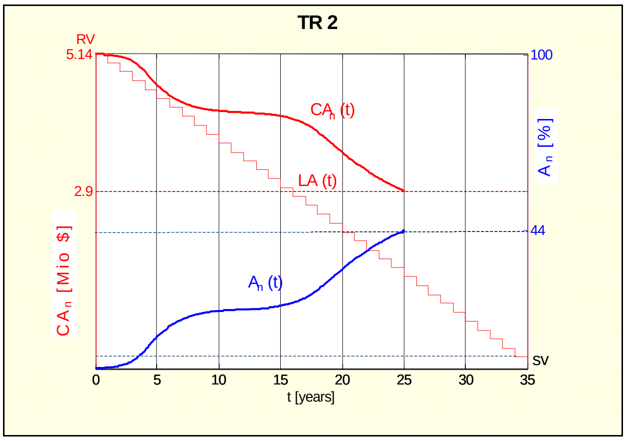

Fig. 4. Function of depreciation based on natural aging

Amortization of TR 3 due to failure-based aging

The underlying event for a sensitivity analysis of this dimension is a steady increase of dissolved hydrogen in oil characterizing the failure mode “partial discharge”. The related Simulink-module is shown in Fig. 2. The results of computation are given in Table 5. Despite the step-by-step observation and the assignment of maintenance scenarios are demonstrated for both the oil and solid insulations in Table 4, the visualisation of component depreciation in Fig. 5 has been carried out only for the latter for visibility reason. Functions $\mathbf{A_f}$ and $\mathbf{A_n}$ show that the failure-based dimension indicate a much higher sensitivity than that of natural aging. It allows manager to control the risk development as a function of time on both the equipment and component levels concurrently. The monetary risk rising due to asset impairment is also displayed for the observed solid insulation in Fig. 5. Tables 5-7 are self-explanatory. Table 5 consolidates the monetary expressed depreciations of components on equipment level, while Table 6 does the same on asset group level. Table 7 reveals the results of decisions regarding the budgeting.

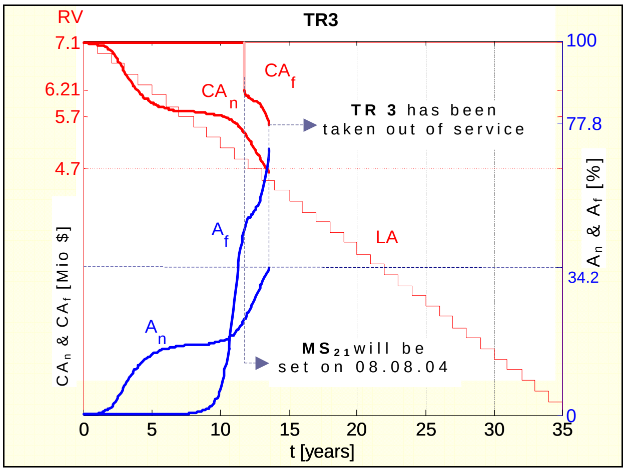

Fig. 5. Depreciation for natural and failure-based aging

Date	OT	MS_{km}		P_k	C_{km}	EC_{km}	Decision on MS_{km}	
	year	cp. table 2.		%	1000$		adjust	else
12.12. 1997	5	CU₁	MS_{11}	16,1	5	0,8	yes	observe
25.11. 2000	8		MS_{12}	19,0	10	1,9	yes	observe
05.07. 2003	11		MS_{13}	20,1	130	26,1	no	observe
08.08. 2004	12		MS_{13}	26,8	130	**34,84**	no	**deploy**
08.08. 2004	12	CU₂	MS_{21}	**55,01**	**1800**	**990,2**	no	**deploy**
***TR*₃**	Cumulated expected repair costs on 08.08.2004					**1025**	Repair in plant	

