The paper presents the results of the analysis of the estimate of the cost of penalty payments for breaching the guaranteed standard of the electricity supply continuity. A real municipal MV cable distribution network was analysed. The estimate of the cost of penalty payments was obtained by simulating supply interruptions in the network by using a modified Monte Carlo method. The analysis is performed for various types of the guaranteed standard. Both the limit of the annual number of supply interruptions for a consumer and the limit of the total annual duration of supply interruptions are considered. The costs of penalty payments for the annual evaluation and the evaluation based on two-year mean values are compared. The results obtained reveal that, for the given network, the cost of penalty payments can represent an amount of money that cannot be neglected. Some conclusions are therefore given at the end of the paper which may be used by the managing staff of the distribution company when optimizing the distribution network just with the aim of reducing the cost of penalty payments.

INTRODUCTION

The liberalization of the electricity market represents a significant change reflecting itself not only in the behaviour of distribution companies but also in the approach to and the requirements for the reliability analysis of distribution networks. In the environment of a liberalized electricity market the level of the electricity supply continuity is regulated by national regulatory bodies which often implement guaranteed standards of electricity supply continuity connected with penalty payments paid to consumers in case of breaching the set limits.

In the Czech electric power sector the quality of electricity supplies and of services connected therewith is regulated by Decree Nr. 306 of the Energy Regulatory Office [1] which defines guaranteed and overall standards of the quality of electricity supplies and of services connected with them. The guaranteed standards now include only the voltage quality standard, the standard of removing the failure burning of the fuse in the customer’s LV connection box and the standard of the electricity supply restoration. The following two standards are defined as overall ones: the standard of the total duration of supply interruptions and that of the frequency of supply interruptions in the transmission system and in distribution systems.

In spite of the fact that the guaranteed standards which would evaluate the annual numbers and the total annual durations of supply interruptions have not yet been used in the Czech Republic but their implementation by the Czech Regulatory Office is only expected (including penalty payments down to LV level), EGÚ Brno, a. s. carried out the first estimates of the annual cost of penalty payments for a municipal MV cable distribution network, based on available data on its failure rate during ten years [2]. These studies revealed that, in the situation existing in the Czech Republic, such payments may involve relatively high amounts of money. A general reliability model for estimating the cost of penalty payments was therefore constructed [3]. This model is based on a modified Monte Carlo method. The used modification enables the input data to be acquired more easily and it directly provides reliability indices from which the cost of penalty payments can then be derived.

GUARANTEED STANDARDS OF ELECTRICITY SUPPLY CONTINUITY AND THE COST OF PENALTY PAYMENTS

In the environment of a liberalized electricity market the level of the electricity supply continuity is usually regulated by national regulatory bodies. The regulation has to ensure that each consumer may acquire a minimum level of the supply continuity at least and that the level of reliability may be successively increased both for individual consumers and within the network as a whole. A tool for reaching this aim are usually the standards of the electricity supply continuity which were divided into two groups in [4] – into the overall and the guaranteed standards.

The guaranteed standards of the electricity supply continuity are intended to be used for the protection of individual consumers and they specify the minimum level of the electricity supply quality which must be maintained for each individual consumer at the evaluated voltage level of the network. They are connected with penalty payments annually paid by the distribution company to consumers for which the set limit of continuity has been exceeded. These standards have already been introduced e.g. in Spain, Portugal, Great Britain and Italy [3 - 5]. However, their concrete terms differ in individual countries.

Basing on reliability indices being evaluated we may define:

- a simple guaranteed standard of the electricity supply continuity. The exceeding of the limit (denoted as $L_i$ in general) of a chosen index is considered as breaching this standard. The index to be chosen may be the annual number or the total annual duration of supply interruptions and the limit may then be the limit of the annual number of supply interruptions.
interruptions \( L_n \) or the limit of the total annual duration of supply interruptions \( L_{t} \) respectively;

- a composed guaranteed standard of the electricity supply continuity. The exceeding of the limit of the annual number of supply interruptions \( L_n \) or of the limit of the total annual duration of supply interruptions \( L_{t} \) is considered as breaching this standard.

