A GRID OPERATION MODEL: RESOURCE DEMAND FOR AN ADEQUATE QUALITY OF SUPPLY

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Abstract - Based on the regulation of grid fees and the regulatory requirements on the quality of supply, grid operators attempt to find an optimal balance between costs and quality of supply. One main aspect of the quality of supply is the non-availability of supply, which strongly depends on the duration of the re-supply process and therefore on the availability of resources. Consequently, grid operators need to analyze the relation between a certain configuration of resources and the corresponding costs and quality of supply. Focusing on the re-supply process in medium- and low-voltage grids, this paper presents a detailed grid operation model which allows to quantify this relation. Depending on legal, regulatory or strategic requirements, this model allows to evaluate and compare different configurations of resources and the resulting quality of supply.

Keywords - grid operation model, resource management, restoration, quality of supply

1 INTRODUCTION

Today's regulation schemes for grid fees in liberalized electricity markets give strong incentives for cost reduction. As a consequence, grid operators try to reduce their operating costs. This may lead to negative effects on the quality of supply, e.g., as empirically shown in [1] for the U.S. energy supply market. To prevent a decrease in the quality of supply, regulators impose quality standards, which are usually linked to financial incentives. Accordingly, grid operators attempt to find an optimal balance between costs and quality of supply.

One main aspect of the quality of supply concerns the availability of electricity to customers, which is usually measured by the non-availability of supply, i.e., by duration, extent and frequency of supply interruptions. Most incidents in the medium-voltage (MV) and low-voltage (LV) power grid result in an interruption of supply and need a supply restoration on site. A temporary non-availability of resources leads to a delay in the restoration and thus directly influences the quality of supply. Resource management is therefore a major challenge for grid operators, in particular to find an organization (spatial and temporal availability) of resources which not only guarantees the required quality of supply, but also minimizes costs.

In order to analyze the relation between the organization and employment of resources and the corresponding costs and quality of supply, a comprehensive model for the operation of the grid is needed [2]. In the past, various models for the calculation of the grid itself (short circuit-, load flow-, reliability-calculation, etc.) have been developed. Nevertheless, an adequate model for the operation of the grid is still missing. Existing models for the re-supply process are not sufficient, since the effects of limited resources and their organization have not been considered. The duration of supply interruptions is typically sampled from corresponding distributions which are, however, independent of the number of available resources [3, 4, 5]. Other work [6] analytically calculates the distribution of the duration of supply interruptions, but again without incorporating effects of a limited number of resources.

This paper presents the first part of a complete grid operation model, which focuses on the re-supply process in medium- and low-voltage grids after incidents with an interruption of supply. The model not only allows to evaluate a given configuration of resources with respect to costs and quality of supply but also enables a detailed analysis of travel and delay times. The new approach is based on the modeling of the operation of the grid rather than the physical and technical processes on the grid itself. In the first part of the paper the new model approach is presented while in the second part it is applied to a large, existing MV/LV grid. Conclusions from this case study are drawn for the organization of a grid operating company.

2 GRID OPERATION MODEL

The idea of the model is to simulate the operational processes for the restoration of supply after interruptions. A schematic view of the modeling approach is given in Figure 1. The model is mainly driven by the demand for resources for the re-supply on the one hand and the available resources on the other hand. The demand for resources is determined by a set of supply interruptions, and the availability of resources is given by a specific number of employees and equipment and the way they are organized. After the assignment of the resources to the interruptions, the total cost and the indices for the quality of supply are calculated. In the following, the components of the model will be described in more detail.

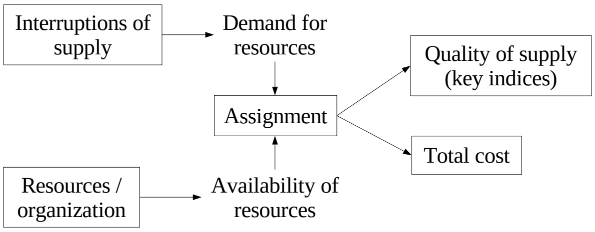

Figure 1: Schematic view of the grid operation model.

