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Optimizing Life-cycle Maintenance and Replacement Strategies at Transmission Systems

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SUMMARY

Transmission system operators (TSO) commonly maintain and replace the assets of extra-high voltage grids according to the time-based strategy. The maintenance and replacement activities at a transmission system determine a major part of operational expenditures respectively capital expenditures. Due to unbundled electrical energy market and incentive regulation in Germany, TSO must operate cost-efficiently. Saving money with a lower level of maintenance activity influences the availability of the assets and the capability of the system. Thus, the asset management has to consider the goal conflict between the expenditures for maintaining or replacing the assets and the availability of the grid at their maintenance strategies. An individual life-cycle optimization of the maintenance and replacement strategy based on reliability assessment, age-depending hazard rates and costs for maintenance and replacement can reduce the expenditures without a decline of availability at the transmission systems.

This paper presents a game-theoretical optimization of life-cycle maintenance and replacement strategies at transmission systems. The method determines the intensity of maintenance and the date of replacement individually for each asset at the grid. Considering the impact on the reliability for each asset, the procedure calculates a strategy improving the expenditures for maintaining and replacing the assets and the reliability of the grid simultaneously. For this, there is a discrete number of options for maintaining or replacing the assets available. The options control the intensity by adapting the maintenance cycles. Using hazard-rates depending on the type of asset, the age and the maintenance intensity, the method determines the influence of each option on the reliability of the grid. When selecting the options for all assets of the grid during the simulation period, the game-theoretical optimization develops a life-cycle maintenance and replacement strategy improving the expenditures, and the reliability. The method is able to consider restrictions at the maximum life-time of the assets and at the maximum expenditures according to the requirements of the TSO.

Applying the optimization to a 220 kV gird with 212 assets, the optimized strategy recommends an increased maintenance intensity predominantly for circuit-breakers and instrument transformers in combination with a mainly reduced intensity for disconnectors and power transformers. Comparing the results of the improved strategy with the assessment of reliability and expenditures at the time-based maintenance and replacement strategy shows the advantages in reliability and expenditures at optimized strategy during a simulation period of 50 years.

KEYWORDS

Transmission system, asset management, life-cycle maintenance and replacement strategies, performance optimization, game-theory, age-depending failure-rates, reliability assessment.

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1. Introduction

Due to the liberalization of common energy markets, transmission system operators (TSO) in Germany had to become legally and economically independent companies. Their investors expect a return on their investment. Because of regulated network charges, the companies have to improve their cost efficiency to reach this target. This affects the asset management. When maintaining and replacing assets at a transmission system, TSO has to consider the expenses in addition to the reliability of the power system. In order to handle these conflictive aims, the optimization of maintenance strategy is recommended [1]. For this purpose, the introduced method selects the maintenance intensity and the date of replacement individually per asset. A game-theoretical procedure optimizes the selection and determines a strategy with benefits in reliability, and expenditures. The optimization improves a maintenance and replacement strategy for 50 years at a 220 kV transmission system. After assessing reliability, and expenditures at time-based strategy, the method of optimization is described. Finally, the contribution presents the result of optimized maintenance and replacement strategy compared to the time-based strategy.

2. Transmission system model

The 220 kV transmission system represents a real part of a 220 kV grid in Germany including 13 substations with one coupling point to the 380 kV grid and eight connections to grids at the 110 kV voltage level. The calculation of power flow considers a peak-load scenario with high feed-in through conventional power plants and a high generation by wind turbines in the northern part of Germany. In total, the analyzed part of the transmission system supplies an aggregated load of 2.1 GW, of which a quarter arises in the 110 kV systems.

2.1. Number and age-dependent hazard rate of h.v. equipment

The developed method focuses on assets at the 220 kV voltage level and optimizes maintenance and replacement strategies depending on major faults. Calculating the maintenance intensity and the year of the replacement individually requires a modeling of each asset. Table 1 summarizes the number of equipment. At the beginning of the simulation, all assets have an average age of 25.3 years. This is used to perform reliability and availability calculations measuring the age dependent influences of a failure at each individual asset on the availability of the transmission system.

