Comparison of Estimates of the Costs of Penalty Payments in a MV Distribution Network Obtained by Simulation and from Observed Data

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Abstract—The paper is devoted to the estimation of the costs of penalty payments to be paid by distribution companies when a guaranteed standard of electricity supply continuity with a limit of the annual number of supply interruptions and a limit of their total annual duration has been introduced. Estimates obtained by simulation and from the observed data for a large 22 kV overhead distribution network are compared. As the electricity supply reliability is being evaluated for individual customers when assessing the compliance with the guaranteed standard, the comparison is carried out at level of individual feeders. Two models of the annual number of supply interruptions on a feeder and two models of the duration of supply interruptions are considered in the simulations. The elaboration of new reliability models was aimed at making the results of the simulation more accurate so that they may enable us to evaluate the effectiveness of the prepared investment and operational interventions to be undertaken in presently operated and in newly designed networks.

Index Terms—distribution networks, reliability, simulation, Monte Carlo, costs of supply interruptions, penalty payments

I. INTRODUCTION

In the present-day environment, managing staffs of the distribution companies are faced with increasing pressure to reduce investment and operational costs of distribution networks. This pressure may result in the deterioration of the reliability of electricity supply to customers which, however, need not manifest itself at once. In order to prevent this, energy regulatory offices in many countries introduce various tools which should afflict financially the companies with an increasingly low level of the reliability of their electricity supply to customers [1], [2]. The overall standards of electricity supply continuity based on aggregated indices for the whole system do not provide sufficient data for evaluating the level of supplying individual supply points in the network and for comparing the performance of the networks. Therefore, the guaranteed standards of electricity supply continuity are being implemented in many EU countries [2]. The guaranteed standards serve mainly as the protection of small consumers and they specify the minimum level of the electricity supply quality which must be maintained for each individual customer at the given voltage level. That is the reason why these standards are based on primary reliability indices (non-aggregated indices connected with individual supply points). For example, the guaranteed standard can include a limit of the annual number of supply interruptions and a limit of their total annual duration. If someone of these limits will not be complied with for any customer of the given distribution company, the company will be obliged to assign and pay a certain penalty to the affected customer.

In the Czech Republic, the observation of overall aggregated reliability indices is only required by the Energy Regulatory Office now. Guaranteed standards of the quality of electricity supply and of related services including, e.g., a standard of supply restoration after failure, a standard of not-breaching the planned duration of electricity supply limitation and a standard of replacing the damaged fuse in customer's premises have been introduced since 2006. The introduction of a guaranteed standard of the electricity supply continuity with limits of the annual number of supply interruptions and of their total annual duration is foreseen in the amendment of the presently valid regulation.

The first analyses already revealed that the costs of such penalty payments may represent a significant risk of financial losses for the Czech distribution companies [3]. It is therefore suitable that appropriate tools for a sufficiently accurate estimation of the costs of penalty payments be available already now. It would be desirable that these tools could be applied both to the present state of the network and to that after possible reconstructions of or investments into the network. As the interventions undertaken in the networks have a long-term validity, it would be advantageous for the distribution companies to respect – when choosing such interventions – the customers’ perspective of the reliability on which the regulatory tools are based.

The authors would like to thank EGU Brno, a.s. for a support during the preparation of the paper. This paper contains also the results of research works funded from project No. MSM0021630516 of the Ministry of Education, Youth and Sports of the Czech Republic.

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II. NON-HOMOGENEITY OF THE RELIABILITY AND NON-LINEARITY OF THE FAILURE RATE OF FEEDERS OF THE DISTRIBUTION NETWORK

The evaluation of the guaranteed standards of electricity supply continuity requires this continuity to be evaluated at level of individual customers (simply speaking at level of individual feeders). However, the performed analyses lead us to conclusion that conventional approaches to modelling the reliability of the distribution networks do not often enable the conditions on individual feeders to be distinguished sufficiently [4] - [6].

From the point of view of the equipment itself the MV overhead lines of the same technical parameters have comparable properties. However, their functional capability as regards the failure rate (they are considered as a transmission element in the system) is predominantly affected by the actioning of external influences (approx. 80%). Considerably different numbers of failures are observed, e.g., even on lines built in parallel when each of them has been built on another side of a valley. Even relatively near lines may be subjected to the actioning of wind and icing in a different way. For that reason, when analysing the reliability of distribution networks we respect the principle of non-homogeneity [4] which manifests itself both in the number and in the duration of supply interruptions to the customer.

