Regulation and classification of voltage dips

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REGULATION AND CLASSIFICATION OF VOLTAGE DIPS

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ABSTRACT

The impact of voltage dips on industrial installations can be very high. However, regulation within the European Standard EN 50160 is not detailed as the cells within the general table are not filled. As there is no reference on the expected number of voltage dips, the responsibilities for network operator and customer are unclear. Therefore the customers face challenges to make analysis on required mitigation measures. The Dutch Regulator requested the network operators to prepare a proposal for a regulatory framework regarding voltage dips. This paper presents the initial proposal for the MV distribution network. Based on the effect of various types of voltage dips to the reduction of active-power for aggregated customers, voltage dip severity weighting factors are developed and used to build the proposal.

INTRODUCTION

As defined in the European Standard EN 50160 [1], a voltage dip is the temporary reduction of the RMS voltage at a point in the electrical supply system below a specified start threshold, usually 90% of the reference voltage, for a duration in the range of ½ cycle to one minute. The severity of the disturbance is represented in terms of the magnitude of the residual voltage and the duration.

Voltage dip is one of the detrimental power quality (PQ) problems that can lead to high economic impact on industrial customers. Because of the significant impact, customers may have to take preventive actions. However, the regulation within EN 50160 is not well defined and the number of expected dips in the cells of the general table are not filled. As there is no reference on the expected voltage dips, the responsibilities for network operator and customer are unclear. As a result, the customers face challenges to make economic analysis on the required mitigation measures.

Many countries in Europe [2-7] are currently discussing this issue and trying to set up a regulatory framework where also voltage dips are included in the National Grid Codes. Figure 1 shows examples of responsibility-sharing curves used in Sweden, Italy and France. In Sweden [2, 3], three areas are defined based on the residual voltage and duration. In the top area (A), it is the responsibility of the customers to make their equipment and installations immune to these dips and no limit is set on the number of voltage dips. However, the network operator is responsible to mitigate dips in the area (B) between the two curves to the extent that the mitigation measures are reasonable; and there shall not be voltage dips in the bottom area (C).

In Italy [2, 4], immunity curves defined by Class 2 and Class 3 testing levels in IEC 61000-4-11/34 [8, 9] are used as reference curves by the Italian regulator to distinguish between “minor dips” and “major dips” where the latter are often the most problematic for customers in the distribution network. From measurement campaigns, the average of voltage dips below the two curves (for Class 2 and Class 3) constitute the “regulated dip-frequency index”.

Figure 1. Responsibility-sharing curves in different countries.

According to the Emerald Contract (EdF) [6], medium- and high-voltage customers in France are responsible for voltage dips with duration shorter than 600 ms and for dips with magnitude of residual voltage more than 70% of the nominal voltage while the network operator is responsible for limiting the number of voltage dips longer than 600 ms and deeper than 70% of the nominal voltage. As in [7], the objective for MV customers is a maximum of five events per year, although it depends on local circumstances; whereas for HV customers the objective is based on the number of dips measured during a four-year period.

The Dutch Regulator also requested the network operators to prepare a proposal for a regulatory framework regarding voltage dips. This paper presents the initial proposal for the Dutch MV distribution network. At present, most of the proposals are based on immunity curves of certain equipment only specified for test levels against Type I and Type II voltage dips. In this work, three clusters are defined for various types of voltage dips based on severity weighting factors that are obtained from the loss of power for aggregated customers during voltage dips. The paper also describes the method to set limits on the number of voltage dips in each cluster.

BUILDING THE PROPOSAL FOR VOLTAGE DIP REGULATION

When building the proposal regarding voltage dips for the regulatory framework, different aspects are considered including- currently occurring dips in the networks, origin of the dips, characteristic parameters (remaining voltage, duration, and type) of the dips, multiple dips (events), and impact of the dips on customers' installations.

