EVALUATION OF LONG-TERM VOLTAGE DIP MONITORING IN HV, MV AND LV NETWORKS

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ABSTRACT

The paper summarizes the results of long-term voltage dip monitoring performed by the E.ON Czech Republic. Recorded data available from several years have been analyzed. The results of monitoring provide information about the number and distribution of voltage dips in all levels of the distribution system during the monitoring period. Besides the mapping of the present level of voltage dip occurrence, there are discussed topical problems connected with voltage dip assessment, e.g. setting of thresholds for voltage dips recording in relation to voltage variations according to the standard EN 50160.

INTRODUCTION

With the introduction of competition between utilities power quality becomes an issue for the regulator that may use economic incentives to guarantee minimum power quality levels.

Power quality legislation in the Czech Republic is based upon the Energy Act (No 458/2000), the Directive about quality of supply and services related to electricity delivery (No 540/2005), the Distribution Code and the European standard EN 50160. They use the concept of guaranteed and overall standards of performance. Guaranteed standards relate to quality factors for individual customers and carry a penalty payment. Overall standards relate to the overall provision of supply and services measured and regulated at the system level.

Voltage quality is not as heavily regulated as commercial quality and continuity of supply. In the Czech Republic continuity of supply has been involved in price regulation since 2013. However, there are not introduced any guaranteed limits for voltage event performance, e.g. supply voltage interruption and dip occurrence.

In the future, network operators may be penalized in cases of non-compliance to some power quality objectives. Because voltage interruptions and dips belong to most monitored events in power systems from point of view of power quality, we may expect establishment of mandatory values of their occurrence as the guaranteed standard, connected with penalty payment. At present, only indicative values for voltage events are given in the standard EN 50 160. For well-defined guaranteed limits, detailed analysis of historical measurements has to be carried out. Results of the initial analysis are described in this paper.

Voltage dip monitoring in the Czech Republic

At present, the E.ON company, the distribution system operator, trader and small electricity producer in South-Bohemia and South-Moravia, belongs to 3 main players in the Czech electricity market. It ensures electricity delivery to approximately 1.5 million customers.

Voltage dip monitoring has started early in the century. The **monitors** are **permanently installed** in:

- all delivery points 400/110 kV and 220/110 kV (in the 110 kV substations)
    - since 2006
    - measurement of line-to-line voltages
- all connection points of 110 kV end-users
- several connection points of 22 kV end-users
- all 110/22 kV substations (on the secondary side)
    - since 2010
    - measurement of line-to-line voltages
- a few 22/0.4 kV substations (on the secondary side)
    - measurement of line-to-ground voltages

Besides permanent monitoring, there are carried out temporary voltage quality (VQ) surveying, e.g. to check the performance of the supply system, or to check customers' complaints. Measuring equipment and data recording methods are chosen according to the purpose of the measurement. At each phase, there are recorded: start and end of voltage dip duration, and residual voltage U_{res} (the lowest r.m.s. value of the voltage recorded during the event) expressed as a percentage of the reference voltage.

The network operator has archived results of measurements and assessment of voltage characteristics together with information on power system conditions and parameters in time of measurement. For voltage dip assessment (number and severity of voltage dips), there are used tables according to the standard EN 50160 and the Distribution Code (annex no. 3) to distribute voltage dips according to their residual voltage and duration time.

RECORDED DATA SELECTION AND PROCESSING

Voltage events, i.e. sudden and significant deviations from normal or desired wave shape, typically occur due to unpredictable events (e.g. faults) or to external causes (e.g. weather conditions, third party actions). Voltage dips and interruptions are, by their nature, unpredictable and vary from place to place and from time to time. Their annual occurrence varies greatly depending on type of supply system and on point of monitoring. Moreover, the distribution over the year can be very irregular. Because the voltage events are largely random with relatively low frequency of occurrence, long monitoring period is needed to obtain fully representative statistics of their occurrence [1].

For this reason, only monitoring points, where data were recorded during several years, have been taken into account. There was used **polyphase aggregation** (an equivalent event characterized by a single duration and a single residual voltage). For polyphase events, a dip begins when the voltage of at least one phase drops below the dip start threshold and ends when all voltages are equal to or higher than the dip end threshold. An interruption occurs when the voltage drops below 5% of the reference voltage on all the phases. Otherwise, it is considered to be a dip on the affected phases. Time aggregation (multiple voltage dips, e.g. effect of reclosing, are considered as a single equivalent event) was not used.

