VOLTAGE DIP ASSESSMENT IN CONTEXT OF VOLTAGE QUALITY REGULATION

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ABSTRACT

Voltage events, namely voltage dips, are not as heavily regulated as continuity of supply, although they can have a similar economic impact on industrial customers as interruptions. Before setting limits of voltage dips for regulatory purposes, a detailed analysis of historical records has to be carried out and various aspects of voltage event assessment have to be considered. In the first part, the results of long-term voltage dip monitoring in the MV system of the company E.ON Distribution are presented. Numbers of dips recorded in individual years are compared to find out the pattern of dip occurrence. In next part, some aspects associated with voltage dip assessment, e.g. counting of multiple dips or clusters of different events (combination of dips and swells or interruption), severity of the events and responsibility for cause of events, are discussed and their impact on number of expected dips is illustrated on the evaluation of measurement records.

INTRODUCTION

In the Czech Republic, continuity of supply has been involved in price regulation since 2013. The mechanism of incentive-based quality regulation is detailed in the 6th CEER benchmarking report on the quality of electricity and gas supply [1]. At present, the discussion about including short interruptions of supply voltage into regulation has started. In the future, it is expected that some voltage quality (VQ) issues will be also under regulation, e.g. voltage dips that, like interruptions, can lead to high economic impact on industrial customers.
As regards voltage events, EN 50160 standard is not satisfactory from a regulatory point of view. No limits for the expected number of voltage events are set in the standard and the responsibility for impact of an event on a customer is unclear. In regulatory framework, it is important to define one or more responsibility-sharing curves which distinguish between voltage events for which regulation would be in place, and events for which the customer would have to take measures [2]. In comparison with continuity of supply, only few European countries have involved voltage events into regulation or prepared a regulatory framework regarding voltage events, for details see [3].
Before setting limits of voltage event occurrence for regulatory purposes, detailed analysis of historical records has to be carried out and various aspects of voltage event assessment have to be considered, e.g. data verification (removal of duplicate records, false records), rare extreme occurrence of the events, counting of multiple events, responsibility for cause of events, and impact of events on customers' installations.
Initial analysis of the long-term voltage dip monitoring was performed four years ago [4]. The results presented in this paper are updated and important aspects of voltage event assessment in context of VQ regulation are discussed.

VOLTAGE DIP MONITORING

In a polyphase system, an event is considered as a voltage dip when the remaining voltage at least in one of the phase-to-phase voltages is below 90% of the reference voltage and at least in one of the phase-to-phase voltages is above 5% of the reference voltage for duration between ½ cycle to 1 minute. In the Czech Republic, voltage dips with duration up to 3 minutes are assessed. Voltage dips and interruptions are, by their nature, unpredictable and vary from place to place and from time to time. Because of voltage dip propagation in the system, the frequency of voltage dips occurrence at a point is higher than interruptions.

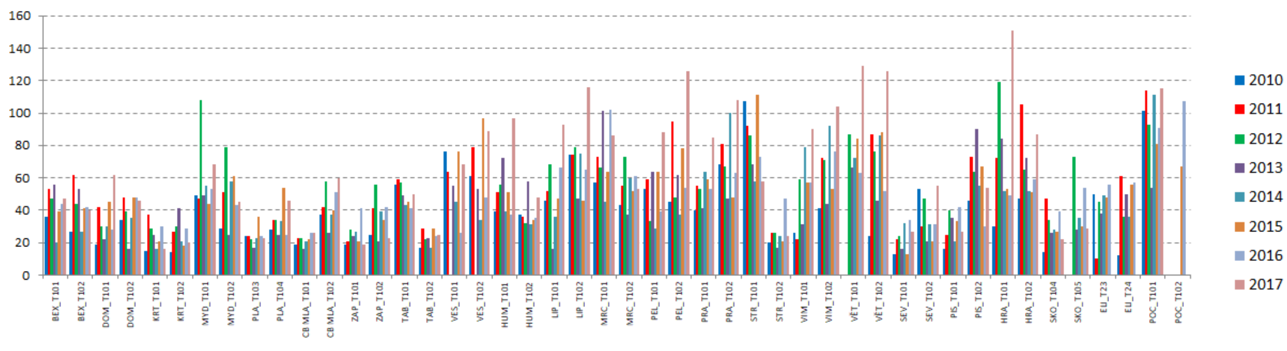

Figure 1 *Number of voltage dips recorded in the 22 kV substations (2010 – 2017)*