The analyses of data on failures lead us also to the conclusion that even the lines of the same (approximately the same) length may have a considerably different failure rate. The assumption of a linear dependence between the frequency of occurrence of failures on a line and its length is thus not justified in such a situation.

This is illustrated by a column graph in Fig. 1 which shows the number of failures on feeders of a 22 kV overhead distribution network with length of 10 km to 15 km during 12 years. Solid lines mark off the zone in which these numbers should move according to the estimation carried out by using the specific failure rate $\lambda_k$ for overhead lines in this network and for feeder lengths $l_k$. Real numbers of failures during 12 years are in the range of 2 up to 141 failures. However, according to the estimation made by using $\lambda_k$ these numbers should move between 17 and 26 failures. A similar non-linear dependence may be observed in cable networks, too [3].

The above-mentioned facts result in the necessity to look for new reliability models which would be able to provide results with acceptable accuracy not only at level of the network as a whole but mainly for individual feeders. A new model for simulating the annual numbers of supply interruptions on feeders and the durations of such interruptions is therefore proposed in Sections III and IV. An approach enabling us to compare easily the proposed models with the existing ones using the real observed data is outlined in Section V.

![Fig. 1. Non-homogeneity of the number of failures on feeders of a 22 kV overhead network with length of 10 km to 15 km during 12 years](image)

III. MODELLING OF ANNUAL NUMBERS OF SUPPLY INTERRUPTIONS

A large 22 kV overhead distribution network with 368 feeders was considered in our study. Its reliability was observed during 12 years. The feeders of this network are equipped with protection devices only at their beginnings. For simplification, a gradual supply restoration is not considered and the influence of failures in other parts of the network (in the LV network and in the transmission system) is neglected.

We did not use the usual sequential simulation using the Monte Carlo method in which the time to supply interruption and the duration of supply interruption are generated for individual feeders of the network at random. Instead, annual numbers of supply interruptions on individual feeders were generated directly. Corresponding durations of individual supply interruptions were then generated to them. This approach not only simplifies the evaluation of the results of the simulation but, especially, it provides advantages when deriving input data of the models based on a limited information about the failure rate of the network under study [7], [8].

If it would be desirable to work with the specific failure rate, the exponential distribution of the time to failure $t_f$ that is usually used in the sequential simulation and has the function of density

$$f(t_f) = \begin{cases} 
\lambda_k \exp(-\lambda_k t_f) & t_f > 0 \\
0 & t_f \leq 0 
\end{cases}$$

(1)

would pass onto the Poisson distribution of a discrete random quantity represented, in this case, by the annual number of supply interruptions on the feeder $N_v$. 

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The probability function of this distribution has the following form:

\[
P(N_v = n_v) = \begin{cases} 
(\lambda_v t_v)^{n_v} \exp(-\lambda_v t_v) & n_v = 0; 1; 2; \ldots, \\
0 & \text{otherwise}
\end{cases},
\]  
(2)

where \( n_v \) is the annual number of supply interruptions on the feeder. This approach to the modelling of annual numbers of supply interruptions will be designated as model \( M_n^{(0)} \).

As an alternative we proposed a model \( M_n^{(1)} \) that tries to express the non-homogeneity of the number of supply interruptions on the feeders in a better way. In this model, individual feeders are divided into several groups according to the number of supply interruptions \( n_{v,s} \) recorded on them during a sufficiently long period of observation (12 years in case of the examined overhead network). This model is based on the customer’s perspective of the reliability. The causes of supply interruptions which are of no interest for the customer are not considered in it.

With regard to the span of the values \( n_{v,s} \) and to the number of feeders in the network we chose five subsets of feeders \( \Pi_{n1}^{(1)} \) to \( \Pi_{n5}^{(1)} \). The following intervals of the numbers of supply interruptions during the period of observation correspond to then: \( n_{v,s} \in (0; 10>, (10; 20>, (20; 40>, (40; 80>, and (80; \infty). A distribution that would best express the annual number of supply interruptions on the feeder was then identified for each of these subsets.

The negative binomial distribution (NBi) having the probability function

\[
P(N_v = n_v) = \frac{\Gamma(\alpha_1 + n_v)}{n_v \Gamma(\alpha_1) \alpha_2} \alpha_1^{\alpha_1} (1 - \alpha_2)^{n_v},
\]
(3)

where \( \alpha_1 \) and \( \alpha_2 \) are parameters of the distribution calculated from the corresponding data revealed to be the most suitable for all subsets.