RESULTS OF LONG-TERM MONITORING

Voltage dip assessment in the 110 kV networks

Voltage dip assessment was made for all delivery points 400(220)/110 kV. Dips have been recorded on secondary side of the EHV/110 kV transformers. Recorded data were evaluated only for the monitoring period 2006-2010. Recorded data from 2011 to 2013 are incomplete because of VQ monitor failures in following years. For this reason they were excluded from the assessment.

Figure 1 illustrates largely random annual occurrence of voltage dips recorded in the 110 kV substations. For example, there were recorded 28 dips in the substation S3 in 2008, four times more that in 2010; compared with the substation S5, where maximal number of dips is only twice higher than recorded minimum.

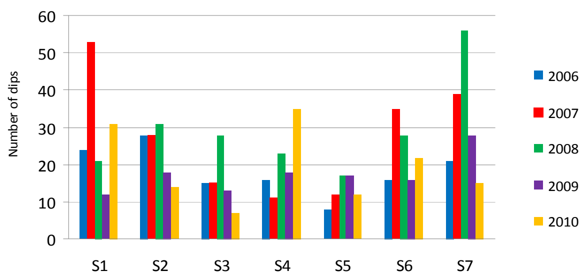

Figure 1 *Number of voltage dips recorded on the secondary side of EHV/110 kV transformers*

Distribution of recorded voltage dip according to their severity is presented in Table 1. Dips with duration longer than 1 second were cumulated into one column. About 80% of recorded dips have duration less than 0.1 second; duration of all dips did not exceed 1 second. That means that the voltage dips were caused by faults.

Table 1 *Percentage occurrence of voltage dips in the 110 kV substations*

Residual voltage U_{res} [%]	**Duration of dips t [s]**				
	0.01≤t<0.1	0.1≤t<0.5	0.5≤t<1	1≤t	Total
85≤U_{res}<90	31.9	4.6	0	0	36.5 %
70≤U_{res}<85	34.7	6.7	0.6	0	42.0 %
40≤U_{res}<70	12.4	5.8	0.4	0	18.6 %
5≤U_{res}<40	1.1	1.2	0.6	0	2.9 %
Total	**80.1 %**	18.3 %	1.6 %	0 %	100 %

Figure 2 shows number of recorded dips in connection points of the selected 110 kV customers. Voltage dips recorded in 2014 (green columns) are divided into two groups. At the top of the columns, there are dips recorded in the fourth quarter of the year when ice coating occurred. Strong increase of dip occurrence due to ice coating was recorded at the customers C1, C4 and C7.

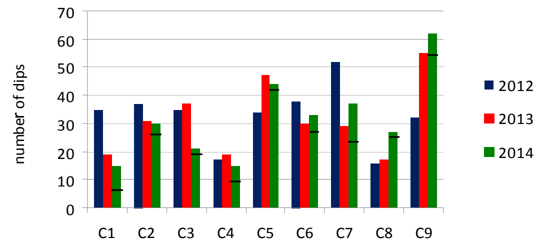

Figure 2 *Number of voltage dips for selected 110 kV customers*

On the basis of results of long-term monitoring we may say that a few tens of voltage dips annually occur in the 110 kV network. But, from results we are not able to predicate expected number of voltage dips in next years.

Voltage dip assessment in the 22 kV networks

Voltage dip assessment was carried out for all 110/22 kV substations. Dips have been recorded on secondary side of the 110/22 kV transformers. Recorded data were evaluated for the monitoring period 2010-2013, when complete annual data were available. Results of voltage dip monitoring in 46 points are shown on Figure 3.

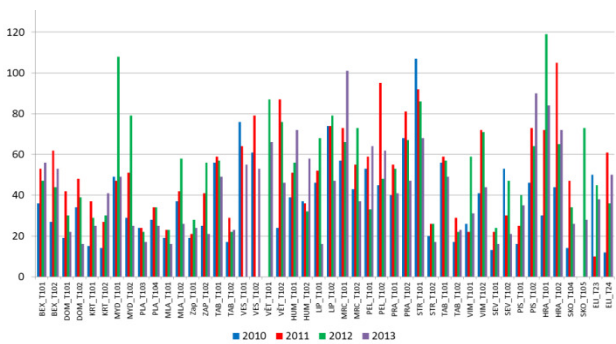

Figure 3 *Number of voltage dips recorded in the 22 kV substations*

Annual number of dips in the MV substations has varied between 10 and 120 dips, which is two times more than in the HV substations. Distribution of recorded voltage dips according to their severity is presented in Table 2. About 75% of recorded dips had duration less than 0.1 second; duration of nearly all dips did not exceed 1 second.