A penalty is paid to affected consumers when the simple or the composed standard has not been met. According to the dependence of these penalty payments on the value of the index being evaluated we may distinguish:

- a jump-like penalty payment which does not depend on the extent of exceeding the limit;
- a proportional penalty payment which depends on the extent of exceeding the limit.

However, only the jump-like penalty payments are considered in the following for the sake of simplification.

In a general case, the cost of penalty payments \( C_{pv,q} \) for feeder \( v \) and year \( q \) of the evaluation period for a simple standard with a jump-like penalty payment may be expressed by equation

\[
C_{pv,q} = c \cdot \alpha \cdot \text{cond} \{ x_{cv,q} \geq L_{t} \},
\]

(1)

where \( c \) is penalty payment per supply point, \( \alpha \) is number of consumers supplied from feeder \( v \), \( x_{cv,q} \) is general index for feeder \( v \) and year \( q \) being compared (total annual number of supply interruptions \( n_{cv,q} \) or total annual duration of supply interruptions \( t_{cv,q} \) on feeder \( v \) in year \( q \) and \( L_{t} \) is limit of the general index \( x_{cv,q} \) (limit \( L_{n} \) or \( L_{t} \)).

The cost \( C_{pv,q} \) for a composed guaranteed standard with jump-like penalty payments is as follows:

\[
C_{pv,q} = c_p \cdot \alpha_v \cdot \text{cond} \{ n_{cv,q} \geq L_{n} \lor t_{cv,q} \geq L_{t} \}.
\]

(2)

The total cost of penalty payments in year \( q \) of the period of evaluation (i.e. the cost for the whole evaluated network) are given by the sum:

\[
C_{p,q} = \sum_{v=1}^{V} C_{pv,q},
\]

(3)

where \( V \) is total number of feeders in the network.

The mean value of all values \( C_{pv,q} \) may be taken as the expected value of the total annual cost of penalty payments \( C_{pp} \). When we want to get a more detailed idea about the total annual cost of penalty payments, it is appropriate to acquire further statistical characteristics from the value of \( C_{p,q} \) and, for example, to draw a histogram of \( C_{p,q} \).

The period of one or of two years may be chosen as a period of evaluation. At a two-year evaluation a sliding two-year mean value of the respective index is compared with the limit.

### ANALYSIS OF THE INFLUENCE OF THE TYPE OF STANDARD ON THE COST OF PENALTY PAYMENTS

The influence of the type of the guaranteed standard on the cost of penalty payments was analysed based on the data from one 22 kV cable distribution network of a large town (with about 1 200 000 inhabitants). The investigated network had 618 distribution feeders with 4683 22/0.4 kV distribution substations which supplied 674 352 supply points. The following standards were considered:

- a composed guaranteed standard with penalty payments paid at exceeding the limit \( L_{n} \) or \( L_{t} \);
- a simple guaranteed standard with penalty payments paid at exceeding the limit \( L_{n} \) (\( L_{n} = \infty \text{ min/year} \) is given in tables 1 and 2 for this case);
- a simple guaranteed standard with penalty payments paid at exceeding the limit \( L_{t} \) (\( L_{t} = \infty \text{ year} \) is given in tables 1 and 2 for this case).

As no guaranteed standard of the electricity supply continuity has been introduced in the Czech Republic till now, which would define reliability indices and their limit values, i.e. the limits at the exceeding of which a penalty payment would be paid to individual consumers, the following chosen values of the limit of the annual number of supply interruptions \( L_{n} \) and of the limit of the total annual duration of supply interruptions \( L_{t} \) were used when assessing the cost of penalty payments:

- \( L_{n} = \{ 2; 3; 4 \} \text{ year}^{-1} \),
- \( L_{t} = \{ 15; 30; 60; 90; 120; 150; 180; 210; 240; 300 \} \text{ min/year}^{-1} \)

The choice of these values is based on limits used in municipal distribution networks of the European countries applying the guaranteed standards of the electricity supply continuity and their spans cover the range which comes into consideration in the municipal distribution networks in the Czech Republic. As the simulations are performed for the MV part of the distribution network only, the chosen limits have been decreased so as to preserve a space for failures occurring in the LV network.

