GRID OPERATION IN THE CONTRARY REGULATION CHALLENGE OF COST REDUCTION AND SUPPLY QUALITY

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ABSTRACT

Within the scope of the regulation grid operators optimise costs and they are responsible for the quality of supply at the same time. Thus grid operators have to solve many optimisation tasks.

This paper deals with the analysis, modelling and optimization of resource management and its influence on the quality of supply and total costs of grid service, especially with the analysis of the different constraints for the optimisation set by European regulators as well as with the analysis and modelling of the restoration process. For answering the question, how to manage a company oriented to cost and quality, a mathematical model is presented, which is able to calculate continuity of supply indices and costs depending on the operational strategy.

1 INTRODUCTION

Quality of supply is a general term and includes four main aspects: security of supply, voltage quality, continuity of supply and commercial quality. In this paper, the continuity of supply is regarded. It refers to the availability of electricity to customers and is usually measured in terms of the non-availability of supply [4, 11].

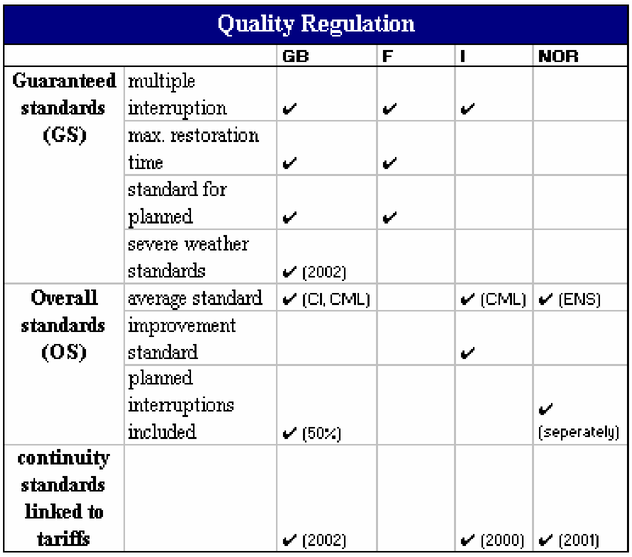
Due to the degree of automation the strongest requirements on the operational optimisation with the goal to keep or to reach a certain quality standard are set in MV and LV. Moreover, the duration of an interruption is the main control variable in operation.

Closer inspection of the restoration process in MV and LV shows several influence possibilities. However, the different driving and working times are the main factors that determine the duration of a supply interruption. Due to that fact the continuity of supply in MV and LV grids depends directly -assuming today's level of automation- on the number of staff in the supplied area involved in the restoration of supply, that is on the resource costs. One problem, which has to be solved in operation is a kind of travelling-repairman-problem [6]. Its goal is to minimize the average time a customer (here interruption) has to wait for a repairman to arrive.

2 QUALITY REGULATION AS A CONSTRAINT FOR OPTIMISATION

With the liberalisation, unbundling and privatisation of energy markets there is a need for regulating the unbundled grid functions. The rate of return regulation, which was introduced in several countries at the beginning (e.g. D, U.S., GB), is criticised for its lack of incentives for efficiency. As economic theory describes, it rather has a tendency for over-investment in quality (overcapitalization) and no incentive for cost efficiency [9]. Within the last years, most countries developed regulation methods with strong incentives for cost reduction, e.g. price or revenue cap regulation. This leads to negative effects on the quality of supply as shown for example empirically for the U.S. energy supply market [10]. Besides, the same study shows that companies with quality standards have reduced quality of supply less than those without.

Therefore, by setting standards for the continuity of supply regulators try to achieve that cost pressure caused by such kind of regulation does not have a detrimental effect on the quality of supply. However, regulators impose different types of continuity standards depending on their main objectives and depending on the change of these objectives the standards vary on size, type and economic effect (table 1). That means, in reverse, that the kind and level of the regulatory requirements have a high impact on the optimal strategy of a supply company. These requirements are the major constraints for operational strategy and grid operators have to pay attention to the fact that regulatory requirements for continuity of supply change over time as shown for some examples in the following.