Table 1 : Number of assets at the 220 kV grid and average hazard rates *h*.

equipment	number	*h* / 1/100a
circuit-breaker (CB)	54	0.58
disconnector (DIS)	41	0.69
busbar-disconnector (BB-DIS)	62	0.69
instrument transformer (IT)	47	0.08
power transformer 220/110 (PT)	8	0.62
total amount	**212**	

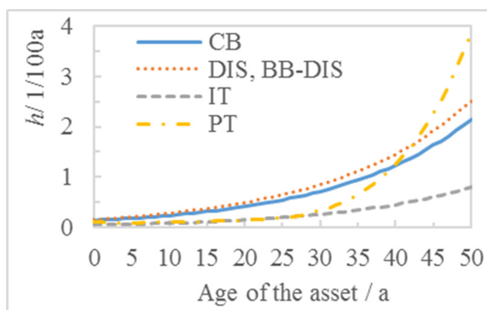

Figure 1: Age-dependent hazard rates *h*.

In addition to the load flow and the age of the assets, reliability calculations are based on the hazard rates [2]. Table 1 shows the average hazard rates of major faults for the considered assets, which are deduced from the information of [3–6]. In order to perform age-dependent reliability calculations, these rates are combined with statistical data of the TSO concerning the aging behavior of the assets and the information provided by [6]. This leads to the age-dependent hazard rates represented by figure 1. The deduction of the hazard rates assumes a continuation of the previous maintenance cycles.

2.2. Expenditures and time cycles for maintenance and replacement

According to the German Standard DIN VDE 0109 "Maintenance of installations and equipment of electrical energy supply networks", the TSO performs the activities of inspection and overhaul [7]. Table 2 shows the common cycles for both activities at the assets of the 220 kV grid, which are presently applied at time-based maintenance strategy. In addition, table 2 depicts the average lifecycle of the assets expected by the TSO and the average duration of repairing the asset (T_R). According to the information of [8], table 2 depicts the average values for the duration of repairing assets at German 220 kV grids.

Table 2: Expenditures and time cycles for maintenance and replacement at regular strategy.

equipment	inspection		overhaul		repair		replacement	
	OPEX / k€	cycle / a	OPEX / k€	cycle / a	OPEX / k€	T_R / h	CAPEX / k€	Lifecycle / a
CB	0.6	2	6.8	8	13.7	45.6	132.0	50
DIS, BB-DIS	0.3	2	3.5	4	7.1	68.5	85.0	50
IT	0.3	2	3.1	8	6.1	28.5	130.0	50
PT	0.6	2	17.1	4	408.3	96.2	2650.0	60

Besides these cycles, the average expenditures for maintaining, repairing major faults and replacing the assets are derived from the experiences of the TSO according to the regular time-based maintenance and replacement strategy. Table 2 depicts the operational expenditures (OPEX) for maintaining, and the capital expenditures (CAPEX) for replacing the assets according to present time-based strategy.

2.3. Time-based maintenance and replacement strategy

In order compare the results of optimized strategy developed in this contribution, this chapter describes the present time-based maintenance and replacement strategy at the considered 220 kV grid. Due to the lifecycle of 50 years for the switchgears, the strategy is simulated for a life-time of 50 years.

2.3.1. Assessment of reliability

A grid simulation software analyzes the reliability at the observed part of the 220 kV grid and performs a reliability and availability calculation based on the peak-load scenario. Doing a failure effect analysis, the amount of interrupted power supply (P_{NS}) at a load and the interrupted power demand (P_{ND}) at a power plant, or coupling point is determined for a major fault at each asset of the grid. Multiplying the summation of P_{NS} and P_{ND} with the age-dependent hazard rate h according to figure 1 and the duration of repair T_R according to table 2 leads to the probable amount of energy not transmitted (W_{NT}). Adapting the age and the hazard rates of the individual assets, the reliability of the grid can be calculated for the simulation period. Figure 2 depicts the development of W_{NT} at the grid related to the annual amount of energy transported by the grid. The calculation considers the common cycles of maintenance and replacement according to table 2. Thus, figure 2 represents the prediction of energy not transmitted for time-based maintenance and replacement strategy. The methode of this contribution analyszes, if an optimized maintenance and replacement strategy improves the reliability at the grid.

