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Impact of Planning Uncertainties in Power Plant Operation Planning

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***Abstract*--Due to the implementation of new markets, i.e. intraday markets as well as the markets for reserve, a higher number of planning uncertainties has to be considered within the operation planning of power plants. Besides outages of thermal power plants and prices at day-ahead wholesale markets, the prices at the intraday market and the market for minute reserve as well as the requested amount of reserve energy by the transmission system operator are not known at the point of time when the operation planning is carried out. Thus, prognoses for these values have to be made. For a better integration of the stochastic characteristics of these values into the planning process, different possible realizations of the uncertain input data in form of scenarios should be modeled instead of a single consideration of estimated values. Within this paper, a stochastic optimization method is described, which adequately integrates the stochastic characteristics of the relevant input parameters into the operation planning process, resulting in distribution functions of typical output values like the contribution margin.**

***Index Terms*--Planning uncertainties, operation planning, intraday market, outages.**

I. INTRODUCTION

POWER plant operators have nowadays different opportunities to market their generation units. In the medium- and long-term, generation units are typically marketed at the futures market as well as the markets for primary and secondary reserve. In the short-term, power plants can be marketed at the day-ahead markets, i.e. the spot market and the market for minute reserve, as well as at the intraday market.

In operation planning, the participation at these markets leads to a more difficult planning task, due to the high number of uncertain input parameters. First, the prices at the day-ahead markets as well as the intraday market are not known at the point of time the planning process is carried out. Second, participation at the markets for reserve results in unknown amounts of reserve energy requested by the responsible transmission system operator (TSO).

Additionally, component-specific uncertainties, i.e. outages of power plants, have to be considered.

Stochastic input parameters can either be approximated by their estimated values or by consideration of their relevant stochastic characteristics. For the former case, the provision of input data is usually simple and the operation planning yields one deterministic result. For the latter case, the determination of the stochastic characteristics usually necessitates additional methods and the amount of data to be processed is much higher. In exchange, the results of the planning process are determined under consideration of uncertain input parameters, resulting in more robust results. Furthermore, the results can be used for risk observation and are therefore important for risk management processes of power plant operators.

Within this paper, a method is described, which integrates the stochastic behavior of input parameters in the optimization process. Thereafter, this method is used to evaluate the impact of planning uncertainties within the operation planning of power plants.

II. ANALYSIS AND SYSTEM MODELING

The system under consideration is presented in the following section. Subsequently, the most important system components are briefly analyzed and modeling parameters are derived. Finally, the relevant planning uncertainties in the operation planning process are analyzed and the employed modeling approach is described.

A. System Overview

The system under consideration is depicted in Fig. 1. Power plant operators are responsible for the operation of the thermal and hydro power plants in their property. These generation units can be marketed at wholesale and reserve markets, depending on the point in time of the optimization [1].

Strengthened by the introduction of 7-Day-Trading on the EEX Power Spot Market [2], the time horizon of an operation planning process can usually be assumed to be one day. Thus, results of planning processes with a longer time horizon, e.g. concluded trades at the futures market or the markets for primary and secondary control reserve, are exogenous input data. Due to the obligation of power plant operators to announce the planned produced energy to the TSO in a time pattern of 15 minutes as well as the obligation to be able to activate the requested minute reserve within 15 minutes, a time pattern of 15 minutes is chosen for operation planning.

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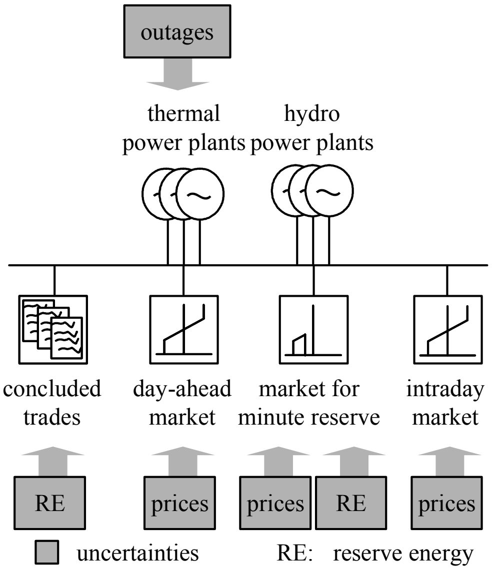


Fig. 1. Overview of the system under consideration.