Quality Regulation

		GB	F	I	NOR
Guaranteed standards (GS)	multiple interruption	✔	✔	✔	
	max. restoration time	✔	✔		
	standard for planned	✔	✔		
	severe weather standards	✔ (2002)			
Overall standards (OS)	average standard	✔ (CI, CML)		✔ (CML)	✔ (ENS)
	improvement standard			✔	
	planned interruptions included	✔ (50%)			✔ (seperately)
continuity standards linked to tariffs		✔ (2002)		✔ (2000)	✔ (2001)

Table 1: Overview on quality regulation

Details of quality regulation

The main objectives of quality regulation are to guarantee a minimum level of quality for each user and to support quality improvement across the system. In order to achieve that, regulators use two different types of standards, guaranteed (individual and worst-served) and overall (average and improvement) standards. Today's regulation schemes combine these two approaches, but for example Italy and Norway started with the overall standards for improving the quality of the system. In contrast, in GB guaranteed standards (maximum duration of interruption) linked to compensations were introduced first [8].

Continuity of supply is quantified with different indices, which measure several attributes of a supply interruption and several aspects of the supply continuity [4, 11]. Basis of these statistical descriptions are:

- duration,
- extent (e.g. affected power) and
- frequency of supply interruptions.

The details of the used indices across Europe are different. For example, the weighting method (number of customers or power affected depending on the objective which kind of customer should be protected) can vary as well as the type of the considered interruptions: planned or unplanned interruptions, short (shorter than 3 minutes, longer than 1 second) or long (longer than 3 minutes) and interruptions from different voltage levels. Moreover, the excluded events differ from country to country. The most common overall standards are:

- customer interruptions per year [11] (CI equivalent to SAIFI, System Average Interruption Frequency Index)
- customer minutes lost per year [11] (CML equivalent to SAIDI, System Average Interruption Duration Index).

Comparative publication of performance figures as a regulation method has indirect effects resulting from the publicity whereas penalty payments or the link between tariffs and continuity have a direct economic and therefore stronger impact. Today nearly all regulation authorities set economic incentives in quality regulation.

In Norway for example, where regulation started in 1992, incentive regulation was introduced in 1997 and combined with quality regulation in 2001 [3]. The regulator's objective is to achieve a socio-economically acceptable level of continuity. Therefore, the costs of energy not supplied (CENS) are linked to tariffs and differ between industrial (6€/kWh, unplanned long interruptions) and domestic customers (0.5€/kWh, unplanned long interruptions) as well as between planned and unplanned interruptions. For each company the expected total interruption costs are calculated annually using historical data and various structural variables. The difference between expected interruption costs and actual interruption costs changes the company's allowed revenues.

The both main objectives of the Italian regulation scheme are to improve the continuity levels and to reduce the regional differences in continuity. Thus, since 2000 improvement standards (zonal and varying between 0% and 16%, basis: two-years-average of CML) were introduced and are linked to incentives/penalties for companies. The goal is to reach 60' CML in rural areas, 40' in semi-urban and 25' in urban areas. These different targets take the structural differences (e.g. load density) into account. Large-area distribution grids with long overhead lines and a small number of customers do not have the same opportunities for reaching a high quality of supply like more intermeshed cable grids with a high density of consumers. The level of interconnectivity, for example, has an influence on the length of an interruption. Other European regulators consider this in the benchmarks for efficiency measurement. Thus, urban grid operators have to fulfil different requirements and optimise their company under different constraints than grid operators for rural areas.

The supplier's (re-)actions for improving the continuity of supply were mainly grid renewal, extension of remote control to MV/LV substations and MV grid automation.

For all of that the CML in the South of Italy adjusted to the North within a few years (fig. 1) and the overall continuity level improved for about 100' between 2000 and 2004.

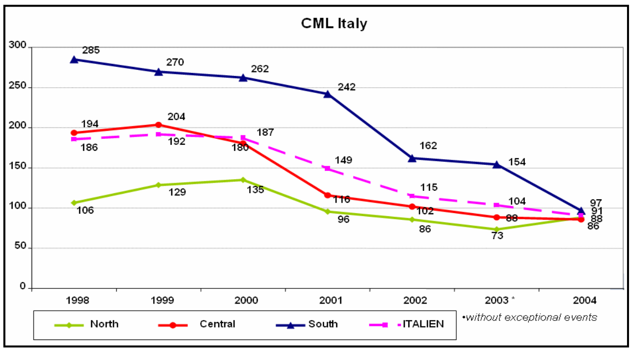


Figure 1: Effects of regulation in Italy [7]

Since 2002, after ten years of price regulation with defined standards and compensation payments for quality of service (e.g. time to restore supply after an outage, supply to worst-served-customers), standards for CML and CI are linked to tariffs in GB. Another change in the British quality regulation concerns standards for severe weather. After severe winds, which affected many parts of England and Wales in October 2002 (2 million consumers affected, on the first day about 45% of the connection points could be restored, last restoration 9 days later) compensation arrangements which depend on the gravity of the situation were introduced.