In the Czech Republic, PQ monitors are permanently installed on the secondary side of all EHV/110 kV and 110 kV/MV transformers since 2006 and 2010 respectively. Few MV/LV substations, as well as important customers are also continuously monitored. In addition, the VQ monitors are installed temporarily, e.g. to check the performance of the supply system, or to verify customers' complaints. 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), for each line-to-line voltage in HV and MV networks, and for line-to-ground voltages in LV networks. Polyphase aggregation (an equivalent event characterized by a single duration and a single residual voltage) is used. Time aggregation (multiple voltage dips are considered as a single equivalent event) is not generally used. Records presented in the next chapter are without any time aggregation.

RESULTS OF LONG-TERM MONITORING

On supply territory of the E.ON company in the Czech Republic, voltage dips have been collected from 46 sites at MV system for monitoring period 2010-2017, a total of 355 monitor-years. Dips have been recorded on MV side of the 110/22 kV transformers. Figure 1 illustrates largely random annual occurrence of voltage dips. Number of dips varies from site to site and from year to year. Annual number of dips in the MV substations has varied between 10 and 151 dips, which is two times more than in the HV substations [4].
Numbers of dips recorded in individual years are compared in Table 1. Maximum annual number of recorded dips varies in narrower band between 101 and 151 events. Average annual number of dips recorded in a monitoring site ranges around 50 dips. About 8.5% of recorded dips are so called "major dips", dips laying below the indicative responsibility-sharing curve [2], based on the preferred test levels and duration for Class 3 specification of equipment dip immunity according to EN 61000-4-11. This reference curve distinguishes between minor and major dip, the latter are often the most problematic for the customers. This responsibility-sharing curve is also marked in Table 2 that presents distribution of recorded voltage dips according to their severity.

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

Residual voltage U_{res} (%)	**Duration of dips t (s)**				
	0.01≤t<0.2	0.2≤t<0.5	0.5≤t<1	1≤t	Total
$80 \le U_{res} < 90$	43.7	5.4	0.9	0.1	50.1 %
$70 \le U_{res} < 80$	20.5	1.1	0.9	0.1	22.6 %
$40 \le U_{res} < 70$	19.7	0.4	0.3	0.2	20.6 %
$5 \le U_{res} < 40$	5.6	0.4	0.1	0.1	6.2 %
$0 < U_{res} < 5$	0.3	0.1	0.1	0	0.5 %
Total	**89.8 %**	7.4 %	2.3 %	0.5 %	100 %

About 75% of recorded dips belong to transient dips with duration shorter than 0.1 second; the duration of nearly all dips did not exceed 1 second. It means that the voltage dips were mainly caused by faults.
Table 1 also shows the average number of major dips per monitoring site per year. Last column shows average number of dips over all measurement locations and all years. In MV system, average number of major dips per site per year varies around 4 events. It should be noted that this number is relatively low in comparison with other European countries where average number of major dips in MV system ranges between 10 and 30 events [1], [2]. Comparison of available data regarding number of major dips in European countries is presented in Table 3. The comparability of the number is of course limited by the difference in network structure.

Table 1 *Voltage dip occurrence and statistics in individual years and for the whole monitoring period 2010-2017*

MV networks	Voltage dips								
	2010	2011	2012	2013	2014	2015	2016	2017	2010-2017
Number of dips recorded at all sites	1687	2272	2326	1927	2010	2275	2257	2894	17648
Number of site-years	43	43	43	45	45	46	46	44	355
Average annual number per site-year	39.2	52.8	54.1	42.8	44.7	49.5	49.1	65.8	49.7
Standard deviation	22.3	24.8	24.0	21.5	22.9	21.9	19.2	37.2	25.6
95% percentile	75.8	84.7	92.4	81.6	90.8	87.0	87.3	126.0	101.3
Maximum annual number of dips	101	114	119	101	111	111	107	151	151
Number of major dips	165	153	235	189	162	160	195	257	1516
Percentage of major dips	9.8%	6.7%	10.1%	9.8%	8.1%	7.0%	8.6%	8.8%	8.6%
Average number of major dips per site-year	3.8	3.6	5.5	4.2	3.6	3.5	4.2	5.8	4.3