Monitoring Data

As also recommended in the CIGRE/CIRED joint working group C4.112 [10], permanent PQ measurements in the Dutch MV-networks are mostly done at the busbars of the HV/MV substations. The measurement data used in this paper are from SASensors and EM720 devices. The SASensor measures waveforms of phase-to-ground voltages with a sampling frequency of 4 kHz (80 samples per cycle) and half-cycle values of per-phase powers for aggregated customers in each feeder. With the EM720 device, three channels are dedicated for recording the waveforms of the three phase-to-ground voltages with a sampling frequency of 1.6 kHz (32 samples per cycle).

In this paper, measurement data of six substations with SASensors for four years and 47 substations with EM720 devices for one year are used for assessing the frequency and severity (magnitude and duration) of voltage dips occurring in the Dutch networks. From the substations with SASensors, the impact of voltage dips on aggregated customers is evaluated and severity weighting factors are obtained for various types of voltage dips.

Characterization and Classification

To detect a voltage dip and to determine its characteristic parameters (i.e. magnitude, duration and type), the characteristic RMS voltage as a function of time of each voltage event is obtained based on half-cycle sliding window [11]. In this paper, a voltage dip is detected and considered to be qualified when the residual voltage is below 90% and above 1% of the nominal voltage for a duration ranging from $\frac{1}{2}$ cycle to 1 minute. Voltage dips related to phase-to-ground voltages are referred to as phase-dips and qualifying dips are classified as one-phase, two-phase and three-phase dips.

To assess phase-phase dips, the phase-phase characteristic voltages are calculated from the waveforms of phase-to-ground voltages recorded in the MV-networks. Then, parameters that characterize the phase-phase dips are determined from the RMS voltage characteristics. Depending on the number of (one, two or three) phase-phase voltages being affected by the dip, qualifying dips are classified as L_{001} , L_{011} and L_{111} . For each type of dip, the distribution of voltage dips in the magnitude-duration plane of the dip table in EN 50160 [1], shown in Table I, represents the frequency and severity of voltage dips.

Table I. Classification of voltage dips in terms of residual voltage and duration according to Standard EN 50160

Residual voltage [%]	Duration [s]				
	$\Delta t \leq 0.2$	$0.2 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 5$	$\Delta t > 5$
$90 > u \geq 80$	A1	A2	A3	A4	A5
$80 > u \geq 70$	B1	B2	B3	B4	B5
$70 > u \geq 40$	C1	C2	C3	C4	C5
$40 > u \geq 5$	D1	D2	D3	D4	D5
$5 > u$	X1	X2	X3	X4	X5

Multiple Dips

Repetitive dips may occur within a short measurement interval due to re-closure of a circuit breaker or self-healing faults in cables or joints. When the measurement window is too short to capture all the multiple dips in one waveform, the measuring device may also register them as separate events each containing one or more dips of common cause.

Figure 2(a) illustrates an event due to self-extinguishing fault. Within 5 seconds measurement interval, the phase-ground voltages consist of six dips that are not seen in the phase-phase voltages (Figure 2(b)). Another multi-dip event possibly caused by the reclosing action of protection device is depicted in Figure 3. Both phase-ground voltages (Figure 3(a)) and phase-phase voltages (Figure 3(b)) of this event comprise two dips characterized by different magnitude, duration and type. From end-users point of view, it is unlikely that equipment and processes will be affected multiple times in such a short period. If the equipment or process fails for the first dip, the successive dips most likely will occur before the equipment recovers.

Multiple dips can have the same common cause (e.g. defect cable joint). Counting them separately would have a significant impact on regulation as they considerably affect the total number of voltage dips while the impact is usually very similar to a single event. Important are the dips leading to a complete or partial interruption of the industrial process. Multiple dips occurring within short time interval (e.g. 1 minute) could therefore be counted as one event instead of multiple dips. In this paper, multiple dips are aggregated into a single event characterized by the magnitude and duration of the most severe dip. In order to obtain the most severe dip, the method of voltage sag energy index [12] is used in this paper. For each dip, the voltage sag energy (E_{vs}) is calculated by (1),

Figure 2. Multiple dips due to self-extinguishing fault- (a) phase-ground voltages, and (b) phase-phase voltages.