As one can see, in spite of similar tendencies in the regulation of the continuity of supply, grid companies across Europe are faced with different constraints for their operational optimisation, depending on the regulator's objectives, on the state of the regulation development and on the supplied area. Therefore, a mathematical model should be able to calculate for varying operational strategies:

1. effects on overall standards (e.g. CML)
2. effects on guaranteed standards
3. effects from exceptional events (adverse weather effect).

3 OPERATIONAL STRATEGY AND MATHEMATICAL MODEL

Supply interruptions are rare events. They occur at certain times and at certain places (components) in the grid and each interruption has its physical cause. However, for optimisation of the operational strategy, outages can be assumed as events that occur at random at any time and point in the grid. In our context the operational strategy is characterised by

- number of technicians in the grid
- number of technicians involved in the restoration of a single interruption
- (starting-)positions of the technicians in the grid
- areas of responsibility during periods of normal work and stand-by service.

Supply interruptions and restoration process

Costs and quality of supply can vary both in the spatial (grid, structure, geography) and in the temporal (e.g. weather conditions) dimension.

An interruption of supply in MV/LV is characterized by the place and time of occurrence, x and t_0 respectively, the affected power $P(t)$ and the duration of the restoration process. A typical interruption/restoration profile is depicted in fig. 2. From the time of occurrence (t_0) until the first restoration (t_{min}), the maximum power $P(t)=P_{max}$ is failed. Between t_{min} and the last restoration (t_{max}), the failed power $P(t)$ follows a decreasing step function.

The restoration time as well as the shape of the profile (number and length of the restoration steps) depends on the voltage level, the grid's design, especially on the switching possibilities and the level of interconnectivity, the number of staff involved in the restoration process and their qualification. Besides, the interruption profiles vary between different types of interruptions (differentiation on voltage level and type of component, i.e. cable, overhead line, substation MV/LV, service connection and fault to ground) and the different structured areas. Empirical studies have shown that for a given class of interruptions (i.e. for fixed voltage level, type of interruption, grid design, etc.), the distributions for the maximally affected power P_{max}, the minimal and maximal interruption duration t_{min} and t_{max} respectively follow an extreme value distribution.

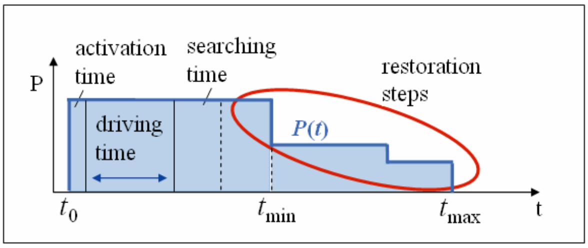


Figure 2: Interruption-profile MV/LV

It has also been shown empirically that in general, the duration between two interruptions of the same class follows an exponential distribution. However, the frequency of interruptions/faults varies among different areas with different grid designs and states (age). The analysis of the interruption data (exceptional events excluded) of a German grid (about 100.000 km of grid lines in MV/LV) shows (fig. 3), that the number of long interruptions in overhead lines per kilometre overhead line varies significantly among areas of different structure (urban, semi-urban or rural) while the fault-rate of cable lines remains nearly constant. Moreover, the frequency among the semi-urban areas varies strongly in spite of the same proportion in overhead lines. Therefore, even in areas with the same structure a different demand for resources arises. It is possible and also necessary to form several spatial clusters which resource management must take into account.

Exogenous factors, especially weather conditions in areas with overhead lines, have a large impact on the fault rates as well. Figure 4 shows the daily number of long interruptions (MV) in 2005. In November an ice storm affected about 10% of the considered grid and led to 60 long interruptions

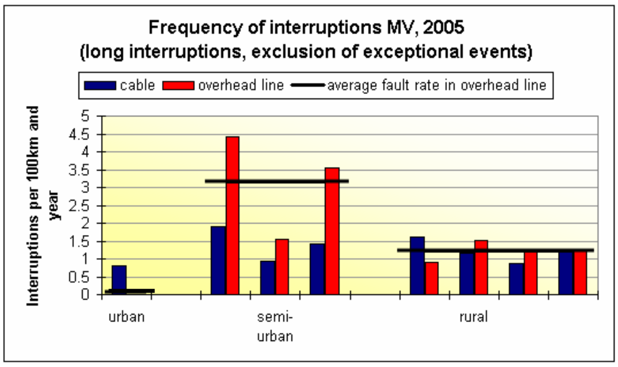


Figure 3: Frequency of faults in MV (urban, semi-urban, rural)