2.1 *Power grid and geographical model*

The power grid is modeled by a sufficiently large number of nodes, each aggregating all the electrical equipment of its corresponding (geographical) area. Although spatially simplified, each desired component of the grid can be included in the model. An incident of a component is hence associated with an incident in the corresponding node. The nodes are connected by a set of edges ("roads"), which represent the spatial structure of the supply area. Each edge is assigned an estimated travel time. Figure 2 depicts the graph (nodes and edges) of an exemplary supply area.

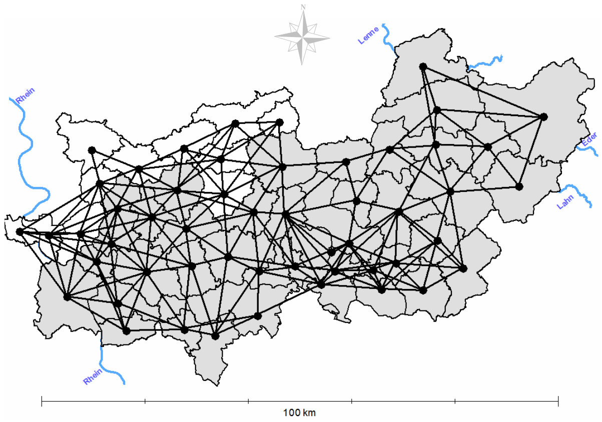

Figure 2: Graph of an exemplary supply area.

2.2 *Interruptions of supply and restoration process*

Previous work [3, 4, 7] often focused on optimal scheduling of the restoration steps, which gave rise to very detailed models for the re-supply processes and the associated tasks. By contrast, the approach in this work assumes a rather aggregated model for the re-supply processes. It describes an interruption of supply by a generic profile (shown in Figure 3) that is characterized by the place and time of occurrence, the affected power and the duration of the restoration process. By simplifying the proceedings once the necessary resources are on site, more emphasis can be placed on the actual assignment and spatiotemporal availability of the resources within the supply area itself.

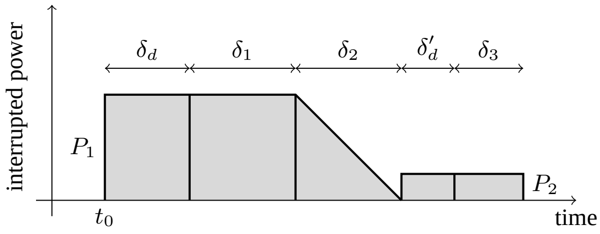

Figure 3: Profile of an interruption of supply.

In the interruption profile, the time of occurrence is denoted by t_0 and the initially interrupted power by P_1. As soon as possible, a resource is activated and sent to the site of the interruption. Let δ_d denote the initial delay (if no resource is available) plus the travel time of the activated resource to the site of the interruption. During δ_1 the interruption has to be analyzed and no power can be restored. Due to the meshed construction of medium-voltage power grids, customers can usually be re-supplied by switching. Consequently, the failed power follows a decreasing step function. To simplify the computations, this step function is approximated by a linear function. Hence, during δ_2, the failed power is assumed to follow a linearly decreasing function. In some cases, additional component repair is required to re-supply the last customers. The repair often needs support of specialized resources. It is characterized by the (remaining) interrupted power P_2, the (possible) delay plus travel time δ'_d of the auxiliary resources and the repair time δ_3. As switching is generally not possible in LV grids, it holds that $\delta_2 = 0$ and $P_2 = P_1$ for interruptions in LV. Focusing on the operational processes (e.g., employment of resources), this characterization of an interruption of supply is sufficient, and the physical processes on the grid itself (e.g., power flow calculations) can be neglected.

The restoration times $\delta_i, i = 1, 2, 3$, denote the working times for a field service employee which is on site and available. It is assumed that the restoration times do not depend on the number of employees and their organization, i.e., $\delta_i, i = 1, 2, 3$, are input data to the model. The values for the interrupted power P_1 and P_2 are also input data to the model. On the other hand, the delay and travel times δ_d and δ'_d strongly depend on the availability of employees and are the main quantities to be calculated within the model.