Probability functions of these chosen distributions are demonstrated in Fig. 2 (they are drawn continuously for the purpose of clarity in spite of the fact that the matter concerns a discrete random variable). Differences between the distributions for individual subsets can be clearly seen here.

The use of the Poisson distribution for individual subsets of feeders would give too optimistic probabilities for multiple supply interruptions. The differences between the Poisson distribution, the negative binomial distribution and the observed data for the subset \( \Pi_{n2}^{(1)} - n_{v,s} \in (20; 40> \), are shown in Fig. 3.

IV. MODELLING OF DURATIONS OF SUPPLY INTERRUPTIONS

Several approaches can also be applied when modelling the durations of supply interruptions. Two models of the durations of supply interruptions on the feeder \( M_t^{(1)} \) \( M_t^{(2)} \) are considered in this paper.

Model \( M_t^{(1)} \) uses the logarithmic normal distribution the parameters of which differ according to the area where the feeder is situated.

Fig. 2. Probability function of the distribution of annual numbers of supply interruptions on feeders in model \( M_n^{(1)} \)

Fig. 3. Model of the annual number of supply interruptions on feeders with 20 to 40 interruptions during 12 years – comparison of the negative binomial distribution (NBi) and the Poisson distribution (Po) with the observed data

Fig. 4. Mean durations of supply interruptions on feeders
However, this model does not enable us to assess the non-homogeneity of durations of supply interruptions caused by the total availability of the whole feeder and of its distribution transformer stations. It is therefore possible to classify the feeders according to the mean duration of supply interruptions on the feeder $t_{pv}$ (model $M^{(1)}$). However, such a classification may be applied to feeders on which at least two supply interruptions were recorded during the period of observation, i. e. on 92% of feeders of the examined network ($M^{(1)}$ should be used for the remaining feeders). As can be seen in Fig. 4, great differences exist between the mean durations of supply interruptions on individual feeders (from 2 min to 893 min). Regarding this span and the number of the recorded supply interruptions (about 13 000) we could define six intervals of the mean duration of supply interruptions on the feeder $t_{pv}$: (0; 60> min, (60; 120> min, (120; 180> min, (180; 240> min a (240; ∞) min.

As the standard deviations of the durations of supply interruptions $\sigma(t_{pv})$ move within a relatively wide span in the majority of intervals $t_{pv}$, the feeders in individual intervals $t_{pv}$ (except for feeders with $t_{pv} \in (240; \infty)$ min) were further divided into two subgroups: feeders with a small standard deviation and feeders with a great standard deviation. We thus obtained 9 subsets of feeders in total for which the logarithmic normal or gamma distributions were used.

V. COMPARISON OF THE RESULTS OF SIMULATION WITH REAL DATA

A. Calculation of the costs of penalty payments

Guaranteed standards of electricity supply continuity may be formulated in several ways [3]. Let us consider that exceeding the limit of the annual number of supply interruptions $L_n$ or the limit of their total annual duration $L_t$ is taken as breaching the guaranteed standard. Such a standard is evaluated yearly and in case of exceeding one of both limits the distribution company is obligated to pay a penalty in the height of $C_p$ (its value does not depend on the extent of exceeding the limits) to each affected customer down to the LV level. The value $C_p = 33 €$ was considered for the needs of our study. It corresponds to the expected height of penalty payments for one supply point in the Czech Republic (1000 CZK) approximately.

As such a standard has not yet been introduced in the Czech Republic it is convenient to carry out analyses for a wider spectrum of possible values of the limits, e. g. for

- $L_n = \{3; 4; 5; 6; 7; 8; 9; 10\}$ rok$^{-1}$,
- $L_t = \{90; 180; 240; 300; 360; 420; 540; 600; 720\}$

min.year$^{-1}$.

The span of the values of these limits are based on limits used by other countries in the guaranteed standards valid for overhead networks and, at the same time, they cover the ranges corresponding to conditions existing in our overhead networks (respecting the fact that only supply interruptions in the MV part of the network are taken into consideration).

Costs of penalty payments for each feeder may then be determined for the chosen combination of limits. By summing up these costs for all feeders in the network we obtain the total costs of penalty payments in the network.

B. Evaluation of the accuracy

Four combinations - $M^{(1)} + M^{(1)}$, $M^{(1)} + M^{(2)}$, $M^{(6)} + M^{(1)}$, $M^{(6)} + M^{(2)}$ were set up from two models (mentioned above) of annual numbers of supply interruptions on the feeders and from two models of durations of supply interruptions. A simulation was carried out for each of them (10 000 years were always simulated). The average annual costs of penalty payments for each feeder $C_{pv}$ and the total average annual costs of penalty payments in the network $C_{pv}^*$ were then calculated from the results of the simulation.