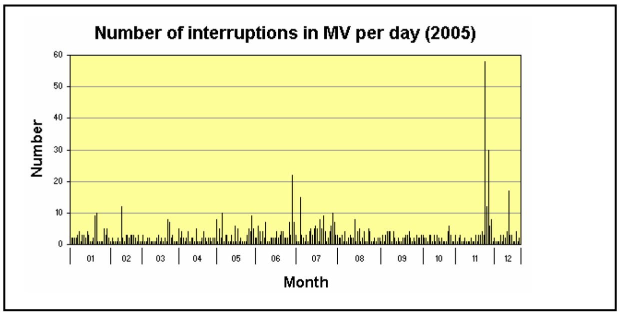


Figure 4: Occurrence of outages over the year 2005 (MV)

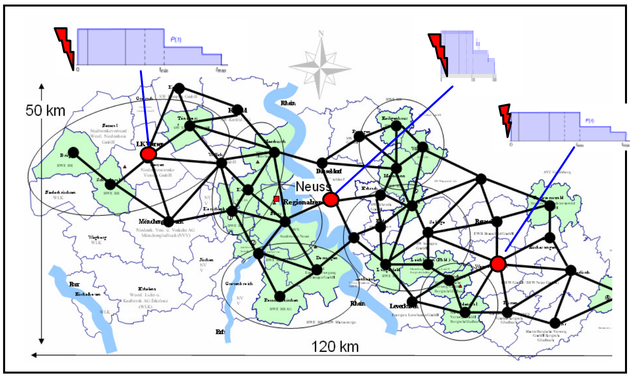


Figure 5: Geography and graph of the supplied area

in MV and to about 1000 long interruptions in LV within two days. To manage such events additional staff is required and the normal organisation must change. Therefore, exceptional events have to be considered separately.

Due to all that a mathematical model has to be able to calculate the effects on the quality of supply (for the whole system as well as for each customer/node) varying

- the number of staff
- their position in the grid
- the kind of exceptional events (scenarios)
- the grid's design and
- the structure of the supplied area.

Model

In the mathematical model, the supplied area is represented by a graph, i.e. a set of nodes and edges (fig. 5). Each node is an aggregation of all electrical components (e.g. substations, lines) in the corresponding geographical area. For first calculations nodes were set in a radius of about 5km. Thus, the results may be affected with some uncertainties arising from such a discretisation.

The edges represent connections (roads) between nodes and are assigned with the corresponding distance and travel time. Consequently, it is assumed that interruptions and therefore a demand for resources only occur in nodes and the travelling of resources is restricted to the above-mentioned graph.

A set of interruptions *I*, an organisation *S* and a set of resources *R* form the input data of the model. The set of interruptions *I* is taken from historical data by assigning each interruption to the nearest node in the model. An organisation *S* is determined by a partition of the graph in areas of responsibility during periods of normal work time and stand-by service.

At each point in time *t*, the currently available resources $R_{avail} \subset R$ (supply of resources) are assigned to the currently active interruptions $I_{active} \subset I$ (demand of resources). A failure $i \in I$ is active, if it has already occurred ($t_0 \geq t$) and if it has not been repaired yet.

In practice the restoration of interruptions in MV is preferred to the restoration of interruptions in LV. The assignment of the appropriate resource, which has to restore the interruption results from an efficiency criterion, which takes into account the affected power, the distance between the resource and the place of the interruption as well as the duration of the restoration.

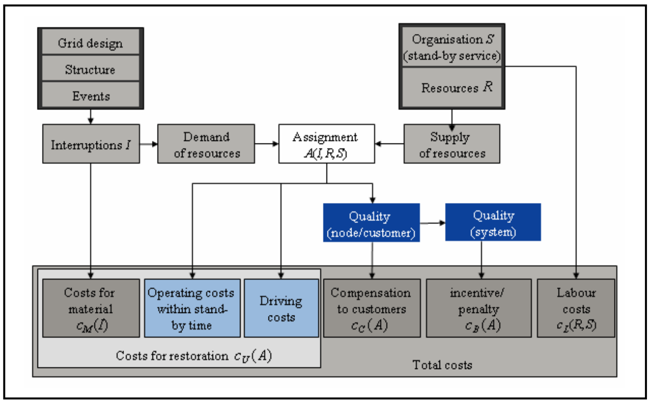


Figure 6: Mathematical model

The performance criterion is motivated by the goal of minimizing the weighted (with the affected power) average interruption duration. This optimization problem is related to the *k*-travelling repairman problem [5, 6]. In the *k*-travelling repairman problem there are *k* repairmen at a common depot *s* and *n* customers (i.e. interruptions of supply in this case) sitting at prescribed distances from each other and the depot. The goal is to find tours on which to send the repairmen that minimize the average time a customer has to wait for a repairman to arrive, while making sure that all customers are served.