Table 3 *Number of major dips in MV systems in various countries (events per monitor-year)*

Country	Major dips	Years
Hungary [2]	13.3	2009
Italy [2]	26.6 – 18.8 – 15.9	2008 – 2009 – 2010
Portugal [1]	19.0	2014

ASPECTS OF VOLTAGE DIP ASSESSMENT IN CONTEXT OF VQ REGULATION

In previous chapter, data was presented without any time aggregation or removal of duplicate or multiple events, only polyphase aggregation was used. In the context of VQ regulation, various aspects of voltage event assessment have to be considered, e.g. data verification (removal of duplicate records, false records), rare extreme occurrence of the events, counting of multiple events, responsibility for cause of events, and impact of events on customers. In following text, the authors would like to call attention to some problems that arise from recorded data evaluation and seem to be important in context of VQ regulation.

Time aggregation

Time aggregation is a possible method of preventing double-counting of events. Voltage dips often occur in clusters, e.g. in period of adverse weather conditions (lightning or wind storms) or typically due to automatic reclosing operation. Time aggregation counts a sequence of events (events within a short time), generally caused by a single power system event, as a single event. Time aggregation interval can range between a few cycles and a few tens of minutes. There are no recommendations or rules for time aggregation in the EN 50160 standard, although it can have significant effect on the results of event assessment. EN 50160 standard states only that "the method used for the aggregation of multiple events can be set according to the final use of the data".
Only general recommendations are given in [5]. The aggregation window between a few cycles and a few seconds eliminated transient events connected for example with event ending. To aggregate multiple dips caused by unsuccessful reclosing after a fault, the sufficient interval is a few tens of seconds, but it depends on breaker characteristic. To eliminate double counting of multiple dips due to autoreclosing, aggregation window can vary in wide range in different countries, between a second to few tens of seconds, but it is generally not longer than 1 minute [5] [3]. For recurrent faults, the interval can be even a few minutes. From practical point of view, aggregation interval can correspond to the recovery time of production processes and can be even a few tens of minutes. The discussion on the choice of time-aggregation interval remains open.
The time aggregation was applied on selected cases with extreme occurrence of events to find out the effect on a number of recorded events.

Effect of time-aggregation interval
Impact of time-aggregation window on dip assessment is illustrated on the case of a LV substation with extreme number of recorded dips in March and summer 2008. In this case, 48 dips were recorded in March, but 35 of them were recorded within 11 hours as a consequence of Emma windstorm that hit the territory of the Czech Republic on 1st March. Figure 2 compares results for various aggregation intervals, applied on events recorded in March. The dark columns present a number of dips after time aggregation. Generally used time intervals are complemented by time interval of 1 day that can be used for information in which days the dips occurred within the monitoring period. In this case, the dips were recorded in 5 days in March only.

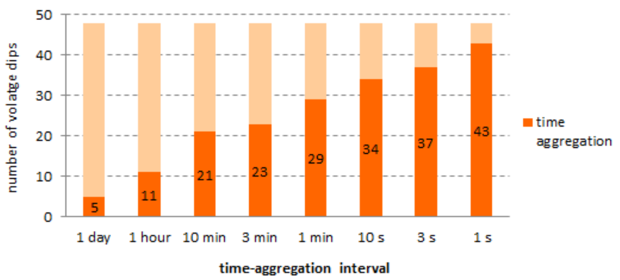

Figure 2 *Effect of various aggregation intervals (dips recorded in March 2008)*

The time aggregation (1 minute) was applied also on records in other months (Figure 3). Aggregation had a greater impact on records in summer months and in months with extreme weather conditions.

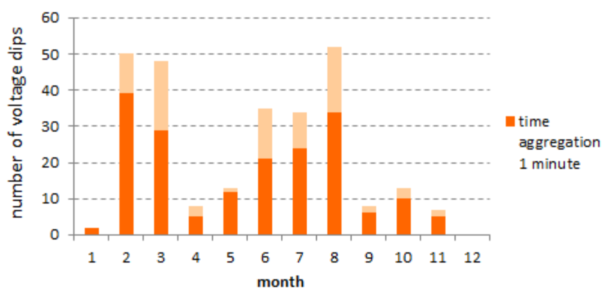

Figure 3 *Impact of time-aggregation (1 minute) on records in individual months*

Figure 4 shows the time-aggregation effect on number of dips recorded in various supply areas. Both transformers are located in the same HV/MV station, but they are separately operated. While the T101 transformer supplies rural area by overhead-line feeders, T102 transformer supplies city cable network. Much higher number of dips was recorded on the secondary side of the T101 transformer, mainly in summer months [4]. The effect of network arrangement (rural area, overhead feeders) and weather condition (i.e. summer storms) is evident.