By analyzing historical data, the failure rates of different types of interruptions and the probability distributions of the input parameters P_1, P_2 and $\delta_i, i = 1, 2, 3$, have been estimated. The types of interruptions are differentiated by voltage level, type of component (e.g., cable, overhead line, substation), and grid design and state. The estimated interruption frequencies and distributions are used to generate interruption scenarios, i.e., sequences of interruptions. By varying the interruption frequencies and distributions, more extreme scenarios (e.g., due to exceptionally adverse weather) can be generated.

2.3 Resources and organization

Whereas a single field service employee – called resource in the following – can usually carry out the first restoration phase of an interruption of supply with standard equipment, the repair phase often requires additional specialized resources. The model therefore involves two different types of resources, each responsible for one phase of the interruptions of supply. It is assumed that each phase can be handled by a single resource (of the correct type). For the repair phase, a single resource is interpreted as a team of (specialized) resources.

A limited number of resources is allowed to travel on the edges which link the nodes of the power grid. The resources are organized in possibly overlapping areas of responsibility, in which they are allowed to work. The areas of responsibility and the availability of the resources are time-dependent, allowing to distinguish between periods of normal work ("day") and stand-by service ("night/weekend"). Whereas all resources are available during normal work, only a subset of (randomly chosen) resources is available during stand-by service.

At the beginning of each period of normal work, the resources are uniformly distributed to the nodes of their corresponding areas of responsibility. This is to model that the resources are not waiting for the next interruption to occur but in reality are occupied with maintenance work. At the beginning of each period of stand-by service, the selected resources are set to the node corresponding to their place of residence where they remain on call in case of an interruption of supply.

2.4 Assignment of resources to interruptions

At a given point in time t, the currently available resources are assigned to the currently active interruptions of supply. An interruption is active, if it has already occurred (i.e., $t_0 \geq t$) and if it has not been repaired yet. It is assumed that the characteristic data of the interruption (P_1, P_2 and $\delta_i, i = 1,2,3$) is revealed as soon as the interruption becomes active. Let $R(t)$ denote the set of available resources and $I(t)$ the set of active interruptions at time t. For $i \in R(t)$ and $j \in I(t)$, define

$$z_{ij} := \begin{cases} 1 & \text{if resource } i \text{ is assigned to interruption } j \\ 0 & \text{else.} \end{cases} \quad (1)$$

The efficiency w_{ij} of assigning resource $i \in R(t)$ to interruption $j \in I(t)$ is defined as

$$w_{ij} := \frac{P_j(t)}{\delta_j(t) + d_{ij}} \quad (2)$$

where $P_j(t)$ denotes the (remaining) interrupted power of interruption j at time t, $\delta_j(t)$ the remaining restoration duration of the current phase, and d_{ij} the travel time of resource i to interruption j. The value w_{ij} can be interpreted as marginal restoration efficiency as it indicates the amount of power which can be restored per time unit. The efficiencies w_{ij} are used to decide the priorities of the interruptions to be re-supplied in case of a shortage of resources as well as to select the nearest resources in case of a surplus of resources. The assignment of resources to interruptions is calculated by maximizing the total marginal restoration efficiency, i.e.,

$$\text{maximize} \sum_{i \in R(t),\, j \in I(t)} w_{ij} z_{ij} \quad (3)$$

subject to the constraints that each resource can be assigned to at most one interruption, i.e.,

$$\sum_{j \in I(t)} z_{ij} \leq 1 \quad \forall i \in R(t), \quad (4)$$

and each interruption must not be worked on by more than one resource, i.e.,

$$\sum_{i \in R(t)} z_{ij} \leq 1 \quad \forall j \in I(t). \quad (5)$$

Consequently, interruptions with higher interrupted power are generally prioritized, e.g., interruptions in medium-voltage are preferred to interruptions in low-voltage. Also, given a single resource and two interruptions with an equal interrupted power and equal restoration durations, the resource is assigned to the closer of the two. In case of a shortage of resources, the interruptions with the least efficiencies will not be assigned and will be delayed.

According to the assignment, the resources travel to their assigned interruptions and repair the failed equipment. The assignment at t remains valid until either an active interruption is repaired, the next interruption becomes active or the availability of resources changes. In any of the three cases, a new assignment is calculated for the new point in time $t'(> t)$.

