EVALUATION OF THE SUCCESSIVE RESTORATION OF ELECTRICITY SUPPLY TO CUSTOMERS IN DISTRIBUTION NETWORKS IN CONNECTION WITH THE REGULATION OF ELECTRICITY SUPPLY CONTINUITY

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ABSTRACT
The restoration of electricity supply to customers after a failure in the distribution network often represents a complex process consisting of many steps (manipulation) to be undertaken in the network. As a result of this various customers on the same feeder affected by the failure perceive a different number of differently long supply interruptions. This paper deals with the influence of the methodology of evaluating supply interruptions on conventional reliability indices and on the costs of penalty payments. This influence is demonstrated with using real operational data from the overhead network of one distribution company for the period of five years.

INTRODUCTION
The reliability of the electricity supply to customers can be evaluated by system reliability indices (SAIFI, SAIDI, etc.) or based on meeting the customer’s standards of electricity supply continuity [1]. In both cases this evaluation requires precise and clear definitions of phenomena and states being examined. So that the evaluation may be correct, we cannot be content with recording the time to restoring the supply to the last affected customer (outage duration) or with dividing this time into three time subsections only. It is necessary to monitor the whole process of supply restoration in individual manipulation steps.

DESCRIPTION OF THE PROCESS OF A SUCCESSIVE SUPPLY RESTORATION
Supply interruption indicates the state of the supply point when this supply point is not capable of supplying electricity. Duration of supply interruption \( t_i \) is the section of time during which the supply of electricity was interrupted. The term “supply interruption” is thus directly related to a certain supply point [2]. In a general view, a limitation of supply could also be defined as the state when the consumer is not enabled to consume the required power in the full magnitude. However, this situation is not the object of our considerations now.

Affected supply is the supply point affected by supply interruption.

Outage is the state in the distribution system originating as a result of a phenomenon (we have in mind the failure here) which led to the interruption of supply to one supply point at least. The outage begins at the moment of the first interruption of supply to the first affected supply point and ends at the moment when the supply from usual sources to all affected supply points has been restored permanently. The outage thus covers also the state at which the supply to all affected supply points has been restored for a certain time but which is followed by another supply interruption caused by manipulations leading to the restoration of a normal operational connection of the network. The total number of supply points affected during the outage (i.e. of those sustaining one supply interruption at least) is marked as \( O_{out} \).

Duration of the outage \( t_{out} \) is the section of time during which the outage lasted.

Manipulation to be undertaken for supply restoration (hereinafter only manipulation) is the phenomenon (activity) aimed at restoring the supply to all affected supply points (i.e. at elimination of all supply interruptions).

Manipulation interval is the section of time between the beginning of the outage and the first manipulation, between two manipulations or between the last manipulation and the end of the outage. The number of affected supply points is constant during the manipulation interval and is marked as \( O_{m} \).

Group of supply interruptions is the totality of interruptions of supply to a supply point which were connected with one outage. The group of supply interruptions starts with the beginning of the first interruption of supply into the given supply point connected with the outage and is ended with the end of the last interruption of supply into this supply point which was connected with the same outage. The duration of the group of supply interruptions will be marked as \( t_{gr} \). The group of supply interruptions is always related to a certain supply point.

Time between supply interruptions \( t_{bi} \) is the time between two subsequent interruptions of supply into the given supply point which belongs to the same group of supply interruptions.

Although the outage concerns the equipment, the time \( t_{out} \) may be also related to the customer’s level (and/or DTS) when evaluating the event. Consequently, there appear three possibilities of which time should be registered for the given customer: 1) duration of supply interruptions, 2) duration of...
the group of supply interruptions or 3) duration of the outage. The number of recorded cases then follows from this, too.

The using of established notions can be illustrated by the example of one outage caused by failure on a MV feeder – Fig. 1. For simplification, the feeder has only three distribution transformer stations DTS1 to DTS3.

The upper graph illustrates the outage, i.e. the state existing in the distribution system. The failure occurred at time 0 and the feeder was switched-off by the feeder circuit breaker subsequently. The consumers connected to all DTSs perceived the first supply interruption. After the first manipulation had been performed, the supply to DTS2 and DTS3 was restored and the first interruption of supply for these stations was ended. However, in the case of DTS1 the first interruption continued till the moment of the second manipulation. If we examine only the graph for DTS1 we can see that DTS1 was energized from the second till the fourth manipulation. However, the matter concerned only a temporary supply restoration because, after the fourth manipulation, the second supply interruption occurred at DTS1 (connected with the same outage). The time between supply interruptions is thus delimited by the moments of the second and the fourth manipulations. The second supply interruption lasted until the outage had been ended.