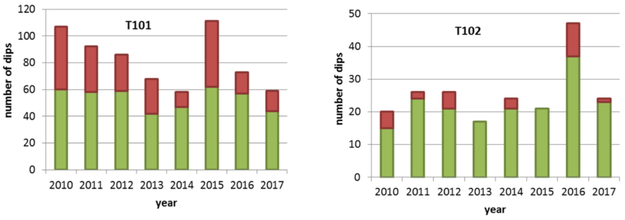

Figure 4 *Effect of time aggregation (10 minutes) for station supplied rural area (T101) and urban area (T102)*

Time aggregation reduces a number of dips mainly in substations in rural areas with higher rate of overhead lines, where multiple dips caused by unsuccessful reclosing after a fault or recurrent faults are more frequent. Time aggregation contributes to more realistic view of network performance by excluding exceptional events in period of adverse weather conditions.

Combinations of different events

Evaluation of records in HV substations identified great number of very deep dips in some substations. Detailed analysis of event records revealed clusters of very short and deep dips followed by an interruption or surrounding a swell. Most of them followed right after a swell. In most cases, the event clusters included several dips with residual voltage below 10% and duration shorter than 0.1 s. Examples of recorded event clusters are in Table 4.

Table 4 *Examples of dip sequences surrounding a swell and followed by an interruption*

Time elapsed (s)	Duration (s)	Retained voltage (%)
	0.01	113.1
0.01	0.02	88.7
0.39	0.01	4.5
0.02	0.01	4.7
0.02	0.01	4.8
0.06	0.01	4.7
0.02	0.01	3.7
0.02	0.01	3.6
0.02	0.05	4.2
0.01	0.02	4.8

Time elapsed (s)	Duration (s)	Retained voltage (%)
	0.02	71.7
0.17	0.01	3.9
0.11	0.01	3.9
0.03	0.02	3.4
0	0.01	4.6
0	0.03	2.5
0.01	0.04	2.8
0	0.03	2.9
0.05	0.04	2.3
0.03	0.05	2.2
0.04	27685.92	0

To take possible effect on end-user equipment into account and preventing double-counting of events, a dip sequence followed by an interruption was counted as single interruption neglecting all dips, and a dip sequence surrounding a swell was counted as single swell and the longest dip. The effect on number of dips in HV sites is clear from Figure 5.

Because of great number of transient dips in the event clusters, the method used for dip sequence counting would have a significant impact on regulation as it can considerably affect the total number of voltage dips or the number of major dips that are expected to cause problems to customers.

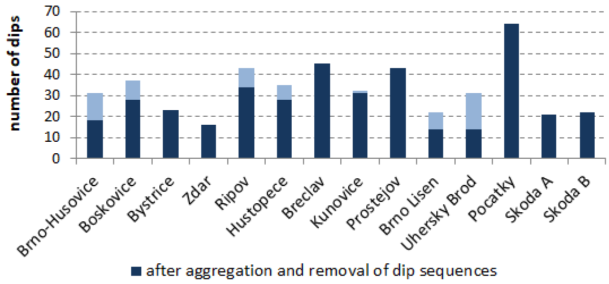

Figure 5 *Effect of aggregation and removal of dip sequences in HV substations (2015)*

Impact of voltage dips on customers

Dips below a voltage-tolerance curve may be treated as major dips. The reference curve to delimit major dips is defined based on immunity test levels or voltage-tolerance curves. The most frequently used reference curves are based on Class 2 and Class 3 of equipment dip immunity. Voltage-tolerance curves are presented in [6], examples of reference curves used for regulation purposes in Sweden, Italy, and France are presented in [3]. The curves differ in excluding transient dips or shallow ones with residual voltage in range (80-90% U_n). The effect of reference curve used for assessment of major dips in HV network presented in previous chapter is shown in Figure 6.