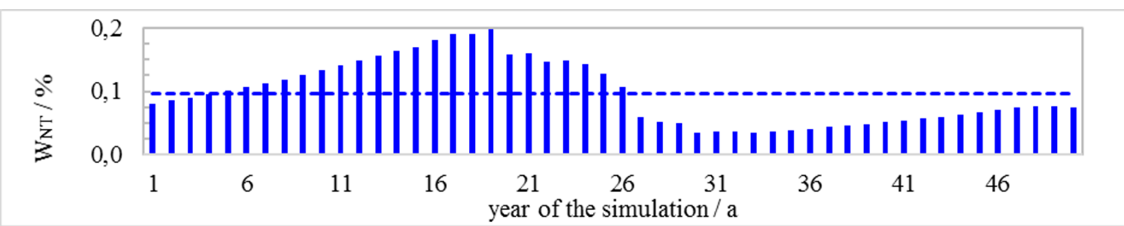

Figure 2: Time-course of energy not transmitted at regular, time-based maintenance and replacement strategy.

2.3.2. Calculation of expenditures

Applying the time-cycles for maintaining and replacing the assets according to table 2 schedule the years of inspection, overhaul, and replacement during the simulation period in case of time-based strategy. With the help of expenditures given by table 2, this determines OPEX, and CAPEX for maintaining and replacing all assets at the grid. In addition, OPEX includes the expected expenditures to repair assets in case of a major fault based on the average repair expenditures presented by table 2 and the age-dependent hazard rate according to figure 1. Summing up the expenditures for all assets and all 50 years calculates the expenditures for the present time-based maintenance and replacement strategy. The time-based strategy causes OPEX of 18.1 M€ and CAPEX of 49.8 M€ at the grid.

3. Method of optimization

After assessing the reliability and the expenditures at the regular, time-based maintenance and replacement strategy, this chapter introduces a game-theoretical method for optimizing the strategy regarding the objectives reliability, and expenditures. Repeating the annual optimization for each year of the simulation period, the method aims on reducing W_{NT} as well as OPEX, and CAPEX of the grid as described in chapter 2.3.2. The optimization selects the maintenance intensity and the year of the replacement for each asset individually and considers the importance of each asset. [9] describes a detailed description of the optimization model based on the multiple-choice knapsack problem. Enabling an application by the TSO, the optimization model defines a discrete number of available maintenance and replacement options from which the optimization method selects an optimal maintenance and replacement strategy.

3.1. Available maintenance and replacement options

The cycles of time-based strategy shown by table 2 provides the basis for developing available maintenance and replacement options with different maintenance intensity. Deducing hazard rates depending on maintenance intensity by [10] requires a constant scope of maintenance and equal inspection cycles for all maintenance options. Thus, the time cycle T_{M} between overhauls influences the maintenance intensity. The options adjust the cycles of overhaul by 2 years. Extending the cycles of regular maintenance by two years leads to options with lower maintenance intensities. A reduction of the cycle by two years improves the maintenance intensity. Table 3 provides an overview of overhaul cycles for the maintenance options at the considered assets.

Table 3: Time cycles of overhaul at available maintenance options of the optimization model.

	Maintenance options		
	intensive	***regular***	***reduced***
equipment	***cycle / a***	***cycle / a***	***cycle / a***
CB, IT	6	8	10
DIS, BB-DIS, PT	-	4	6

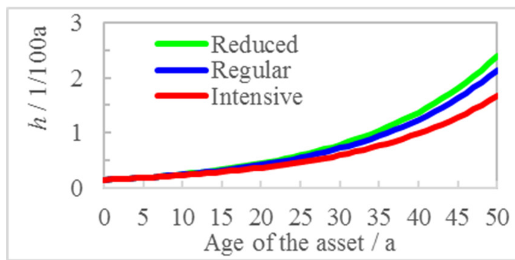

Figure 3: Hazard rate h of 220 kV circuit-breakers depending on age and maintenance option.