As result of the assignment $A(I,S,R)$ of resources to interruptions the indices for continuity of supply and costs are calculated:

- Average interruption duration T_U
- SAIFI
- SAIDI
- Average minimal interruption duration
- Average maximal interruption duration
- Compensation payments (node/customer)
- Costs for the restoration
- Labour costs

The total costs are calculated by adding up labour costs, costs for the restoration, compensation payments, and incentive/penalty. The labour costs $c_L(R,S)$ are costs for staff and stand-by service and depend on the given organisation *S* and the set of resources *R*. Costs for the restoration $c_U(A)$ are costs for material $c_M(I)$, which only depend on the given set of interruptions, as well as driving costs and payments for restoration work done out of stand-by. The two latter are a result of the assignment *A*.

The compensation payments $c_C(A)$ are calculated for each supply interruption and over all affected customers if, as result of the assignment, a maximal allowed duration is exceeded. The incentive/penalty payments $c_B(A)$ arise from the integration of the realized supply quality over all nodes. Hence we have

Total costs $= c_L(R,S) + c_U(A) + c_C(A) + c_I(A)$

An overview of the described model is given in figure 6.

First results

The calculated average system quality of supply (CML) for one year and a given area, with and without exceptional events, under the variation of the number of resources is shown in figure 7. In 'normal' years it is possible for a grid company to reach a high quality of supply with a small number of resources. However, in periods with the occurrence of exceptional events the supply quality decreases significantly for an insufficient number of technicians. In these cases it is important to have the possibility to call in additional resource in a certain time (special organisation).

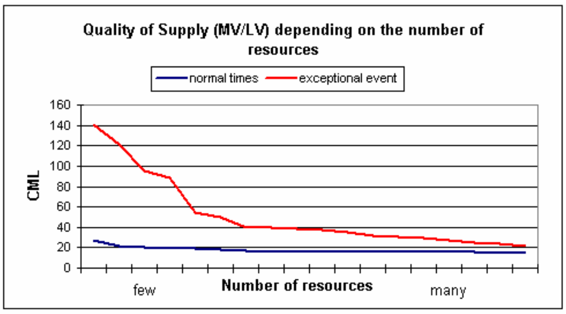


Figure 7: Frequency of faults (urban, semi-urban, rural)

Moreover, it can be shown, that the organisation for supply restoration in MV and LV without regarding exceptional events has to be optimised for the fast restoration of interruptions in MV. The influence of interruptions in LV is marginal during normal times and under today's fault rates. However, in times with a lot of faults (adverse weather effect on overhead lines), interruptions in LV must not be neglected due to their large number of occurrence.

Furthermore, for controlling the overall quality of supply in a grid company, the model allows to find internal standards for areas with different structures by a parameter variation. A first analysis approves that a certain level of continuity of supply can be achieved in an urban area by lower service costs than in a rural area.

4 CONCLUSIONS

By setting standards for the continuity of supply linked with compensations or grid tariffs the regulators try to achieve that cost pressure caused by regulation does not have a detrimental effect on the quality of supply. Depending on the regulator's main objectives and the change of these objectives over time the standards vary in size, type and economic effect across Europe. At the same time these standards are the major constraints for the optimisation of grids and grid services and have to be taken into account.

Due to the technical equipment the strongest requirements on the operational optimisation with the goal to keep or to reach a certain quality standard are set in distribution grids, especially in MV and LV. The duration of supply interruptions is the main control variable in operation and mainly influenced by the number of staff and their positions in the supplied area. Therefore, the continuity of supply depends directly -assuming today's level of automation and grid state- on the resource costs. Moreover, the structure of the supplied area as well as exceptional events directly influence the continuity of supply and costs and have to be taken into account separately for the optimisation.

With the developed mathematical model for the restoration process it is possible to calculate several indices of the continuity of supply and resulting costs for varying frequencies of interruptions, grid design, structure, time period and number of staff.

Hence, it is possible to analyse the dependencies between regulatory requirements and the operational strategy.

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