The height of penalty payments per supply point \( c_{p} \) was given by the amount of 33 € in all investigated cases. With regard to the fact that, at jump-like penalty payments, the cost of penalty payments is directly proportional to the height of penalty payments per supply point \( c_{p} \), it is easy to assess this cost for other values of \( c_{p} \) as well.

### Annual evaluation of the guaranteed standard of electricity supply continuity

The mean annual cost of penalty payments \( C_{pp} \) for the annual evaluation of compliance with the composed guaranteed standards of the electricity supply continuity is given in Table 1 and in Fig. 1. This cost moves in the range from 0.2 mil. € to 5.5 mil. € per year depending on the strictness of the values of the limits. This cost span represents penalty payments for 0.95% to 26.70% of the total number of supply points in the network. Although the penalty payments would have to be
TABLE 1 – Mean cost of penalty payments $C_{pp}$ at annual evaluation

<table>
<thead>
<tr>
<th>$L_o$ [year$^{-1}$]</th>
<th>$C_{pp}$ [thous. €.year$^{-1}$]</th>
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<tbody>
<tr>
<td>2</td>
<td>5455</td>
</tr>
<tr>
<td>3</td>
<td>5443</td>
</tr>
<tr>
<td>4</td>
<td>5440</td>
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<td>$\infty$</td>
<td>5440</td>
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<tr>
<td>60</td>
<td>4966</td>
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<tr>
<td>90</td>
<td>4911</td>
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<tr>
<td>120</td>
<td>4900</td>
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<td>150</td>
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<td>180</td>
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<td>210</td>
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<td>240</td>
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<td>300</td>
<td>4899</td>
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<tr>
<td>$\infty$</td>
<td>4899</td>
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</tbody>
</table>

assigned only to a small part of the consumers, these would involve no small amounts of money for the distribution company.

It can be seen in Fig. 1 that the cost $C_{pp}$ decreases rapidly with the value of the limit $L_o$ ranging from 15 min. year$^{-1}$ up to 60 min. year$^{-1}$. At higher values of this limit the decrease of $C_{pp}$ is not so pronounced any more.

It becomes evident that the choice of the limit $L_o$ has no significant influence on the height of the cost $C_{pp}$ at low values of $L_o$ (for $L_o \leq (60 \div 90)$ min. year$^{-1}$ approximately). Therefore, it would have no practical importance to use a composed guaranteed standard in these cases and it would be sufficient to evaluate the exceeding of the limit of the total annual duration $L_t$ only. However, considerable changes of the cost $C_{pp}$ take place at the changing value of the limit $L_o$. It should be noticed that the choice of the limit $L_t$ becomes significant at values of $L_t$ higher than (150 $\div$ 210) min. year$^{-1}$ at $L_o = 2$ year$^{-1}$ and (240 $\div$ 300) min. year$^{-1}$ at $L_o = 3$ year$^{-1}$ – penalty payments should be predominantly assigned to individual consumers only for exceeding the limit $L_o$.

In case of a composed limit, the existence of areas where only the influence of the setting of one of the limits manifests itself may be identified. Such areas are illustrated in Fig. 2.

The performed analyses reveal that, within the investigated combinations of limits of the composed standard, there exist combinations at which a dominant part of supply points with assigned penalties receive penalty payments just due to the exceeding of one of the limits only.

This situation relating to the investigated distribution network is illustrated in Fig. 3 where the boundary between these two areas is indicated by a light strip. This conclusion has a practical impact on decision making of the managing staff of the distribution company when choosing interventions to be undertaken in the network in order to reduce the cost of penalty payments. The fact is that there exists a combination of limits the setting of which as a target value of the level of supply reliability leads to the orientation of these interventions to the duration of supply interruptions (i.e. to the speed of disconnecting the failed section and to supply restoration). On the contrary, there also exists a field of combinations of limits where it is suitable to direct attention to reducing the number of supply interruptions.
It should be however noticed that this conclusion cannot be taken as a generally valid rule. When undertaking any intervention, particular situation in individual points of the network must be taken into account as well. If only the limit of the total annual duration of supply interruptions \( L_n \) were evaluated when applying a simple standard (see Table 1), the cost \( C_{pp} \) would amount to \((0.1 \div 5.4)\) mil. € year\(^{-1}\). Such values would not differ too much from the cost at a composed standard with \( L_n = 4\) year\(^{-1}\).