Scaling the expenditures of time-based maintenance according to the cycles of table 3 determines operational expenditures for all maintenance options. Besides that, the optimization can select the replacement of assets causing CAPEX according to table 2. Modifying the cycle of overhaul influences the intensity of maintenance and the hazard rate of the asset, which changes the reliability of the grid. Due to the information according to [10], an extended cycle increases the age-dependent hazard rate at the circuit-breakers compared to the regular maintenance shown by figure 1. In contrast, a shortened maintenance interval reduces the hazard rate. Figure 3 depicts the relationship between hazard rate, maintenance option, and age of the asset for the example of the 220 kV circuit-breakers. Thus, an individual amount of $W_{\mathrm{NT},i,\mathrm{j}}$, $OPEX_{i,\mathrm{j}}$, and $CAPEX_{i,\mathrm{j}}$ characterize the options j of each asset i. Due to the influence of the hazard rate on W_{NT}, the selection of maintenance and replacement options affects the objective functions of the optimization.

3.2. Objectives of optimization

In accordance with the assessment of the time-based maintenance and replacement strategy at section 2.3, the annual optimization aims on minimizing W_{NT}, $OPEX$, and $CAPEX$ in order to improve expenditures and, reliability. Equations 3 - 5 describe the objective functions of the annual optimization. The procedure of optimization selects a maintenance and replacement option for each asset. Summing up the values of $W_{\mathrm{NT},i,\mathrm{j}}$, $OPEX_{i,\mathrm{j}}$, and $CAPEX_{i,\mathrm{j}}$ for all assets and selected options develops a maintenance and replacement strategy for the grid. The selection observes the multiple-choice constraint at equation 6, so that the method applies exactly one maintenance and replacement option at the same time.

$$\text{Min } W_{\text{NT}} = \sum_{i=1}^{n} \sum_{j=1}^{m} x_{i,j} W_{\text{NT},i,j}(age_i) \quad (3)$$

$$\text{Min } OPEX = \sum_{i=1}^{n} \sum_{j=1}^{m} x_{i,j} OPEX_{i,j} \quad (4)$$

$$\text{Min } CAPEX = \sum_{i=1}^{n} \sum_{j=1}^{m} x_{i,j} CAPEX_{i,j} \quad (5)$$

Multiple-choice constraint

$$\sum_{j=1}^{m} x_{i,j} \text{OPEX}_{i,j} = 1 \quad \forall\, i = 1, .., \text{n assets} \quad (6)$$

i	number of the individual asset
n	amount of assets in the grid
j	number of maintenance option
m	amount of available maintenance options
$x_{i,j} = \{0; 1\}$	option j at asset i selected if $x_{i,j} = 1$
W_{NT}	energy not transmitted of the grid in MWh/a
$W_{\text{NT},i,j}$	W_{NT} for option j at asset i in MWh/a
$OPEX$	operational expenditures of the strategy in €
$OPEX_{i,j}$	OPEX of option j at asset i in €
$CAPEX$	capital expenditures of the strategy in €
$CAPEX_{i,j}$	CAPEX of option j at asset i in €

At this contribution, a game-theoretical optimization performs the improved selection of annual maintenance and replacement options for each asset of the grid in order to optimize the maintenance and replacement strategy.

3.3. Game-theoretical optimization

The method of game theory reproduces the decisions of individuals mathematically. All players of a mathematical game correspond to human individuals. They behave rationally and take decisions improving their own benefits.

The implementation described in the following uses the information about game-theoretical optimization procedures presented by [11, 12]. Transferring game theory to maintenance and replacement strategy, the three objectives build up the players W_{NT}, *OPEX*, and *CAPEX*. Each player aims on selecting a strategy, which improves its own benefit. The objective functions according to equations 3 – 5 measure the benefit of each player. Besides that, a sigmoid utility function evaluates the benefit of a strategy for each player, transfers the objective functions into a system with a uniform dimension and converts the minimization task into a model maximizing the benefit of each player.