Table 2 *Percentage occurrence of voltage dips in the 22 kV substations*

Residual voltage U_{res} [%]	Duration of dips t [s]				
	0.01≤t<0.1	0.1≤t<0.5	0.5≤t<1	1≤t	Total
$85 \le U_{res} < 90$	25.4	6.3	0.3	0.3	32.3 %
$80 \le U_{res} < 85$	14.3	3.7	0.3	0.1	18.4 %
$70 \le U_{res} < 80$	16.3	4.3	0.8	0.2	21.6 %
$40 \le U_{res} < 70$	15.6	4.8	0.5	0.2	21.1 %
$5 \le U_{res} < 40$	3.2	2.6	0.2	0.2	6.2 %
$0 < U_{res} < 5$	0.1	0.1	0.1	0.1	0.4 %
Total	**74.9 %**	21.8 %	2.2 %	1.1 %	100 %

Number of dips again varies from place to place and from year to year. Figure 4 shows distribution of voltage dips over years in selected MV substations. In the first substation, distribution over years is very irregular compared to the second one. The third case shows regular distribution with sporadic and significant deviation. The last two distributions illustrate the fact that occurrence of dips greatly depends on network arrangement. Both MV substations are part of a 110 kV/MV substations. The first MV substation (i.e. bus-bar A fed by transformer T101) supplies rural area by overhead lines, the second one (i.e. bus-bar B fed by transformer T102) supplies urban area by cables.

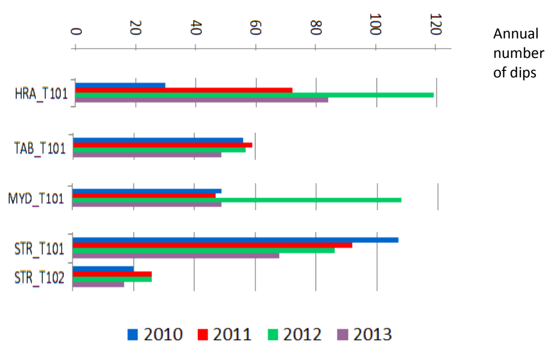

Figure 4 *Irregular distribution of voltage dips in selected MV substations*

The fact that the dip distribution over the year can be very irregular is also shown on dip monitoring carried out in a MV customer connection point (Figure 5). The customer is fed by long overhead power line from the 22 kV supply substation.

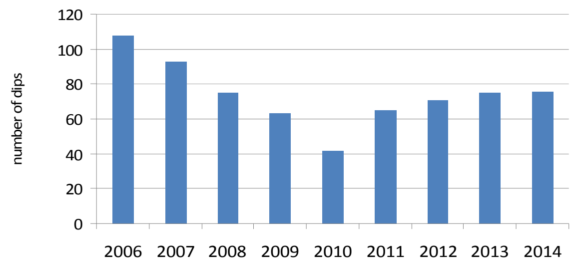

Figure 5 *Number of voltage dips for a MV customer*

In comparison with the supply MV substations (see Table 2 and 3) number of dips with duration longer than 0.5 s is higher. Among 592 voltage dips, there were also recorded 13 dips with the residual voltage below 5% of the nominal voltage. That is roughly five times more than in the supply MV substations.

Table 3 *Percentage occurrence of voltage dips in a MV customer connection point*

Residual voltage U_{res} [%]	Duration of dips t [s]				
	0.01≤t<0.1	0.1≤t<0.5	0.5≤t<1	1≤t	Total
$85 \le U_{res} < 90$	19.8	4.7	2.9	0.9	28.3 %
$80 \le U_{res} < 85$	15.9	4.1	0.2	0	20.2 %
$70 \le U_{res} < 80$	20.1	2.8	0.2	0	23.1 %
$40 \le U_{res} < 70$	13.3	5.2	1.0	1.1	20.6 %
$5 \le U_{res} < 40$	1.5	1.5	0.2	2.6	5.8 %
$0 < U_{res} < 5$	0	0.5	0	1.5	2.0 %
Total	70.6 %	18.8 %	4.5 %	6.1 %	100 %

Voltage dip assessment in the 0.4 kV networks

Permanent VQ monitoring is carried out only in a few 22/0.4 kV substations. Monitors are placed on secondary side of the MV/LV transformers. Types of MV feeders and supplied LV network (overhead lines, cables, mixed) are different for particular monitoring points, but no effect on number of dips was found out. Annual number of dips in the substations has varied between 26 and 265 dips, which is two times more than in the MV networks.