As already described in chapter I, some input data are just known with uncertainties. The uncertainties to be considered in the operation planning process are also shown in Fig. 1.

B. *System Components*

Due to the time pattern of 15 minutes, more technical restrictions of the generating units have to be considered compared to a time pattern of one hour which is commonly used in mid-term planning processes [3]. Furthermore, the operation planning is the final planning task and thus a high modeling accuracy has to be chosen. The impact of these two facts on the modeling of the generation units is briefly analyzed in the following sections.

1) *Thermal Power Plants*

In addition to the common modeling of thermal power plants, i.e. minimum up- and down-times, minimum and maximum power output level and non-linear efficiency curves [4], maximum ramp rates have to be considered in operation planning [1]. Furthermore, the consideration of start-up curves depending on the previous standstill time is necessary to adequately model the amount of energy already produced during start-up [5].

Due to the high modeling accuracy, outages of thermal power plants cannot be modeled using the method of power reduction which is often used in energy procurement planning [3]. In operation planning, non-movable outages must be modeled accurately, whereas movable outages, i.e. outages that can be shifted by 12 hours or more, are either known in time and can be considered in the input data or can be shifted behind the end of the planning horizon.

2) *Hydro Power Plants*

Hydro power plants have high ramp rates and short activation times. Thus, the time pattern of 15 minutes and the desired high modeling accuracy have no impact on the modeling of these technical restrictions. Due to the flow times of run-of-river plants, which can amount up to several hours, and discrete working points of the pumps of pump-storage power plants, the “state-of-the-art” model of hydro power plants has to be extended by these two restrictions [1].

Due to the simple configuration as well as the fact, that they are not exposed to aggressive chemical substances or relevant thermo-mechanical tensions, hydro power plants feature high reliabilities of 99% and more [6]. Therefore, outages of hydro power plants are not considered in this paper.

C. *Planning Uncertainties*

For the modeling of price uncertainties, i.e. the uncertainties at the spot and intraday market as well as the market for minute reserve, as well as for the modeling of the unknown amount of reserve energy requested by the responsible TSO, scenario analysis can be used [7]. Generally, this method can also be used for modeling outages of power plants. However, this would lead to a dramatical increase of the computation time due to the growing number of scenarios to be modeled.

For computation time reasons, another approach is chosen, which follows the optimization. For each unit, an outage draw considering the unit-specific failure frequency and down-time is performed, resulting in scenarios within the scenario tree modeling the other uncertainties, as shown in Fig. 2, in which the affected power plant is not available.

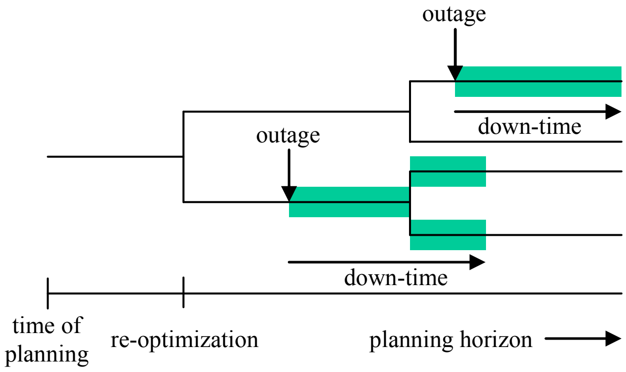


Fig. 2. Modeling of outages in a scenario tree.