On the contrary, if only the limit of the annual number of supply interruptions \( L_n \) were considered, the cost \( C_{pp} \) would move in the interval of \((0.1 \div 1.4)\) mil. € year\(^{-1}\) which approximately corresponds to the cost at a composed standard with \( L_n = 300\) min. year\(^{-1}\).

**Evaluation of the guaranteed standard of electricity supply continuity based on two-year mean values**

The using of two-year mean values for the evaluation of the guaranteed standard of the electricity supply continuity enables the year-to-year variation of the number of supply interruptions and of their total duration to be equalized. In the investigated distribution network the estimated mean cost of penalty payments \( C_{pp} \) moves in the interval of \((0.03 \div 8)\) mil. € per year approximately, depending on the strictness of the values of limits (for more details see Table 2). This means that about 0.2% to 40% of supply points would receive penalty payments.

The dependence of the cost \( C_{pp} \) on the setting of limits is very similar to that described in the preceding section (i. e. in case of the annual evaluation). The only deviation can be seen in a more profound decrease of \( C_{pp} \) with \( L_n \) growing up between 15 min year\(^{-1}\) and 90 min. year\(^{-1}\).

However, if we compare the cost \( C_{pp} \) for the annual and the two-year evaluation (Tables 1 and 2) we may see that the two-year evaluation brings about a lower cost \( C_{pp} \) for the majority of investigated cases. For \( L_n \geq 60\) min. year\(^{-1}\) the cost decreases by 15% to 73%. A greater decrease corresponds to higher values of \( L_n \).

**TABLE 2 – Mean cost of penalty payments \( C_{pp} \) when evaluating the standard based on two-year mean values**

| \( L_n \) [min. year\(^{-1}\)] | \( L_{pp} \) [thous. €.year\(^{-1}\)]
<table>
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<tbody>
<tr>
<td>2</td>
<td>3</td>
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<tr>
<td>15</td>
<td>8036</td>
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<tr>
<td>30</td>
<td>5787</td>
</tr>
<tr>
<td>60</td>
<td>2789</td>
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<tr>
<td>90</td>
<td>1560</td>
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<td>120</td>
<td>1048</td>
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<td>150</td>
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<td>240</td>
<td>676</td>
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<td>300</td>
<td>661</td>
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<tr>
<td>( \infty )</td>
<td>657</td>
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</table>

On the contrary, for \( L_n = 15\) min. year\(^{-1}\) and \( L_n = 30\) min. year\(^{-1}\) the cost of penalty payments is higher by 16% to 47% at the two-year evaluation compared to the annual one. This is caused by a high strictness of the value of the limit \( L_n \). A great part of the total annual durations of supply interruptions namely attains the double and even higher values of \( L_n \). The mean values thus exceed \( L_n \) in two subsequent periods of evaluation. The result may be that the penalty payment for a considerable exceeding of \( L_n \) in the given year may be paid twice although the total annual durations of supply interruptions are zero both in the preceding year before and the subsequent year after the given year.

**CONCLUSION**

The results of the performed analysis reveal that the implementation of guaranteed standards of the electricity supply continuity may represent a risk of great financial losses for the distribution companies because the annual cost of penalty payments can amount to several hundreds of thousands or even millions € depending on the strictness of limits applied. In case of a composed standard we may specify combinations of limits of the annual number of supply interruptions and of their total annual durations at which the exceeding of only one of the limits dominates. This may be used when making decisions about interventions to be undertaken in the network in order to reduce the cost of penalty payments.

In most cases, the cost of penalty payments may be reduced when evaluating the standards based on two-year mean values. However, there exist limits or combinations of them which lead (thanks to their high strictness) to the increase of the cost of penalty payments.

Although the discussed guaranteed standards of the electricity supply continuity have not yet implemented in many countries (including the Czech Republic), the cost of penalty payments for the expected setting of limits may already be included into optimization functions. The resulting optimization interventions would thus reflect, already now, the customer’s view of the reliability which represents a distinct trend in the field of the reliability of distribution networks.

**REFERENCES**