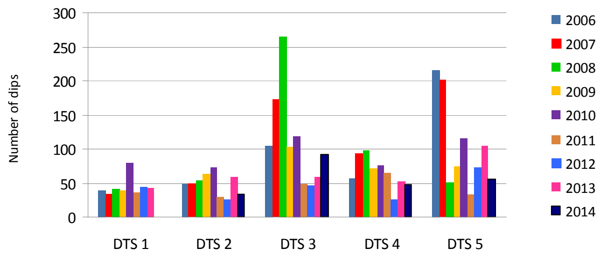

Figure 6 *Number of voltage dips recorded in the LV networks*

In monitoring point DTS1, number of dips recorded in 2010 was twice higher than in previous years. The strong increase is related to snow calamity in January 2010 when more than a half of annual number was recorded in January. In monitoring point DTS3, impact of fault localisation in upstream network on number of recorded dips was observed. In 2008, 16 consecutive dips with duration about 0.1 s were recorded within 20 minutes.

Table 4 *Percentage occurrence of voltage dips in the LV networks*

Residual voltage U_{res} [%]	**Duration of dips t [s]**				
	0.01≤t<0.1	0.1≤t<0.5	0.5≤t<1	1≤t	Total
$85 \le U_{res} < 90$	23.1	5.0	2.2	1.3	**31.6 %**
$80 \le U_{res} < 85$	10.7	5.2	2.3	0.5	18.7 %
$70 \le U_{res} < 80$	8.3	8.1	2.8	0.7	19.9 %
$40 \le U_{res} < 70$	8.3	11.8	2.0	0.2	22.3 %
$5 \le U_{res} < 40$	0.9	2.9	0.7	2.0	6.5 %
$0 < U_{res} < 5$	0	0.1	0	0.9	1.0 %
Total	**51.3 %**	33.1 %	10.0 %	5.6 %	100 %

About 94% of recorded dips did not exceed 1 second. About 32% of recorded dips was in range (85-90% U_n), partially overlapping the range of voltage variations. The shallow dips result from load changes and low short-circuit level in LV networks [2].

SUBJECTS FOR FURTHER ANALYSIS OF RECORDED DATA

The results of long-term monitoring provide information about the number and distribution of voltage dips in all levels of the distribution system (HV, MV and LV) during the monitoring periods. However, only initial analysis of historical measurements was carried out in this paper. Due to huge amounts of recorded data detailed analysis has not been made till now. Subjects for further analysis are: detailed analysis of voltage dip occurrence over a year, impact of upstream or downstream voltage levels on total number of recorded dips [3], impact of network arrangement (short-circuit level, network layout, total length of power lines, type of power lines).

As example of detailed analysis, voltage dip occurrence in a 110/22 kV substation is analysed (see Figure 7). Transformers (T101 and T102) in the substation are separately operated. T101 is connected to bus-bars A and supplies rural area by overhead lines. T102 is connected to bus-bars B and supplies urban area by cables.

Much higher number of dips was recorded on the secondary side of the transformer T101, mainly in summer months. The effect of network arrangement (rural area, overhead feeders) and weather condition (i.e. summer storms) is evident.

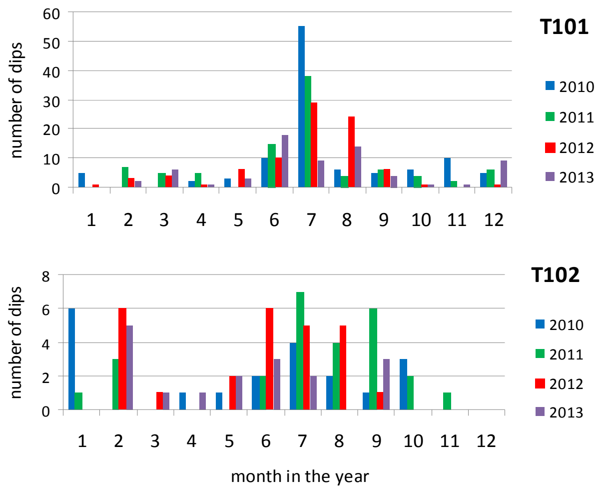

Figure 7 *Number of voltage dips on the secondary side of the T101 and T102 transformers*

TOPICAL PROBLEMS CONNECTED WITH VOLTAGE DIP ASSESSMENT

Besides the mapping of the network performance from the viewpoint of voltage dips the authors would like to call attention to problems arisen from recorded data evaluation.