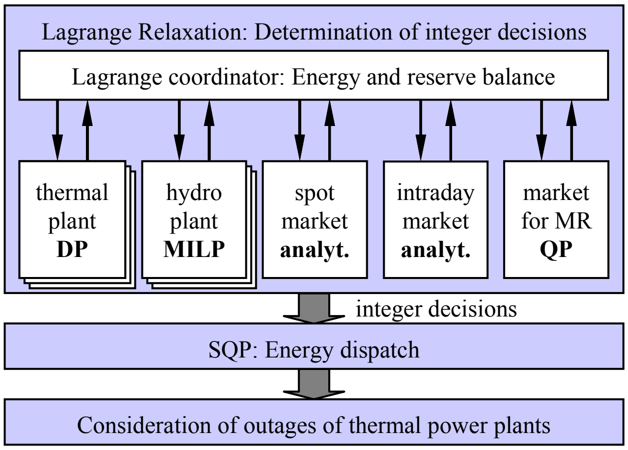
To substitute the dropped out energy, a special reserve contract with high costs is applied in the first hour of an outage. This procedure considers that in this time span no energy can be procured at public trading platforms.

In the following hours, the dropped out energy is purchased at the intraday market with the respective costs.

By this procedure, the number of scenarios modeling the other uncertainties remains identical, although the outages are part of the scenario tree.

III. OPTIMIZATION METHOD

An overview of the method used for the evaluation of the impact of planning uncertainties on operation planning of power plants is given in Fig. 3.



DP: Dynamic Programming
MILP: Mixed Integer Linear Programming
MR: Minute Reserve
QP: Quadratic Programming
SQP: Successive Quadratic Programming

Fig. 3. Overview of the optimization method.

Due to the complex structure of the optimization problem, a decomposition approach is applied in the first stage. By use of Lagrange Relaxation, the problem is divided into subproblems on a system level. Each system component, i.e. each thermal power plant, each interconnected group of hydro power plants and each market, is solved individually applying the most appropriate algorithm. Input parameters for the optimization of the different subproblems are the Lagrange multipliers for the coordination of energy and reserve balances. These multipliers can be interpreted as price incentives and thus, a price incentive is reduced for the next iteration if a requirement is exceeded, and vice versa [8].

This iterative method leads to the problem that the exact fulfillment of system constraints, i.e. the energy and reserve balances, cannot be guaranteed. Hence, a hydrothermal energy dispatch based on the determined integer decisions of the first stage, i.e. the operation status of thermal power plants (standstill, start-up or operation) as well as the operation status of the pumps of hydro power plants, is performed in the second stage which optimizes the remaining continuous non-linear optimization problem by means of successive quadratic programming.

In the third stage, the special consideration of the outages of thermal power plants described in section II.C is carried out.

IV. EXEMPLARY INVESTIGATIONS

In this section, the optimization method described in this paper is used to evaluate the impact of planning uncertainties on operation planning of power plants.

First, the model system under investigation is described. The results of the investigations on planning uncertainties are presented in the latter sections.

A. Model System

The model system used for the exemplary investigations is based on German power supply companies. It is set up according to the structure of the German generation pool and represents approx. 5% of the installed generation capacity.

The hydrothermal generation system consists of 10 thermal power plants with different generation techniques and typical characteristics respectively as well as one pump-storage power plant and one interconnected group of hydro power plants.

In a previous simulation, a typical day-ahead planning for the considered hydrothermal generation system was carried out, in which the generation pool was marketed at the spot market and the market for minute reserve.

Besides the obligation to fulfill the concluded trades determined in the day-ahead planning process, participation at an intraday market is possible in operation planning.

The scenario tree used for modeling uncertain prices at the intraday market as well as uncertain amounts of requested minute reserve energy consists of 25 scenarios. For the investigation on outages of thermal power plants, representative and generation technique-specific values for failure frequency and down-time are assumed, which are input data for the special consideration of these outages described in section II.C. Detailed information on this input data can be found in [8].