The objective of these simulations was to evaluate the accuracy of individual combinations of models. Such an evaluation can be made by using the observed data. As the guaranteed standards evaluate the electricity supply continuity at level of individual feeders (more precisely of individual consumers), it is appropriate both to analyse the differences of the whole-network quantities obtained by simulation and from the observed data, and to emphasize the accuracy of simulation at level of individual feeders as well.

The available time series (12 years) is relatively short for these purposes. Of course, it is also burdened with a year-to-year fluctuation that is typical for the failure rate of overhead distribution networks. For that reason, usual statistical tools and tests cannot be used. So that the accuracy of the considered combinations of models may be evaluated, the costs $C_{pv}$ were compared with the average annual costs of penalty payments $C_{pv}^*$ on the feeder $v$ derived from the real data on supply interruptions for a 12-year period of observation.

The relative difference of the average annual costs of penalty payments on the feeder $v$ obtained by simulation compared with the costs obtained from the data (expressed in percentage) is given by equation

$$\delta C_{pv} = \frac{C_{pv} - C_{pv}^*}{C_{pv}^*} \times 100$$

(4)

Distribution functions of the absolute values of relative differences of the average annual costs of penalty payments $|\delta C_{pv}|$ are drawn in Fig. 5 for the four examined combinations of models and for one chosen combination of limits of the guaranteed standard of electricity supply continuity ($L_n = 6$ year$^{-1}$ and $L_t = 600$ min.year$^{-1}$). It can be seen that the combinations of limits, in which the annual supply interruptions were simulated differently on individual feeders according to their number of supply interruptions during the period of observation by using the negative binomial distribution ($M^{(1)} + M^{(1)}$ a $M^{(6)} + M^{(2)}$), provided us with results with a more favourable distribution of differences when compared with the real data.
Fig. 5. Distribution functions of the absolute values of relative differences of the average annual costs of penalty payments on the feeders for the examined combinations of models when considering the limits \( L_u = 6 \text{ year}^{-1} \) and \( L_t = 600 \text{ min.year}^{-1} \)

### Table I

**Number of feeders accounting for 25% and 50% of the costs of penalty payments**

<table>
<thead>
<tr>
<th>( L_n )</th>
<th>( L_t )</th>
<th>4</th>
<th>6</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{[year]^{-1}}</td>
<td>\text{[min.year]^{-1}}</td>
<td>720</td>
<td>720</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td><strong>Feeder accounting for</strong></td>
<td><em><em>25% of ( C_{pp}^</em> )</em>*</td>
<td>\text{[%]}</td>
<td>\text{[%]}</td>
<td>\text{[%]}</td>
<td>\text{[%]}</td>
</tr>
<tr>
<td>\text{[%]}</td>
<td>\text{[%]}</td>
<td>3.8</td>
<td>3.0</td>
<td>4.4</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Feeder accounting for</strong></td>
<td><strong>50% of ( C_{pp} )</strong></td>
<td>\text{[%]}</td>
<td>\text{[%]}</td>
<td>\text{[%]}</td>
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</tr>
<tr>
<td>\text{[%]}</td>
<td>\text{[%]}</td>
<td>10.3</td>
<td>8.4</td>
<td>11.4</td>
<td>10.3</td>
</tr>
</tbody>
</table>

For nearly 50% of the total number of 368 feeders the difference \( | \delta \| \) of these combinations of models did not exceed 30% while, when applying the approach based on the specific failure rate \( (M_n^{(0)}) \), the difference \( | \delta \| \) did not exceed 30% only on 27% of the feeders approximately.

Complying with the results obtained, the classification of feeders according to the mean duration of supply interruptions on the feeder yields no pronounced effect (model \( M_t^{(2)} \)), when compared with the classification made only according to the area where the feeder is situated (model \( M_t^{(1)} \)).

Nevertheless, it may be stated that, in the given case, the distribution \( | \delta \| \) obtained by using the models \( M_n^{(1)} + M_t^{(2)} \) is more favourable than that obtained by using \( M_n^{(1)} + M_t^{(1)} \).