It can be said that the consumers connected to DTS1 registered a group of supply interruptions consisting of two interruptions and that the duration of the group of supply interruptions for DTS1 was equal to the duration of the outage (\(t_{ig}^{(DTS1)} = t_{out}\)). However, another situation existed in the case of DTS2. DTS2 also registered a group of supply interruptions including two interruptions but this group lasted only till the third manipulation. DTS3 was affected by one supply interruption only (\(t_{i1}^{(DTS3)} = t_{ig}^{(DTS1)} < t_{out}\) in this case).

**SOME RESULTS OF THE ANALYSIS OF A SUCCESSIVE SUPPLY RESTORATION IN A 22 kV OVERHEAD NETWORK**

Although Fig. 1 may create an impression of a theoretical examination and the established notions may seem superfluous at the first sight, it can be demonstrated on the example from a 22 kV overhead distribution network that the differences between supply interruptions, the group of supply interruptions and the outage are not negligible.

Based on data from the control system we have reconstructed the whole development of the process of a successive restoration of electricity supply to customers. The data analysed were available at the level of individual DTSs for the period of five years.

The frequencies of the number of manipulation intervals in the course of the outage provide the first view of the “broken character” of the process of a successive supply restoration (Fig. 2). Most frequently, the supply is restored after one manipulation interval (55% of cases) and the consumer perceives only one supply interruption in connection with a certain outage (failure). However, the average number of manipulation intervals is 3.3 and in 120% of outages the supply is restored to all affected consumers during more than 8 manipulation intervals (both long-term and short-time outages are included).
Observed distributions of durations $t_i$ (without dividing them into long-term and short-term durations), $t_{ig}$, and $t_{out}$ are shown in Fig. 3 from which the differences of views of “interruptions” are clearly evident. Individual supply interruption in DTSs (as perceived by customers) lasted only 35 min on the average and in 10% of cases they exceeded 93 min. The average duration of the group of supply interruptions is 66 min and in 10% of cases these durations exceed 187 min. The average duration of the outage (related to each considered DTS) makes 152 min and in 10% of cases it exceeds the value of 359 min.

**IMPACTS OF VARIOUS VIEWS OF THE “INTERRUPTION”**

Various views of the interruption have a direct impact on the values of derived reliability indices. One of their consequences are also different results of the evaluation of meeting the standards of electricity supply continuity (both system-related standards and customer’s standards). The customer’s standards often include a limit of the annual number of supply interruptions or a limit of their total annual duration (interruptions longer than 3 min are usually considered).

The average annual number of supply interruptions for DTS was equal to 3 during the period of observation, the average annual number of groups of supply interruptions for DTS was by 13.3% lower (2.6) and the average annual number of outages related to DTS was by 6.7% lower (2.8). The maximum recorded number of supply interruptions for DTS amounted to 31 per year. In the case of the groups of supply interruptions and of outages only 23 cases per year were recorded.

It could appear at first sight that the numbers of the groups of supply interruptions most agree with the numbers of outages. As only the cases of supply interruptions with duration of not less than 3 min were evaluated, small differences exist between these numbers.

As the aggregated index $SAIFI$ originates just from the annual numbers of supply interruptions/outages and respecting the number of consumers at individual DTSs, certain differences appear also in the values of $SAIFI$ calculated for supply interruptions, for groups of supply interruptions and for outages.  

The analysis of total annual durations is represented by empirical distribution functions in Fig. 4. Great differences exist between them. The total annual durations increase especially in the case of outages ($t_{out}$). There are about 9% of cases with duration up to 15 min while in the case of supply interruptions the total annual did not exceed this value in 25% of cases.

The lowest average total annual duration can be observed in supply interruptions (203.1 min). The same average is higher by 38% for groups of supply interruptions and even by 214% for outages. Regarding the fact that a certain aggregation of data (though only on the level of DTSs and without respecting the number of affected customers) can be observed even in these values, it may be expected that relatively great differences will appear also in aggregated indices $SAIDI$ which are usually monitored.

For getting idea about a different impact of considered views of the costs of penalty payments we calculated average annual costs of penalty payments for a composed customer’s standard of electricity supply continuity setting a limit of the annual number of supply interruptions $L_n$ and a limit of their total annual duration $L_t$ (a logical “or” is valid between these limits, i.e. the penalty shall be paid when one of these limits or both two limits have been exceeded) [3]. All combinations of the following chosen values of these limits were evaluated:

- $L_n = \{6; 7; 8; 9; 10\}$ 1/year,
- $L_t = \{300; 360; 420; 540; 600; 720\}$ min/year.