2.5 Evaluation

After the restoration of all considered interruptions, the desired indices of the quality of supply and the total cost are calculated. The individual modeling of each interruption of supply allows an explicit analysis of travel and delay times. The calculated key indices comprise

- interruption duration (customer average interruption duration index, CAIDI, according to [8]),
- non-availability of supply (system average interruption duration index, SAIDI, and average system interruption duration index, ASIDI, according to [8]),
- minimum and maximum durations of all interruptions,
- duration until arrival on site and delay times of all interruptions,
- energy not delivered in time, and
- total cost.

The total cost is calculated as the sum of labor costs, costs for restoration and compensation payments. The labor costs consist of labor costs for staff during normal work and stand-by service. The costs for restoration include costs for material, driving costs, and payments for restoration work during stand-by service. The compensation payments are payments to customers who suffered from supply interruptions longer than a given maximal standard.

According to the regulatory or internal requirements, (a subset of) these key figures can be used to evaluate a given organization of resources. Moreover, by comparing the calculated key figures of a (parameterized) set of different organizations of resources, the most adequate organization with respect to the given requirements can be determined.

3 CASE STUDY

This section presents exemplary evaluations of the model applied to an existing supply area. The aim is to illustrate how the relation between a configuration of resources and the desired key indices can be analyzed qualitatively and quantitatively.

The considered area has an approximate size of 2500 km^2 and includes both rural and urban zones. The corresponding grid consists of approximately 13500 km of cable lines (MV+LV), 6100 km of overhead lines (MV+LV), and 6000 substations MV/LV. In the model, this area is represented by 55 nodes, each covering a zone with a diameter of approximately 8 km. The nodes are connected by 179 edges with an average travel time of 21 minutes.

In this case study, two scenarios of interruptions are used. Table 1 shows the key data of the scenarios. Scenario “normal” corresponds to a typical set of interruptions during one year and has a rate of 1 interruption per 8.4 hours. Scenario “extreme” models a short period (48 hours) with a large number of interruptions, e.g., due to a storm, and has a rate of 1 interruption per 13.2 minutes.

	number of interruptions		
scenario	MV	LV	period
“normal”	203	839	1 year
“extreme”	99	119	48 hours

Table 1: Scenarios of interruptions.

In this case study, an organization of resources is characterized by four parameters, which are defined as

n_A	the number of areas of responsibility,
ρ_N	the number of resources during periods of normal work given as ratio to the current number ($=: n_N^0$),
n_S	the number of resources during periods of stand-by service, and
1_A	$\in$ {yes, no}, indicating whether (“yes”) or not (“no”) the resources are allowed to work outside their area of responsibility.

The areas of responsibility are the same for periods of normal work and stand-by service.

Six different organizations of resources are considered, each with a varying number of resources during periods of normal work. The parameters of the organizations are given in Table 2. Whereas all organizations $O_k, k \neq 4$ have a fixed number of resources for stand-by service for all values of ρ_N, the corresponding value n_S for organization O_4 is equal to $\rho_N \cdot n_N^0$, the number of resources during normal work. Hence, in organization O_4, all resources are permanently available.

organiz.	n_A	ρ_N	n_S	1_A
O_1	11	$\{0.1, 0.2, \ldots, 1\}$	15	no
O_2	11	$\{0.1, 0.2, \ldots, 1\}$	11	no
O_3	11	$\{0.1, 0.2, \ldots, 1\}$	11	yes
O_4	11	$\{0.1, 0.2, \ldots, 1\}$	$\rho_N \cdot n_N^0$	yes
O_5	8	$\{0.1, 0.2, \ldots, 1\}$	8	yes
O_6	4	$\{0.1, 0.2, \ldots, 1\}$	4	yes

Table 2: Parameterized organizations of resources.

Exemplary evaluations for the following key figures are presented:

- non-availability of supply,
- duration until arrival on site, and
- maximum duration of an interruption.

In order to average the effects of the random starting points of the resources and the random selection of resources for stand-by service, each variant was calculated 20 times and the subsequent results are averages over these 20 runs.