Setting start threshold for voltage dip recording

On the basis of analysis of voltage dip occurrence in LV networks, issue concerning to dip recording has risen. Table 4 shows that about third of dips are shallow with residual voltage in range (85-90% U_n).

According to the EN 50160 standard, during stabilised operation of the network, 95% of r.m.s. voltage values measured over 10 minutes shall be within the range $U_n \pm 10\%$ during each period of one week, and within the range U_n +10/-15% during 100% of time. This means that also voltage variations during 5% of time may be within range (85-90% U_n), i.e. within range for voltage dips (see Figure 8). Voltage dip is a temporary reduction of the r.m.s. voltage below a specified start threshold (90% U_n). Assessment of voltage dips is based on r.m.s. voltage values measured over a half of period [4].

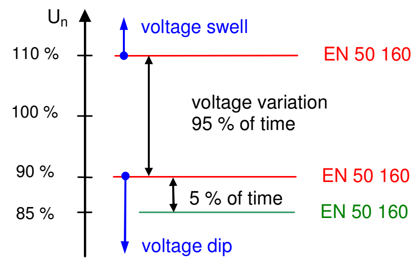

Figure 8 *Ranges for voltage variations and voltage dips according to the standard EN 50160*

In January 2013, voltage dip monitoring lasting a week was carried out in a LV connection point with very low level of short-circuit power. There was recorded extreme number of shallow dips caused by load changes (Table 5).

Table 5 *Number of voltage dips in a LV connection point (one week in January 2013)*

Residual voltage U_{res} [%]	**Duration of dips t [s]**				
	0,01≤t<0,1	0,1≤t<0,5	0,5≤t<1	t≤ 1	Total
85≤U_{res}<90	**10 631**	**2 232**	**65**	**108**	**13036**
70≤U_{res}<85	6	0	0	11	17
5≤U_{res}<70	0	0	0	0	0
Total	10 637	2 232	65	119	13053

One other example, there were recorded repeating voltage changes with value of several percent and with duration of hundreds milliseconds. The r.m.s. value of voltage does not cross the threshold 90% U_n (the 10 min mean r.m.s. values of the voltage was about 95 % U_n). From the viewpoint of voltage variations the voltage quality is in compliance with the EN 50160 standard. Nevertheless, there were recorded several tens of dips with residual voltage in range (89–89.9 % U_n) during the monitoring period.
This raises the questions: Is it actually serious event to be good for recording? Do shallow dips in range (85-90% U_n) have serious effect on customers´ equipment operation? Should shallow dips be included into VQ assessment and compliance with binding values for voltage dip occurrence? These questions are very important for network operators, because majority of customers is connected to LV networks. In case of non-compliance with VQ limits the operators might face penalty payments, although customers would not notice any VQ problem.

Determination of limits for voltage dips

To establish limits for voltage dips we have to put the question: Is it possible to set limits of voltage dip occurrence (expected number of events) on the basis of voltage dip monitoring? Although recorded data give a real picture about event occurrence in past, expected number of dips in years to come is hardly predicable, because faults as the main cause of dips are largely random [5]. Annual number of recorded dips can be several times higher or lower than in previous year.
Wide difference of voltage dip level in individual points of monitoring, respectively during monitoring period raises questions: How long should the monitoring period be to obtain relevant statistics about dip occurrence? Is it possible to consider data obtained from long-term monitoring as relevant picture of monitored network because of changes of network arrangement? Should guaranteed limits or voltage dip indices take into account only a number or also severity of voltage dips?

CONCLUSIONS

To set limits for voltage dips the detailed assessment of long–term monitoring has to be carried out. Results of initial assessment of long-term voltage dip monitoring in the Czech Republic are published in this paper.
Largely random annual occurrence of voltage dips was recorded in all voltage levels. Annual number of dips recorded in some point was several times higher or lower than in previous years. Impact of weather condition (i.e. summer storms, ice coating or snow calamity) as well as network arrangement is evident.
Annual number of dips in MV networks varies between 10 and 120 dips, which is two times more than in HV networks. Nearly all voltage dips in all voltage levels have duration less than 1 second. More than 75% of dips recorded in HV and MV levels have duration less than 0.1 second, in LV level only about 50% of recorded dips.
VQ monitors are placed only in a few MV/LV substations. Annual number of dips at LV level of the substations varies between 26 and 265 dips, which is two times more than in MV networks. During several temporary VQ surveying in LV networks, there was also recorded extreme number of shallow dips (more than ten thousands) with the residual voltage just below the start threshold for voltage dip recording. The question is whether these voltage events are actually serious problem.

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