At the beginning of the game, an initial strategy plans to maintain all assets with regular intensity. The method performs an iterative optimization of the initial strategy, where a step of the iteration corresponds to a round of a game. Each round allows a change in a maintenance option for a single asset. Adapting the options for each available asset one by one creates the maintenance and replacement strategies. Then, the method evaluates the objectives and the benefits of each player for all strategies. Since the TSO aims on an optimal solution of all three objectives, the method accepts only strategies increasing the global benefit, which is equivalent to the sum of the benefits of all three players. The optimization rejects all strategies reducing the global benefit. After that, the method determines a dominant player, which has the highest number of remaining strategies improving the benefit of the corresponding player. Finally, the procedure allows the dominant players to select the strategy with the highest value of its individual benefit. According to the selected strategy, the method changes the option for an asset and excludes the asset of further rounds of the game. The new round starts with the remaining assets and uses the selected strategy as initial solution. Since the method narrows the set of possible strategies iteratively and depending on the individual and global benefits, the game theory provides a fast and intuitive calculation of optimized strategies. The procedure repeats the iteration until there are no assets left, or until there does not exist any strategy increasing the global benefit. Selecting an option for all assets, the method optimizes annual maintenance and replacement strategy. The optimization limits the maximum age of the assets according to table 2. Furthermore, annual CAPEX is restricted to 1.25 time the annual depreciation while OPEX keeps the expenditures for maintaining the assets with regular intensity.

The annual optimization of maintenance and replacement strategy is repeated for each year of the simulation period by updating the information about the age-distribution. Since the maintenance intensity depends on the cycle, the optimization method is able to select maintenance and replacement options at assets completing their prior maintenance cycles. Thus, the method collects the available assets for the optimization at the beginning of each year. Aggregating the annual strategies develops a maintenance and replacement strategy for the simulation period of 50 years. The next chapter presents the results of game-theoretical optimization applied to the introduced 220 kV grid.

4. Results

The game-theoretical method optimizes maintenance and replacement strategy at the introduced 220 kV transmission system. Table 4 depicts the results of the optimization and compares the objectives of optimized strategy with regular, time-based maintenance and replacement strategy. The developed method is able to reduce the average reliability and the operational expenditures at the same time. Due to the restricted maximum age according to time-based strategy, the method cannot reduce capital expenditures. Thus, an increase of CAPEX is comprehensible.

Table 4: Results of optimization and changes to regular time-based strategy.

	optimized strategy	changes / %
W_{NT} [a] / %	0.085	- 11.6
OPEX [b] / M€	16.7	- 7.3
CAPEX [b] / M€	51.2	2.7

a. W_{NT} is expressed in average value over 50 years.
b. Expenditures are summed up over 50 years.

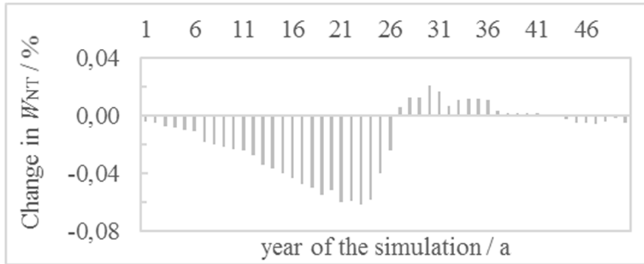

Figure 4: Time-course of annual changes in reliability in reference to W_{NT} of regular strategy at figure 2.

Besides improving the average W_{NT}, time-course of optimized strategy has advantages over regular strategy as shown by figure 4. This illustration depicts the annual difference in W_{NT} between optimized and regular strategies with negative values indicating the superiority of optimization. Thus, optimized maintenance and replacement strategy increases the availability at the grid in the first half. Since optimization has to keep a limit in CAPEX, regular strategy can replace more assets at the beginning of the second half and reaches higher levels of availability at the beginning of the second half. Optimization compensates for this at the end of the simulation.