The investigations are carried out for an exemplary working day in summer.

B. Exemplary Investigations

The impact of intraday planning uncertainties, i.e. the prices at the intraday market, the amount of requested minute reserve energy as well as outages of thermal power plants, on power plant operation planning will be analyzed in the following investigations. The quantification of the impact is carried out by comparing the contribution margin of deterministic and stochastic optimization results on the one hand and by analyzing the distribution function of the contribution margin in stochastic optimization on the other hand.

1) Prices at the Intraday Market

In this investigation, the impact of uncertain prices at the intraday market will be singularly analyzed, i.e. the requested amount of minute reserve is assumed to be exactly known and power plant outages are neglected.

Fig. 4 shows the contribution margin of the deterministic optimization as well as the expected value of the contribution margin of the stochastic optimization. The deterministic result is slightly higher by 0.2%, because the planning tool determines the optimal solution for one deterministic scenario. This corresponds to an ex-post consideration, in which no planning uncertainties exist and the contribution margin based on optimal power plant operation is calculated. On the contrary, the operation schedule of power plants in stochastic optimization is determined in a way that a flexible reaction on different future developments is possible. This especially applies to the deterministic root of the scenario tree. The determined operation schedule for the root is unique and therefore optimal for the following scenarios as a whole, but not optimal in terms of a single scenario.

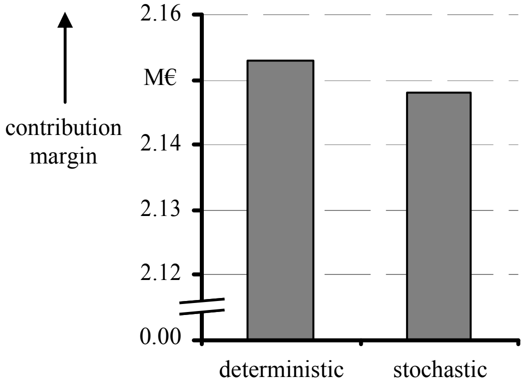


Fig. 4. Expected value of the contribution margins.

The distribution of contribution margins is depicted in Fig. 5. The deviation from the contribution margin of the deterministic optimization is lower than 1% except for one scenario with a deviation of 1.5%. The lower bound of the distribution function is limited to the value of an optimization without the possibility of intraday trading, resulting in limited risks on the one hand. On the other hand, good price constellations at the intraday market might result in major improvements of the contribution margin, corresponding to high chances.

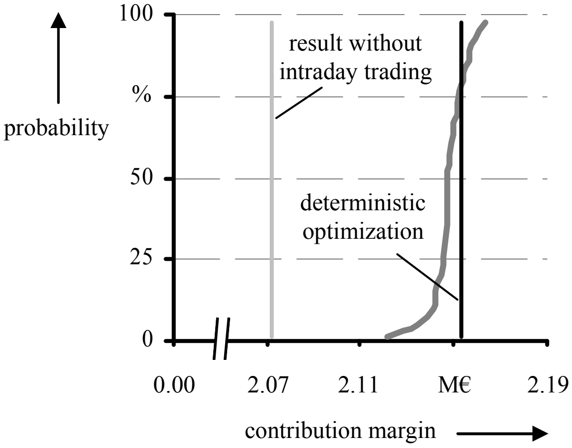


Fig. 5. Distribution of the contribution margins.

The contribution margin of the deterministic optimization is higher than approx. 75% of the 25 contribution margins modeled by the scenario tree. As described before, the determination of power plant operation for one deterministic scenario is optimal, whereas the stochastic optimization yields an operation schedule, which is optimal in terms of all considered scenarios, but usually worse than in a deterministic consideration.

2) *Request of Minute Reserve Energy*

The impact of the unknown amount of requested reserve energy by the TSO is analyzed in analogy to the investigation of unknown prices at the intraday market. Prices at the intraday market are modeled with their expected values, whereas the amount of reserve energy is modeled using the scenario tree described in section IV.A. Outages of power plants are again neglected.

