A proposal on voltage dip regulation for the Dutch MV distribution networks

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Summary
Voltage quality regulation has been an ongoing discussion in many countries in the world to set up a regulatory framework where also voltage dips are included in the national grid codes. Regarding voltage dips, the regulatory framework is useful for establishing the coordination between the network operators, the equipment manufacturers, and the customers. The voltage dip regulation can provide benefits for the involved parties. By defining the responsibilities for the network operators and the customers, it can help distribution system operators to evaluate the quality of supply voltage and to take possible measures when the number of dips exceed the reference values defined in the regulation. The regulatory framework can also help customers to make an economic analysis for choosing appropriate mitigation methods to reduce the expected economic damages caused by voltage dips. This article presents two approaches for classifying different types of voltage dips into various clusters. Using datasets of voltage dips from the Dutch MV networks, the paper also describes the methodology for setting limits on the number of voltage dips for the regulatory purpose.

KEYWORDS
dip clustering, dip regulation, power quality, responsibility sharing, voltage dip, weighting factors

1 | INTRODUCTION

Voltage dip is the temporary reduction of the RMS voltage at a particular point on an electricity supply system below a dip start-threshold followed by its quick recovery to the dip end-threshold after a brief interval.1−3 Typically, a voltage dip is associated with the current increase on the system or installations during short-circuit faults mostly occurring in the grid.

List of symbols and abbreviations:

| Symbol | Description |
|--------|-------------|
| $\lambda$ | Average occurrence of dip events in a specified period |
| $e$ | Base of natural logarithm |
| $P_{sub-pre}$ | Pre-dip power of the entire substation |
| $N_{pre}$ | Total number of events in $i^{th}$ row and $j^{th}$ column of a cell |
| $P_{load-gen}$, $P_{gen-gen}$ | Post-dip power of loads/generations in a feeder $(f)$ |
| $\Delta P_{sub-load}$, $\Delta P_{sub-gen}$ | Change of load/generation power in the substation |
| $L_{001}$ | One phase-to-phase dipped voltages |
| $L_{011}$ | Two phase-to-phase dipped voltages |
| $L_{111}$ | Three phase-to-phase dipped voltages |
| SADSI | System average dip severity indices |
| $U$ | Magnitude of remaining voltage |
| WF | Dip severity |
| $X_{12}$ | Cluster $X$ $(A, B, C)$ for unbalanced $(L_{001}$ and $L_{011}$) dips |
| $X_p$ | Cluster $X$ $(A, B, C)$ for p-type $(L_{001}$, $L_{011}$, and $L_{111}$) of dip |

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connection of heavy loads (such as big motors), or excitation of high-power transformers.\textsuperscript{4-6} The level of the disturbance is usually determined by magnitude of the remaining voltage and duration. In a polyphase system, an event is considered as a voltage dip when the remaining voltage at least in one of the phase-phase voltages is below 90\% of the nominal and at least in one of the phase-phase voltages is above 5\% of the nominal voltage for a duration between $\frac{1}{2}$ cycle to 1 minute.\textsuperscript{1,2}

The main reason why there is significant interest in voltage dips is its huge economic impact especially on industrial customers.\textsuperscript{4,5} The economic losses incurred by various customers depend on the frequency and severity of voltage dips observed at their connection points. Because of the propagation from one part of the network to another, the frequency of voltage dips occurrence at a point is higher than interruptions, and the annual economic impact on industrial customers can be significantly larger.\textsuperscript{4,5,7-10} The standard IEC 61000-2\textsuperscript{8} provides examples of statistical indices on voltage dips and short interruptions based on measurement results from different countries in the world. It is stated in the document that the frequency and probability of the occurrence of voltage dips are highly unpredictable both in time and place as it varies depending on the type of network and the point of observation.

The European Standard EN 50160\textsuperscript{2} is normally used in the European countries as a basis for describing the expected quality of the supply voltage. This standard provides a voltage dip classification table allowing for a more harmonized way of presenting data throughout Europe. For the regulatory purpose, this classification is useful in evaluating the frequency of voltage dip occurrences over a certain period of time. It also gives the opportunity to apply the concept of “responsibility-sharing” between customers, equipment manufacturers, and network operators. However, no limits are set on the expected number of voltage dips, and customers usually face challenges to make the economic analyses on the possible mitigation techniques.

The Dutch regulator wants to include limits regarding voltage dips in the national grid code, and the network operators have been requested to prepare a proposal for the regulatory framework. This paper describes two approaches of classifying voltage dips into different clusters and defining limits on the number of dips for the regulatory purpose. The first method considers voltage-tolerance curves of equipment dip immunity levels for making the clusters. The second approach considers the relative loss of power for the aggregated customers connected to the Dutch MV networks to obtain severity weighting factors (WFs) for building the proposal. Dip data monitored from several MV networks over long period are used for setting the limits on the number of dips with both clustering approaches. This can help both the network operators and the customers in evaluating the quality of supply voltage and estimating the related costs.

The rest of the paper is organized as follows. Section 2 presents examples of responsibility-sharing practices regarding voltage dips. Different aspects required for building a voltage dip regulation proposal are described in Section 3. Then, the description of two methods for making the regulation, namely, equipment dip immunity-based approach and severity WF-based approach, are given in Section 4. In Section 5, the two methods are compared by pointing out the main advantages and drawbacks of each method. Finally, the concluding remarks are presented in Section 6.