### VI. Practical Application of the Costs of Penalty Payments on the Feeders

Although the guaranteed standards of electricity supply continuity have not yet been implemented in many countries, in some of them (e.g., in the Czech Republic) we may see a marked trend to make the requirements on the electricity supply quality more stringent. The requirements are imposed by regulatory bodies on the distribution companies through standards of different types. As the interventions undertaken in the network manifest themselves for a long period of time, it is convenient to include the costs of penalty payments into optimization processes already now.

The evaluation of the guaranteed standards yields some advantages when compared with the conventional evaluation of the reliability based on the estimation of the energy probably not supplied and of the price for it. The application of the guaranteed standards really respects the customer’s perspective of the reliability. Their introduction would mean a real (not only fictive) risk of financial losses for the distribution companies. This approach also enables the reliability to be easily expressed in financial terms because it is not necessary to estimate the costs of the energy not supplied which is very problematic in case of small consumers. As we proceed by individual feeders (more precisely by individual supply points) when evaluating the standard, we can easily find the feeders that are most contributing to the total costs of penalty payments. The interventions in the network can then be undertaken with a precisely defined aim and with a clear impact on the reduction of these costs.

An example from the 22 kV overhead network may be given for illustration. The performed analyses revealed that only a small number of worst feeders dominantly account for the costs of penalty payments for the whole network \( C_{pp}^* \) (assessed from the observed data only). As can be seen in Table I, only about 8% to 11% of exposed feeders account for 50% of the costs \( C_{pp} \), depending on the choice of the limits \( L_u \) and \( L_t \). These several feeders are thus convenient candidates for undertaking appropriate measures from which the company could expect an appreciable contribution to the reduction of possible costs of penalty payments.

### VII. Conclusion

The introduction of guaranteed standards of electricity supply continuity with penalty payments for their breaching represents an important step that can have a strong impact on the economy of the distribution companies. The costs of penalty payments are real costs, no fictive ones (as, e.g., sometimes the costs of energy not supplied for small consumers for whom the estimate of the price of energy not supplied is highly problematic). The evaluation of these standards requires another approach to be applied to observing and analysing the reliability of the network than that based on using usual aggregated indices (SAIFI, SAIDI, etc.). We assume that the problem does not consist in the evaluation made year-by-year but especially in the level at which this evaluation is carried out. The fulfillment of the guaranteed standards is evaluated for individual consumers (under simplification used in this paper: at level of individual feeders). On the contrary, the overall standards, or the aggregated indices (SAIFI, SAIDI, etc.) are evaluated for considerably larger complexes – for the network as a whole. The differences between individual feeders then wear away and a mutual compensation of errors take place. Therefore, it is necessary to look for such tools that would enable us to obtain a true picture of the reliability at level of individual feeders.
With this objective in mind we proposed a new model of the annual numbers of supply interruptions on the feeders and a new model of their durations. The estimates of the costs of penalty payments resulting from the performed simulations were compared with the estimate based on the observed data for a twelve-year period of observation. It was revealed that the created models $M_1(1)$ and $M_2(1)$ give better results at level of individual feeders than usual models do ($M_0(0)$ and $M_1(1)$).

Therefore, when simulating the annual numbers of supply interruptions it is useful – for the distribution network under study – to respect the non-homogeneity of supply interruptions on individual feeders and to exploit the classification of feeders according to their number of supply interruptions for a sufficiently long period of time. The principle of non-homogeneity also respects the classification of feeders according to the mean duration of supply interruptions and to the standard deviation when simulating the durations of supply interruptions. Complying with our experience, such approaches give good results for other networks as well.

A quality modelling of the reliability of individual feeders enables us to identify the worst feeders in the given network. It is then useful to concentrate attention just to these feeders when refurbishing and retrofitting the network because, as it became evident, only several worst feeders mostly participate in the costs of penalty payments. In the examined network, only about 8% to 11% of feeders account for 50% of the costs of penalty payments (depending on chosen values of the limits of the guaranteed standard of electricity supply continuity).

The results of studies based on the above models may also be used by the Energy Regulatory Office when setting up the tools of regulation. This setting cannot be made, for example, by a simple copying of foreign standards of electricity supply continuity but it necessitates more profound analyses of conditions existing in the networks to which these tools will be applied.

So that the application of such standards may become a real source of motivation for the distribution companies, it is necessary to consider carefully the particular setting of limits based on detailed analyses respecting external conditions in which the given networks operate. We assume that the application of the guaranteed standards provides a useful solution that may motivate the distribution companies to maintain the respective level of reliability in their networks and, at the same time, it clearly identifies the bottlenecks in the network.

VIII. REFERENCES


IX. BIOGRAPHY

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