As shown in Fig. 6, the contribution margin resulting from the deterministic optimization is higher by 0.8% compared to the expected value of the contribution margin of the stochastic optimization.

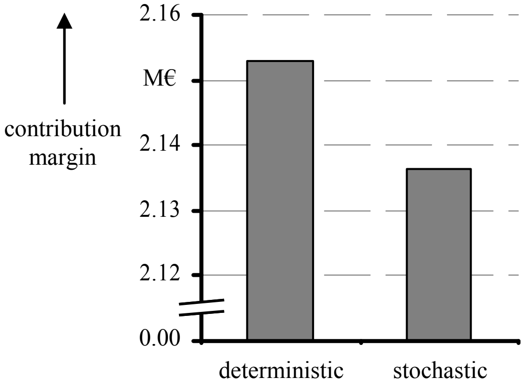


Fig. 6. Expected value of the contribution margins.

The distribution of the contribution margins shown in Fig. 7 shows a nearly linear character. A higher requested amount of reserve energy directly results in a higher contribution margin, due to high energy rates. Hence, lower amounts of requested reserve energy result in lower contribution margins. Therefore, the variation of the requested amount of minute reserve energy in the 25 scenarios has a near linear impact on the contribution margin.

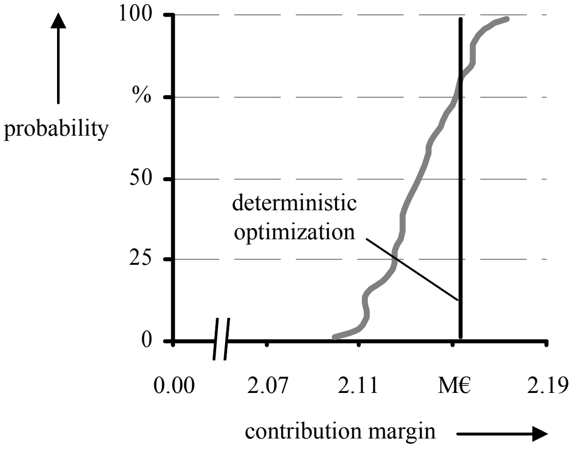


Fig. 7. Distribution of the contribution margins.

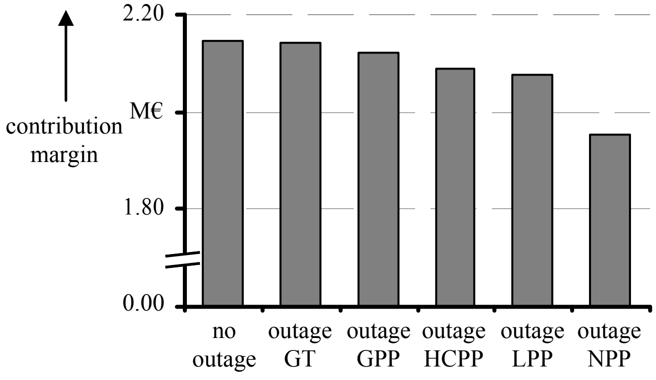
3) *Outages of Thermal Power Plants*

By modeling price uncertainties at the intraday market and uncertain amounts of the requested reserve energy using scenario analysis, each scenario of the scenario tree represents a possible realization of these impact factors, whereas all scenarios are different. Applying the special consideration described in section II.C to model outages, these differences in scenarios would not be seen due to the high reliability of thermal power plants and thus an occurrence of outages in just a low number of scenarios. If outages are the only uncertainty to be considered, most scenarios would actually be identical. To assess the impact of outages of thermal power plants in a suitable way, an approach has to be chosen, which evaluates the impact of the uncertainty on a low number of scenarios.