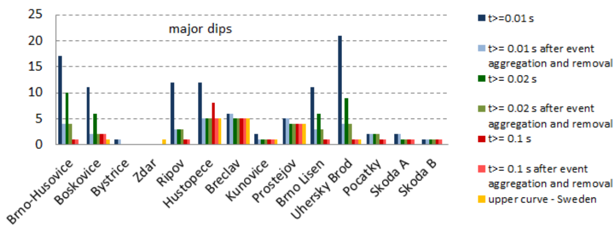

Figure 6 *Effect of reference curve and dip sequence counting on number of major dips*

The used reference curves (Figure 7) are based on the indicative responsibility-sharing curve [2]. The first approach counts all dips lying below the "dark blue" reference curve (dark blue columns in Figure 6). The above mentioned dip sequence counting (aggregation or removal of dip sequences) significantly reduces the number of major dips (light blue columns). Compared to the first approach, the other ones exclude also dips shorter than 0.02 s (green) respectively 0.1 s (red). The comparison is completed with the upper reference curve used for systems above 45 kV in Sweden (yellow) [7].

U (%)	Duration of dips t (s)				
	0.01≤t<0.02	0.02≤t<0.1	0.1≤t<0.2	0.2≤t<0.5	0.5≤t<60
80≤U<90					
70≤U<80					
40≤U<70					
5≤U<40					
0<U<5					

Figure 7 *Reference curves used for major dip counting*

Level of equipment dip immunity is quantified by immunity classes defined by voltage-tolerance curves [6]. Equipment dip immunity could be considered to set up the responsibility-sharing curve used for regulation purposes. The voltage-tolerance curve of given class is different for balanced and unbalanced voltage dips. Rate of balanced and unbalanced dips in LV networks, where most of customers is connected, is affected by fault in MV and HV networks, as well as propagation of unbalanced dips through Dy_n transformers in MV/LV substations. Higher rate of unbalanced dips is expected in LV networks (see Figure 8).

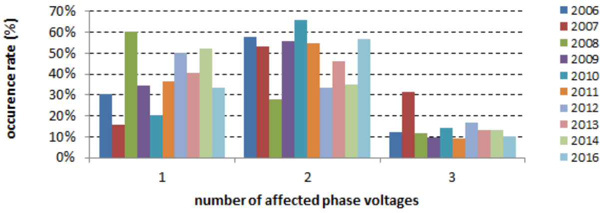

Figure 8 *Rate of unbalanced dips in a LV site*

For this reason the balanced and unbalanced dips should be assessed separately (Type III, Type II and Type I). Regarding dip regulation in MV networks, monitored voltages (phase-phase or phase-ground), dip types and their impact on LV end-users should be considered [3].

Responsibility for cause of events

Voltage dips monitored on a distribution network may have origin in faults occurring in the same network, in upstream networks, also in downstream networks, or in any customer's or producer's plants connected to the distribution network. From point of regulation, there is necessary to allocate the responsibility for cause of events with negative impact on customers.

Figure 9 shows distribution of voltage dips recorded in a 110 kV substation according to origin of the dips. To determine origin of dips in the 110 kV network, a dip occurrence time was compared with signals coming from 110 kV line protections. In this case, about 40% of recorded dips had origin outside the monitored network. The result is similar to results published in [8], where is stated that about 34 % of voltage dips monitored in MV network at national level in Italy are coming from HV network.

Figure 9 *Origin of voltage dips recorded in a 110 kV substation*

CONCLUSION

The paper focuses on some aspects of voltage event assessment that have to be considered in the context of VQ regulation. To set clear rules for measurement and recorded data processing, i.e. verification, removal of duplicate records, false records is very important although this issue was not discussed in the paper. In the paper, the attention is mainly focused on time aggregation because great discussion about it is expected. Time-aggregation seems to be good tool for more realistic view on system performance and impact of events on customers. Discussed issue was the counting of event clusters containing combination transient dip sequences and swells or interruptions; other issue for discussion is how to assess rare extreme occurrence of the events. Introduction of responsibility-sharing curve into event regulation and setting up its borders are also hot topics. In our country, the band for voltage variations in LV networks is +10/-15% during 100% of time and partly overlaps the band for voltage dips. Last but not least issues are the introduction of voltage dip indicators and the decision if the system or site indices would be under regulation.

Acknowledgments

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