Figure 3. Multiple dips due to reclosing of actions of protection device- (a) phase-ground voltages, and (b) phase-phase voltages.

$$E_{vs} = \int_{t_{1x}}^{t_{2x}} \left(1 - \frac{u_x^2}{u_n^2}\right) dt + \int_{t_{1y}}^{t_{2y}} \left(1 - \frac{u_y^2}{u_n^2}\right) dt + \int_{t_{1z}}^{t_{2z}} \left(1 - \frac{u_z^2}{u_n^2}\right) dt \quad (1)$$

where u_x , u_y and u_z represent the RMS values below the dip threshold, u_n is the RMS value for the nominal voltage, t_1 and t_2 are the dip-start and dip-end times of the dips associated to each phase-ground or phase-phase voltage. The dip with the highest voltage sag energy index is considered as the most severe dip and the corresponding dip parameters are used to represent the multiple-dip event for regulatory purpose. As illustrated in Table II, applying the method for the multi-dip event shown in Figure 3 indicates that the second dip is more severe and associated parameters can be used to represent the multi-dip event.

Table II. Severity of individual dips for multi-dip event in Figure 3

Phase-dip	Dip characteristics	Dip characteristics			
		u [pu]	Δt [ms]	Type	E_{vs} [ms]
Phase-dip	dip1	0.45	1280	2	1320
	dip2	0.16	1100	3	1457
Phase-phase dip	dip1	0.63	1280	2	758
	dip2	0.16	400	3	830

To get better insight into the effect of aggregation with multiple dips, the average number of voltage dips over all measurement locations before and after aggregation are compared in Table III. It can be seen that 1 minute aggregation reduced the number of phase-dips by 45.5% and that of phase-phase dips by 13.4%. A very significant reduction in the number of dips is more pronounced for phase-dips than phase-phase dips due to high number of multiple dips are associated with one-phase dips that are not seen in the phase-phase dips.

Propagation of Voltage Dips

The dips detected at the monitoring location may emanate from the HV- or MV-networks. Most end-users, however, are in the LV-networks that are connected to the MV-networks by Dyn transformers. The characteristics of voltages, mainly with unbalanced dips, are often different at different voltage levels [13]. Phase-phase dips in MV-network propagate through Dyn transformers as phase-dips in the LV-networks, and end-users are essentially affected by phase-phase dips in the MV-networks [13, 14].

The transfer of voltage dips affects the frequency and severity of voltage dips at the customer installations as

compared to the monitoring locations. In Figure 2, none of the phase-phase voltages qualify for a dip despite the event consists of six qualifying phase-dips. For the event shown in Figure 3, both phase-ground and phase-phase voltages comprise two dips. However, the magnitude is shallower for the first dip while the duration is shorter for the second dip in the phase-phase voltages than the phase-ground voltages. Considering the average number of voltage dips over all measurement locations, it is addressed in Table III that the number of voltage dips experienced by end-users is much lower than the monitored phase-dips.

Table III. Effect of aggregation on the average number of phase-dips and phase-phase dips per year

Phase-dips	Phase-dips		Phase-phase dips	Phase-phase dips	
	No agg.	1 min agg.	No agg.	1 min agg.	
1-ph	10.43	4.74	L001	2.92	2.67
2-ph	9.79	5.54	L011	2.16	1.91
3-ph	7.2	4.66	L111	4.71	3.9
Total	27.42	14.94	Total	9.79	8.48

Impact of Voltage Dips on Customers

From RMS power characteristics of aggregated customers in each feeder of an MV-network, the impact of voltage dips on combined customers are estimated based on the change in power at the HV/MV substation before and after the dip events. During each dip event, the losses of power in all feeders are combined to evaluate its impact on the aggregated customers (consisting of different customer categories) in the entire network. Figure 4 shows an example of a voltage dip characterized by 0.36 p.u magnitude and 320 ms duration, and leading to the absolute loss of 7 MW loads in the entire MV distribution network.