3.1 Non-availability of supply

In the following, the non-availability of supply is measured by the SAIDI and the ASIDI for low- and medium-voltage, respectively.

Figure 4 shows the total SAIDI/ASIDI (MV+LV) for the “normal” scenario of interruptions and organizations O_1, O_2, O_3 in relation to the different numbers of available resources during normal work.

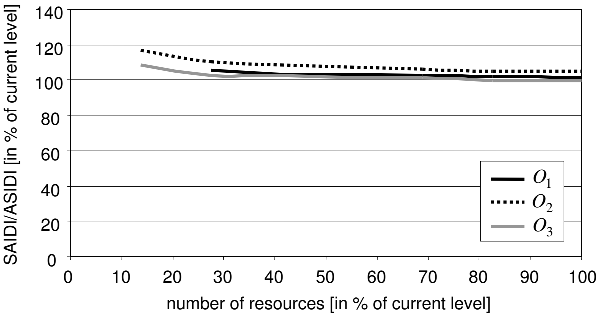

Figure 4: Total SAIDI/ASIDI (MV+LV) for organizations O_1, O_2, O_3 and scenario “normal”.

For all three organizations, a number of resources of more than 40% during normal work has almost no influence on the total non-availability of supply. First, it is to remark that the current number of resources ($\rho_N = 1$) is not laid out for the restoration of interruptions only, but also for maintenance work, which amounts for about 95% of the yearly volume of work. In addition, due to the small number of simultaneous interruptions and the prioritization of MV-interruptions in the assignment, no MV-interruption has to be delayed, even in the case of very few resources. As a consequence, only an increasing number of LV-interruptions has to be delayed for fewer resources. As the contribution of LV to the total non-availability of supply can be neglected, this key figure is hardly influenced by the considered number of resources. However, there are differences between the non-availability of supply of the three organizations. Organization O_1 outperforms organization O_2 for all considered numbers of resources. It can be concluded that the number of resources during stand-by service, which is larger for organization O_1, leads to this effect. Additionally, organization O_3 outvalues organization O_2 for all considered numbers of resources. This is due to the fact that the resources of organization O_3 are allowed to work outside their area of responsibility. Although having fewer resources during stand-by service, O_3 results in approximately the same non-availability of supply as O_1.

In Figure 5, the total SAIDI/ASIDI (MV+LV) for the "extreme" scenario of interruptions is depicted for organizations O_2, O_3, O_4, and O_5. Contrary to the "normal" scenario, the total non-availability of supply is significantly influenced not only by the considered number of resources during normal work but also by the number of resources during stand-by service. This is due to the large number of simultaneous interruptions in the "extreme" scenario. Furthermore, the effect of allowing the resources to work outside their area of responsibility is considerably higher (compare O_2 and O_3). Due to the permanent availability of the resources, organization O_4 clearly outvalues the other organizations. This hints at the necessity of additional resources during periods with a highly increased number of interruptions.

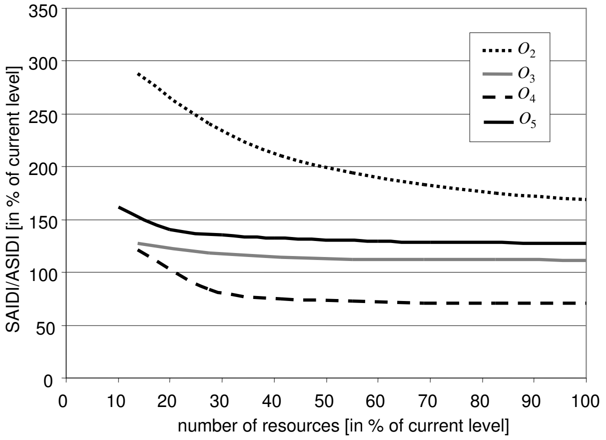

Figure 5: Total SAIDI/ASIDI (MV+LV) for organizations O_2, O_3, O_4, O_5 and scenario "extreme".

3.2 *Duration until arrival on site*

The duration until arrival on site is defined as the time between the occurrence of the interruption and the first time a resource arrives on site. The duration until arrival on site is an important internal performance measure but also a possible regulatory key figure.