Table. 4. Time-table for scenario setting & readjustment

Controlled units **[CU$_k$]**		Failure modes **[FM$_{ki}$]**		Failure mode related Condition indicators for TR$_3$						$A_{f,ki}$	$P_k \cong \max(A_{f,ki})$	C_{km}	$EC_{km} = P_k * C_{km}$	EMB_n	R_n
of n-th TR **[TR$_n$]**		i	of **CU$_k$**							%		1000 $			%
CU₁	insulation oil	1.	failure based degradation	O_2	acid	H_2O	Tδ	BV	CN	26,8	26,8	130,0	34,84	1025,0	53,1
CU₂	solid insulation	1.	discharge	C_2H_2	C_2H_6					0,1	55,0	1800,0	990,18		
		2.	partial discharge **(PD)**	H_2	CH_4	$\frac{dH_2}{dt}$				55,0					
		3.	overheating	CH_4	C_2H_x (x=2,4,6)		C_3H_y (y=4,6,8)			0,1					
		4.	cellulose degradation	CO	CO_2					0,3					
CU₃	tap changer									0,02	0,02	0,0	0,0		
CU$_k$	etc.									0,0	0,0	0,0	0,0		

Table 5. Calculation table for expected maintenance budget for failure-based observation dimension

Table 6. Assessment error of strait-line depreciation on transformer group level

TR n	***UL***	***OT***	***IR***	***PP***	***SV***	***RV***	***LA***	***CA***	*LA – CA*
	Jahr		**%**	**$10^6 * \$$**					
TR **1**	35	37	1,6	2,18	0,04	3,8	3,76	2,39	1,37
TR **2**	35	25	1,8	2,75	0,05	5,14	3,64	2,24	1.40
TR **3**	35	12	1,2	4,68	0,07	7,1	2,41	1,73	0.68
TR **123**						Sum:	9,81	6,36	3,45
	Cumulated assessment error on 08.08.2004								**3,45**

Table 7. Budgeting report according to the natural and failure-based aging dimension

items of assets	aging dimension	controlled unit	grade of depreciation	Estimated Breakdown Probability	Amount of max. loss	Current expected loss **$EL_n = P_n * RV_n$**	decision on budget taken by asset manager for financial planning annual maintenance budget	Investment budget for planning horizons Short term	Long term
			%		**$10^6 * \$$**				
TR_n		**TR_n**	**A_n**	**P_n**	**RV_n**	**$EL_n(t)$**	**$10^6 * \$$**		
TR_1	**natural**	TR_1	63,1	63,1	3,76	2,37		2,37	
TR_2		TR_2	44,0	44,0	5,09	2,24			2,24
TR_3		TR_3	24,9	24,9	7,03	1,75			
TR_3	**failure based**	**CU_{nk}**	**A_{fk}**	**P_{nk}**	**C_{nkm}**	**$EC_{nkm}(t)$**			
		CU_{31}	26,8	26,8	0,13	0,035	0,13		
		CU_{32}	55,0	55,0	1,8	0,99	1,80		
Total budgeted Costs as proposal							**1,93**	**3,76**	**2,24**

CONCLUSIONS

(1) It has been demonstrated that the conventional depreciation practice is not sensitive enough for supporting asset-management activities aiming at cost optimisation by means of condition-based maintenance strategy.

(2) Using the capability of fuzzy reasoning we also showed that the computation of depreciation grade of failure-prone equipment components might be carried out condition dependent by processing condition relevant field data online.

(3) According to the information demand from various organisation functions the two-dimensional observation of assets degradation has been introduced and its results has been compared to the traditional strait line amortisation regarded as basis for the analysis. The consolidation of this comparison on transformer group level reveals, that as for the natural aging there is an assessment error of strait line method, which amounts to $ 3,45 million.

(4) The presented procedure for transforming condition related engineering data into financial risk indicator allows software engineers to link the so far autarkic operating online-monitoring systems with integrated business software solutions e.g. SAP.

(5) Contrary to the lifetime management method using questionable statistical data, the presented condition-based approach focuses on the individual properties and historical operational circumstances of the observed equipment. As a consequence of the applied cause-impact based fuzzy-inference technique the reliability of remaining lifetime estimation has been increased significantly.

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