Figure 4. The loss of power for a typical voltage dip

For all phase-phase dips collected from the six substations during four years, the relative losses associated with each dip are calculated. As discussed more in [15], the average relative loss over all dips within each cell is evaluated to determine the weighting factors (WFs) representing the severity of various types of voltage dips. When completing values of WFs that correspond to voltage dips in each cell of the EN 5160 general dip table, missing values are interpolated and the 95-percentile of the average WFs is proposed as voltage dips severity indices for industrial processes. Values of WFs for the three types of dips, adopted from [15], are shown in Table IV.

Table IV. Weighting factors (%) for three type of dips

(a) WFs for L_{001} dips					
Residual voltage [%]	Duration [s]				
	$\Delta t \leq 0.2$	$0.2 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 5$	$\Delta t > 5$
$90 > u \geq 80$	1	3	5	5	5
$80 > u \geq 70$	3	12	15	15	15
$70 > u \geq 40$	8	25	28	29	29
$40 > u \geq 5$	18	33	37	38	39
$5 > u \geq 1$	20	33	38	39	40

(b) WFs for L_{011} dips					
Residual voltage [%]	Duration [s]				
	$\Delta t \leq 0.2$	$0.2 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 5$	$\Delta t > 5$
$90 > u \geq 80$	4	18	26	27	27
$80 > u \geq 70$	11	25	27	30	31
$70 > u \geq 40$	27	36	37	38	41
$40 > u \geq 5$	42	48	55	58	61
$5 > u \geq 1$	45	53	63	66	67

(c) WFs for L_{111} dips					
Residual voltage [%]	Duration [s]				
	$\Delta t \leq 0.2$	$0.2 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 5$	$\Delta t > 5$
$90 > u \geq 80$	17	31	36	39	44
$80 > u \geq 70$	27	35	38	42	48
$70 > u \geq 40$	40	41	44	53	60
$40 > u \geq 5$	49	53	58	78	85
$5 > u \geq 1$	52	58	66	87	94

The values in each cell represent the severity of the dips relative to a complete interruption. For instance, an L_{011} dip in cell X_5 is as severe as 0.67 times that of 1 minute interruption. An important feature is that the value of WF for each type of dip increases when the dip is deeper and longer. For dips of the same magnitude and duration, the WFs increase with poly-phase dips.

DEFINING LIMITS FOR VOLTAGE DIPS

In order to set limits for regulatory purpose, three clusters are defined for various types of voltage dips. From the average voltage dip profiles, the proposal is based on the 95% values of number of dips per year in each cluster.

Voltage Dips Clustering

Using the voltage severity WFs, obtained from the impact of voltage dips on aggregated customers connected in the entire MV-network, the effect of different types of voltage dips are classified as BIG, MEDIUM or SMALL. This

divides the voltage dip table into three clusters for regulatory purposes. Voltage dips with WFs above 50% (i.e. leading to the loss of more than 50% of the pre-dip power of customers) are considered as BIG effect and clustered as cC; dips with WFs in the range of 30%-50% as MEDIUM effect and clustered as cB; and dips with WFs below 30% are considered as SMALL effect and clustered as cA. Based on these criteria, the area of each cluster on the duration-magnitude planes for the three types of voltage dips are shown in Table V.

Table V. Clusters for the three type of voltages dips

(a) Clusters for L_{001} dips					
Residual voltage [%]	Duration [s]				
	$\Delta t \leq 0.2$	$0.2 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 5$	$\Delta t > 5$
$90 > u \geq 80$	cA1				
$80 > u \geq 70$	2.61				
$70 > u \geq 40$					
$40 > u \geq 5$		cB1			
$5 > u \geq 1$		0.06			

(b) Clusters for L_{011} dips					
Residual voltage [%]	Duration [s]				
	$\Delta t \leq 0.2$	$0.2 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 5$	$\Delta t > 5$
$90 > u \geq 80$	cA2				
$80 > u \geq 70$	1.27				
$70 > u \geq 40$		cB2			
$40 > u \geq 5$		0.44	cC2		
$5 > u \geq 1$			0.19		