Figure 6 shows a part of the empirical distribution function of the duration until arrival on site for all interruptions of the scenario "normal" for the organizations O_3 and O_6, each with $\rho_N = 0.2$. Whereas with organization O_3, 90% of all interruptions have a duration until arrival on site of at most 30 minutes, organization O_6 only results in a duration until arrival on site of slightly less than 50 minutes with the same probability. Again, the results indicate a strong influence of the number of resources during stand-by service. As organization O_6 has much less resources during stand-by service than O_3, more interruptions are delayed and the duration until arrival on site is worse.

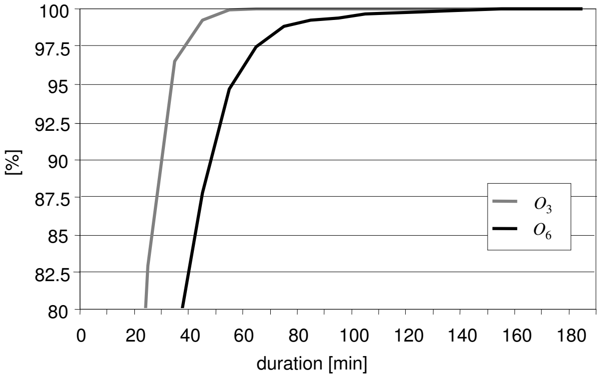

Figure 6: Empirical distribution function of the duration until arrival on site for organizations O_3 and O_6 (with $\rho_N = 0.2$) and scenario "normal".

3.3 *Maximum duration of an interruption*

The maximum duration of an interruption is the time between the occurrence of the interruption and the last restoration by switching or repair. This key figure is of interest if the regulator requires compensation payments for interruptions with a maximum duration of more than an accepted limit.

In Figure 7, the average of the maximum duration of all LV-interruptions of the "extreme" scenario is depicted for organization O_5. This key figure reacts even more sensitively to the number of resources during normal work than the non-availability shown in Figure 5.

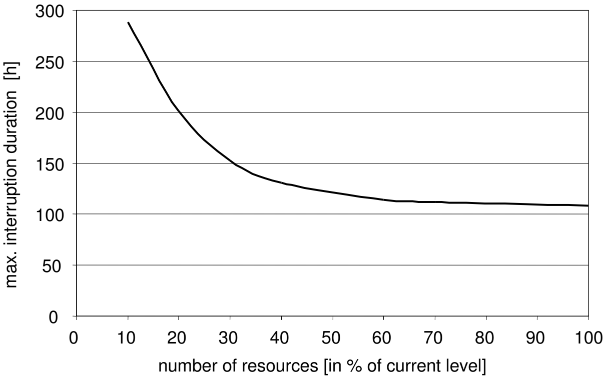

Figure 7: Average of the maximum duration of all LV-interruptions of the "extreme" scenario for organization O_5.

Furthermore, Figure 7 shows that LV-interruptions cannot be neglected in case of an extreme scenario, although their contribution to the highly aggregated key figure "non-availability" is marginal. Beside the compensation payments, such long-lasting LV-interruptions lead to a bad reputation of the grid operating company.

4 CONCLUSIONS

In order to satisfy regulatory requirements and increase the competitiveness, grid operators need to analyze the relation between the organization and employment of resources and the corresponding costs and quality of supply. Due to the detailed modeling of the availability of resources and the interplay with the re-supply process after interruptions of supply, the presented approach enables grid operators to quantify this relation.

The case study confirms that the presented model allows to quantify effects of different organizations of resources on costs and quality of supply. It also illustrates how the calculated key figures can be used to compare different organizations of resources with respect to various regulatory requirements.

The model provides a useful tool to support strategic decisions concerning the organization of resources. According to legal, regulatory or internal requirements, the best organization of resources among a parameterized set of alternatives can be found.

In further work the existing grid operation model for MV/LV-interruptions will be extended. Models for interruptions in high- and extra-high-voltage as well as maintenance and grid construction will be added. This will result in a complete grid operation model to evaluate the organization of grid service companies.

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