For this reason, the conditional value at risk (CVaR) is chosen. The CVaR represents the weighted average of the contribution margins lying within a certain probability [9]. For example, the $CVaR_{10}$ is the weighted average of the worst 10% of the scenarios.

In a stochastic investigation, an outage in a good scenario not necessarily results in a higher risk. The high contribution margin in that good scenario might compensate the costs of the outage, resulting in a contribution margin that is still higher than the contribution margin in scenarios where no outage occurs. To consider such effects, the investigation is carried out under consideration of uncertain prices at the intraday market and uncertain amounts of requested reserve energy.

The impact of outages of thermal power plants on the contribution margin is shown in Fig. 8 for six different stochastic simulations. In the reference case, all power plants can be operated normally, i.e. no outage occurs. The other five cases have been chosen representatively from a high number of investigations considering outages. In each simulation, an outage of one power plant of a specific generation technology occurs. The dropped-out energy is substituted by a reserve contract with specific costs of 150 €/MWh in the first hour. In the remaining time, the dropped-out energy is substituted by purchasing energy at the intraday market.



GT: gas turbine power plant
GPP: gas power plant
HCPP: hard coal power plant
LPP: lignite power plant
NPP: nuclear power plant

Fig. 8. Contribution margins of different outage scenarios.

An outage of the gas turbine power plant has just a minor impact on the contribution margin, due to the low amount of dropped-out energy and the high specific generation costs. The impact of an outage of one of the other power plants is significantly higher. The additional costs of the outage result from two aspects. First, the difference of the specific generation costs and the specific costs for the substitution of the dropped-out energy, i.e. the specific costs of the reserve contract in the first hour and the specific prices at the intraday market in the remaining time of the outage, and second, the amount of energy to be substituted. Thus, the impact of an outage of a base-load power plant, i.e. nuclear and lignite power plants, is highest. In this investigation, the outage of the nuclear power plant has the highest impact with a reduction of the contribution margin by 9% compared to the reference case, due to the highest installed power and the lowest specific generation costs.

The distribution of the contribution margins within an outage simulation is depicted in Fig. 9 for the above mentioned six cases. In most cases, about 20% of the scenarios are influenced by the outage, which explains the deflection of the curves. The contribution margin is significantly reduced in these scenarios, which can be seen most considerably in the distribution function of the nuclear power plant. The outage of the hard coal power plant affects by chance the highest number of scenarios, resulting in a reduction of the contribution margin for about a third of the scenarios.

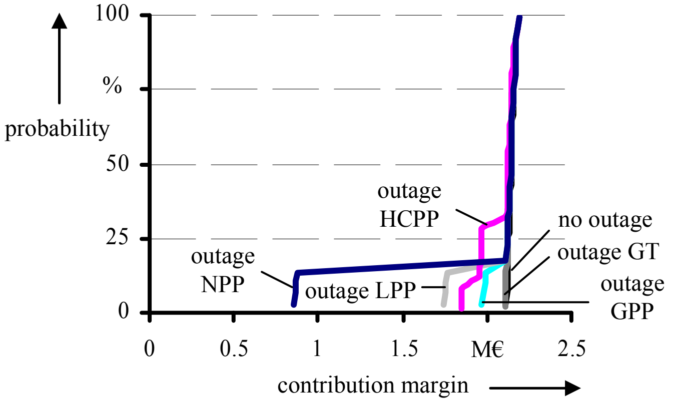


Fig. 9. Distribution of the contribution margin for six outage simulations.

As mentioned before, the additional costs caused by an outage consist of the costs for purchasing energy at the intraday market and the costs for the reserve contract. The impact of the costs for the reserve contract on the $CVaR_{10}$ is shown in Fig. 10.

For a reserve contract with no costs, the additional costs caused by an outage correspond to the intraday trading costs. This impact is higher for cases with high dropped-out energy and a high difference between the prices at the intraday market and the specific generation costs. Here, the outage of a fossil-fired power plant results in a maximum reduction of the contribution margin of 0.27 M€ compared to a reduction of the contribution margin of 1.10 M€ in case of an outage of the nuclear power plant.