(c) Clusters for L_{111} dips					
Residual voltage [%]	Duration [s]				
	$\Delta t \leq 0.2$	$0.2 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 5$	$\Delta t > 5$
$90 > u \geq 80$	cA3				
$80 > u \geq 70$	0.56	cB3			
$70 > u \geq 40$		3.13			
$40 > u \geq 5$			cC3		
$5 > u \geq 1$			0.22		

The approach is chosen because it considers the immunity of several equipment and installations connected in the MV distribution networks against the three types of dips. Because of the small effect they have on end-users, L_{001} dips do not include cluster cC. On the other hand, cluster cA covers very small area for L_{111} dips due to the fact that these dips have very significant effect on most customers. To get better insight into sharing the responsibilities among different parties, the immunity curve of Class C equipment, proposed by the CIGRE/CIRED/UIT JWG C4.110 [5], is put along with the clustering in Table V. All L_{001} and L_{011} dips with MEDIUM and BIG effect are below the curve. However, L_{111} dips (magnitude above 80% and duration between 0.2 - 5 s) with MEDIUM effect are above the curve and this could be because of customers that use devices with lower immunity level than Class C devices.

Voltage Dips Limit for Each Cluster

Taking into account the propagation of voltage dips and aggregating multiple dips into a single event, a customer in the LV-network would experience on average 8.48 dips per year. It is obtained that most (~81%) of the dips have

duration shorter than 200 ms and a vast majority (~90%) of the dips have residual voltages above 40% of the nominal voltage. The share of L_{001} , L_{011} and L_{111} dips to the average number of voltage dips over all monitoring locations is about 32%, 22%, and 46% respectively.

For each type of voltage dip, the average number of dips belonging to the clusters cA, cB and cC, shown in Table V, are obtained by adding the number of dips within cells of the same cluster. Then, the number of dips belonging to similar cluster can be added to reduce the clustering into three general categories. Assuming that the occurrence of voltage dip events is random and consecutive events are independent to each other, the probability of occurrence of events, with a known average rate, occurring in a fixed period of time can be predicted using the Poisson's distribution function [16]. Figure 5 shows that the average number of voltage dips belonging to clusters cA, cB and cC are 4.44, 3.63 and 0.41 dips per year with probabilities of occurrence 18%, 20% and 50% respectively. For the 95% of the time in a year, the average occurrence voltage dips in each cluster can be limited to 8, 7 and 2 dips respectively. From this point of view, total of 17 dips per year, and maximum of 7 and 2 dips per year for clusters cB and cC can be considered as indicative limits for the network operator.

Figure 5. Probability distribution and cumulative function of average voltage dip occurrences for the three clusters voltage dips.

In practice, dips in cluster cA have very little impact on customers' installations and end-users are expected to choose equipment that ride-through such dips. For voltage dips in cluster cB and cC, the network operators should take measures to mitigate the dips where possible, and they take responsibility to avoid the dips from exceeding the maximum limit. Due to limited amount of dips, cB and cC can be combined in one cluster (with average of 4 dips per year) that would make the application of the Poisson's distribution function more practical. In this case, the number of dips will be restricted to 8 for the 95% of the time in a year. During periods when the number of voltage dips exceed the objective reference values, there is an indication of alarming power quality problems and the network operators should investigate the problem.

DISCUSSION

Based on the current knowledge, a proposal for the Dutch grid code is made by the Dutch DNOs. As not all details

and implications of the method described in this paper are well known, simplifications might be required in the final proposal. Some simplifications in the proposal for the grid code, which is still under consideration, are:

- making no distinction in 1-, 2- or 3-phase dips;
- limiting the number of clusters to two, due to limited number of dips;
- small differences in the definition of events/counting of dips, due to the use of more measured data;

CONCLUSION

This initial proposal on regulation of voltage dips for the Dutch MV distribution network provides an approach of classifying voltage dips into three clusters based on their impact on aggregated customers. Objective number of dips for each cluster is proposed to indicate the minimum quality of supply beyond which the network operators are triggered to investigate the serious disturbance.

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