Figure 5a depicts the allocation of maintenance and replacement options to the types of assets. In total, the optimization recommends predominantly a reduced maintenance option at 56.3 % of the decisions for all assets. While the limit of maximum ages causes three quarters of the replacement activities, the optimization replaces a quarter of the assets prematurely. The method chooses especially disconnectors for replacement prior to their maximum age, while maintaining them with reduced intensity. A reduced intensity is also dominant in the strategies of busbar-disconnectors and power transformers. Due to high capital expenditures, the improved strategy does not replace power transformers ahead of their lifetime. In contrast, the optimization selects predominantly intensive maintenance at the circuit-breakers and recommends a replacement at the end of their maximum lifetime. This is similar to the result of the instrument transformers.

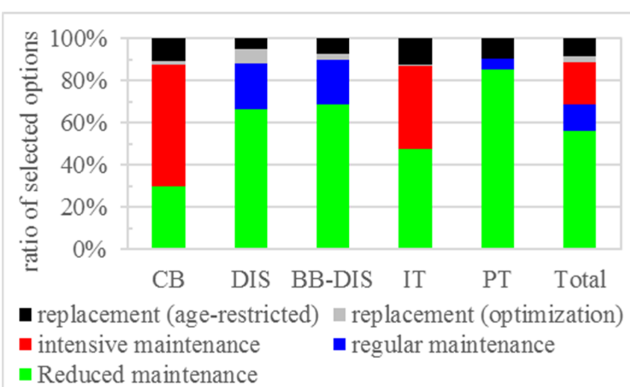

Figure 5a: Selected options depending on the type of asset.

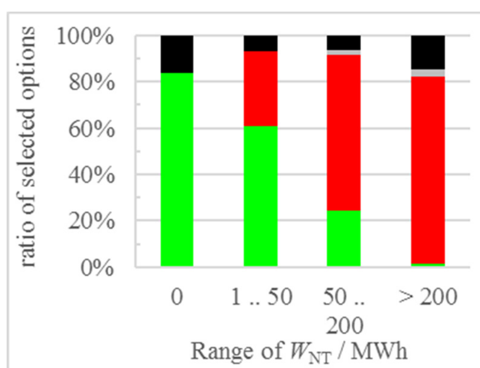

Figure 5b: Selected options at circuit-breakers depending on impact on reliability.

When selecting an option, the method takes the influence of each asset on the reliability of the grid into account. Figure 5b depicts the selected maintenance and replacement option depending on the amount of W_{NT} at the corresponding asset. The optimized strategy maintains assets with a low influence on the reliability of the grid with reduced intensity. When considering assets with high energy not transmitted, the method recommends the intensive maintenance predominantly. Furthermore, the method selects an early replacement only for assets with high amount of W_{NT}. Since the selection depends on the reliability assessment of the assets, the game-theoretical optimization provides comprehensible results improving expenditures, and reliability compared to time-based maintenance and replacement strategy.

5. Conclusion

This contribution presents an age-depending assessment of reliability at transmission systems and uses the analysis to optimize life-cycle maintenance and replacement strategy. The developed game-theoretical optimization method determines the maintenance intensity and the year of the replacement for each asset individually. Considering the energy not transmitted and the expenditures for each option and all assets, the procedure improves the reliability of the grid and the operational expenditures. The optimized strategy recommends an improved maintenance intensity for circuit-breakers and instrument transformers, while the cycles between overhaul are mainly extended for disconnectors, busbar-disconnectors and power transformers. In addition, the method applies shorter life-cycles especially for disconnectors. Since the decision depends on the energy not transmitted, the optimization should be performed for each grid individually considering the load flow and the age-distribution of the assets. Summing up, this tool supports the asset management and develops an optimized life-cycle maintenance and replacement strategy with individual schedules for maintaining and replacing each asset at the considered transmission system. The asset individual selection is able to optimize the performance of maintenance and replacement strategies depending on the objectives expenditures, and reliability. Future research work uses the results of optimization to derive improved maintenance and replacement strategies for switchgears.

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