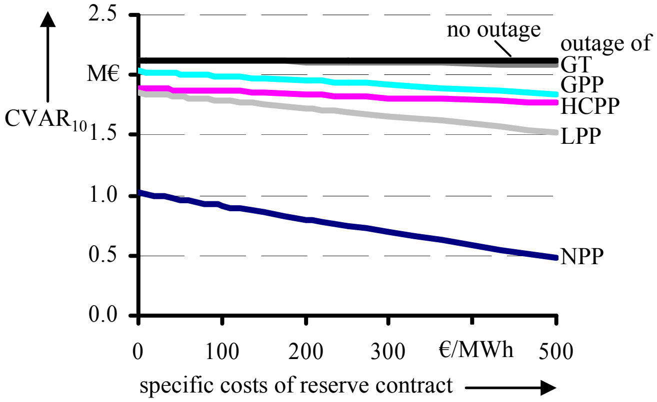


Fig. 10. Impact of specific costs of the reserve contract on CVAR$_{10}$.

Increasing costs of the reserve contract result in a further reduction of the CVaR$_{10}$ according to the amount of the dropped-out energy. The impact of the outage of the nuclear power plant again is highest, whereas even for high costs of the reserve contract, the outage of the gas turbine power plant still has no high risks.

V. CONCLUSION

The results of the investigations show that uncertain prices at the intraday market have no high impact on the contribution margin assuming that the prices at the intraday market are of the same level as prices at the spot market. In this case, the power plants are operated according to the price level at the spot market and the low price difference to the intraday market can only be used sporadically. Assuming higher price differences at the two markets, the impact would be higher due to more arbitrage opportunities. Nevertheless, the participation at the intraday market offers a new degree of freedom in power plant operation planning and thus the contribution margin cannot be worse than the one without intraday trading. This equates to limited risks compared to high chances on higher contribution margins in case of adequate intraday market prices.

The unknown amount of reserve energy requested by the TSO has in contrast a higher impact on the contribution margin. This is based on the energy rates for reserve energy, which are significantly higher than the generation costs of the power plants. Thus, a higher / reduced requested amount of reserve energy directly results in a higher / lower contribution margin. In this investigation, a linear dependency between the requested amount of reserve energy and the contribution margin could be seen.

Regarding the analyzed uncertainties, outages of thermal power plants have the highest impact on the contribution margin. The dropped-out energy is substituted by a reserve contract in the first hour and by intraday trading in the remaining time of the outage. The difference between the prices for the substituted energy and the specific generation costs can especially be high for base-load power plants, resulting in high financial losses.

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VII. BIOGRAPHIES

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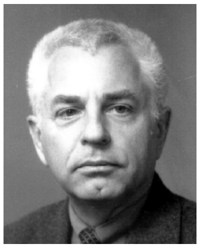

Hans-Jürgen Haubrich was born in Montabaur, Germany, on March 1st, 1941. He studied Electrical Engineering at Darmstadt University of Technology where he graduated in 1965 (Dipl-Ing.). Thereafter, he was member of scientific staff at the Institute of Electrical Energy Supply of Darmstadt University of Technology where he graduated in 1971 (Dr.-Ing.). 1971-1973 he was Freelance for Brown Bovery AG, Mannheim, Germany and 1973-1989 he was member of staff of Vereinigte Energiewerke Westfalen AG, finally as head of the Central Planning Department. In 1985 he was appointed as honorary professor at the University Bochum. Since 1990 he is Professor and head of the Institute of Power Systems and Power Economics at RWTH Aachen University. Since 1997 he is additionally member of the Academy of Science of the federal state North-Rhine Westphalia. Since 2003 he is director of the "Forschungsgemeinschaft für Elektrische Anlagen und Stromwirtschaft e.V." (FGH), Mannheim, Germany.