Beside a composed standard we also considered a simple standard with limit $L_n$ only ($L_t = \infty$ min/year) and a simple standard with limit $L_t$ only ($L_n = \infty$ 1/year).
A jump-like penalization was considered in all cases with the penalty per one supply point $c_p = 1000$ CZK (40 € approximately). Relative differences of the average annual costs of penalty payments as assessed based on groups of supply interruptions against the costs assessed based on supply interruptions are shown in Table 1. In the case of a composed customer’s standard this difference can be positive as well as negative. If a simple standard defines only the limit $L_{L_{\text{th}}}$, the evaluation of the groups of supply interruptions leads to lower costs of penalty payments when compared with the evaluation of individual supply interruptions. On the contrary, a standard including only the limit $L_t$ leads to higher costs.

### CONDITIONED GROUP OF SUPPLY INTERRUPTIONS AND A LIMIT OF THE MAXIMUM TIME BETWEEN SUPPLY INTERRUPTIONS

From the viewpoint of the customer, the evaluation of reliability based on individual supply interruptions and based on groups of supply interruptions represents two “extreme” approaches. The evaluation based on outages is not correct from the customer’s viewpoint. A repeated supply interruption in the course of supply restoration is the necessity in many cases and the customer would have to tolerate and expect it provided it takes place within a reasonable time after the ending of the preceding supply interruption. A compromise is the introduction of a limit of the maximum time between supply interruptions $L_{\text{tbi}}$. When this time limit elapses, the subsequent supply interruption (although it was connected with the same outage) will be evaluated as a further “case”. It is therefore convenient to introduce the notion “conditioned group of supply interruptions” defined as follows (see Fig. 5):

The conditioned group of supply interruptions is a totality of supply interruptions at a supply point connected with the outage, but the time between any two interruptions following one after another did not exceed the limit of the maximum time between interruptions $L_{\text{tbi}}$.

#### Tab. 1 Relative differences of the average annual costs of penalty payments as assessed based on groups of supply interruptions against the costs assessed based on supply interruptions

<table>
<thead>
<tr>
<th>$L_t$ [min/year]</th>
<th>$\delta C_{\text{ep}}$ [%]</th>
<th>$L_{\text{th}}$ [1/year]</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>$\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>-6.8</td>
<td>15.4</td>
<td>19.6</td>
<td>23.1</td>
<td>26.1</td>
<td>42.6</td>
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<tr>
<td>360</td>
<td>-1.7</td>
<td>11.3</td>
<td>15.5</td>
<td>19.1</td>
<td>22.2</td>
<td>46.4</td>
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</tr>
<tr>
<td>420</td>
<td>-2.3</td>
<td>7.6</td>
<td>11.4</td>
<td>14.3</td>
<td>17.7</td>
<td>57.6</td>
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</tr>
<tr>
<td>540</td>
<td>-7.8</td>
<td>0.4</td>
<td>3.4</td>
<td>6.5</td>
<td>9.2</td>
<td>78.4</td>
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<tr>
<td>600</td>
<td>-10.0</td>
<td>-2.5</td>
<td>0.4</td>
<td>2.6</td>
<td>4.6</td>
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<tr>
<td>720</td>
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<td>-9.3</td>
<td>-7.9</td>
<td>-9.0</td>
<td>-9.4</td>
<td>90.6</td>
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</tr>
<tr>
<td>$\infty$</td>
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<td>-20.6</td>
<td>-29.8</td>
<td>-40.9</td>
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<td></td>
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</table>

Fig. 5 Conditioned group of supply interruptions and a limit of the maximum time between supply interruptions

The suggested approach to the evaluation of reliability and especially the setting of the limit of the maximum time between supply interruptions $L_{\text{tbi}}$ still requires a further study. For orientation, it may be only estimated that the limit $L_{\text{tbi}}$ should move in the interval between 5 min to 30 min.

### CONCLUSION

The process of a successive restoration of electricity supply to customers is no simple process. A clear description of this process requires the distinguishing between supply interruptions, groups of supply interruptions and outages. Each of these views leads to a different evaluation of the reliability of the distribution system irrespective of whether it is carried out by using system reliability indices or the costs of penalty payments. A precise description of the states in the system is also necessary when comparing the reliability of distribution systems.

Present dispatcher systems enable us to monitor individual manipulations in the network leading to the restoration of electricity supply to customers. Under interconnection of data about states of switching elements with network topology and with data about the connection of customers these systems are also able to generate (at level of DTSs at least) the records about individual supply interruptions (including their relation to corresponding outages). Although these detailed records represent a great amount of data, it is possible to work them up into practically applicable outputs.

### REFERENCES