## 2 | RESPONSIBILITY-SHARING PRACTICES

An integral part of regulation is defining the responsibilities to be shared among different parties involved in the delivery and usage of power. Regarding voltage dips, responsibility-sharing curves are used to define the voltage quality requirements of the network in coordination with the performance of equipment or installations. These curves could be defined based on test levels recommended by some international standards (eg, IEC 61000-4-11/34\textsuperscript{11,12}), or on immunity requirements for industrial equipment (eg, SEMI F47/ITIC\textsuperscript{13,14}). These curves set up a boundary between voltage dips for which customer equipment or installations should be immune and the number of events that should be limited by the network operators.

Examples of responsibility-sharing curves used for the MV distribution networks in Sweden, Italy, and France are depicted in Figure 1. In Sweden,\textsuperscript{15} the upper curve (solid line) and lower curve (dot-dash line) divide the voltage dip table into three areas based on the remaining voltage and duration. As discussed in several reports,\textsuperscript{15,20,21} voltage dips above the upper curve are expected to have little impact on end-user installations, and it is the responsibility of the customers to make their equipment or installations immune against these dips. No limit is set on the number of dips in this area. In the area below the lower curve, the quality of supply voltage is considered to be insufficient, and voltage dips in this area are unacceptable. In the area between the two curves, the impact of voltage dips is limited, and the network operator has the responsibility to mitigate the voltage dips to the extent that the mitigation measures are reasonable. The equipment manufacturers must assure that their equipment are immune to voltage dips above the upper curve and must assure that different classes of equipment immunity are able to cover the area between the two curves.
In France, sharing the voltage dip-related inconveniences are defined based on contractual agreement between the network operators and the customers. Voltage dip duration of 600 ms and remaining voltage of 70% of the nominal voltage are adopted in the Emerald Contract (EdF)\textsuperscript{18,19} as threshold values that are applicable to medium- and high-voltage customers under contract. According to the contract, customers are responsible for dealing with voltage dips shorter than 600 ms and for dips with magnitude of remaining voltage above 70% of the nominal voltage (see Figure 1). The network operators are responsible for limiting the number of voltage dips longer than 600 ms and deeper than 70% of the nominal voltage. The limit on the number of voltage dips per year for the MV customers is set based on the local circumstances, whereas for HV customers the objective is based on historical performance of the networks.\textsuperscript{22,23}

For the distribution networks in Italy,\textsuperscript{16,17} immunity curves defined by Class 2 and Class 3 testing levels in IEC 61000-4-11/3\textsuperscript{11,12} 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 the customers. From measurement campaigns, the EN50160 standard table is used to classify dips when estimating the numbers of voltage dips, process immunity, and related costs for customers. In this case, the “regulated dip-frequency index” is the average of voltage dips below the two curves (for Class 2 and Class 3).

Responsibility-sharing curves for voltage dips also exist outside of Europe (eg, South Africa). A South African user specification standard\textsuperscript{24} classifies voltage dips into Y, X, S, T, and Z categories, shown in Table 1, based on a combination of network protection characteristics and customer load compatibility. This PQ standard places the responsibility with the customer for voltage dips in area Y that are expected to occur frequently in typical HV and MV systems. The number of dips is limited for all other dips. The X-areas (X1 and X2) reflect voltage dips with normal clearance times, and hence a significant number of events in this area. Customers should attempt to protect their plant against at least X1-type dips. The T-type area reflects voltage dips due to close-up faults, which are not expected to happen too regularly—and which a utility should specifically address if excessive. S-type dips, which may occur with impedance protection schemes or with delayed voltage recovery, are not as common as X- and Y-type. Z-type dips are very uncommon in HV systems as this generally reflects problematic protection operation.\textsuperscript{25} The allowed number of X-type dips is more than S-type dips, and the sum of X- and S-type dips is more than T-type dips.

At present, most of the proposals are based on immunity curves of certain equipment which are only specified for test levels against Type I and Type II voltage dips. Although the same test levels and immunity curves are considered for equipment against one-phase and two-phase dips, the performances of equipment are different in practice. Moreover, the dip immunity test levels and voltage-tolerance curves in the existing standards are not applicable for three-phase equipment or installations.

### TABLE 1 Voltage dip classification and responsibility-sharing according to the South African standard NRS-048\textsuperscript{24}

| Remaining Voltage, % | Duration, ms |
|---------------------|-------------|
|                     | $20 < \Delta t \leq 150$ | $150 < \Delta t \leq 600$ | $600 < \Delta t \leq 3000$ |
| 90 > u $\geq$ 85   |             |             |             |
| 85 > u $\geq$ 80   |             |             |             |
| 80 > u $\geq$ 70   |             |             |             |
| 70 > u $\geq$ 60   |             |             |             |
| 60 > u $\geq$ 40   |             |             |             |
| 40 > u $\geq$ 0    |             |             |             |

In this case, the “regulated dip-frequency index” is the average of voltage dips below the two curves (for Class 2 and Class 3).
3 | IMPORTANT ASPECTS FOR BUILDING VOLTAGE DIP REGULATION

Voltage dips are monitored in the Dutch HV and MV networks, and there has been a growing interest from the regulatory body to set up a regulation and include it in the national grid code. This paper discusses a proposal on voltage dip regulation for the Dutch MV distribution networks. When building the proposal, different aspects are considered including:

- Monitoring voltage events,
- Assessing and presenting the monitored dip data,
- Impact of voltage dips on customers connected to the MV networks.

3.1 | Monitoring voltage events

System performance analysis is usually an issue for a network operator. To deal with the growing pressure from customers and regulatory agencies to provide information on the actual power quality levels, the network operators have to be aware of the quality of the supply voltage in the networks. The use of PQ monitors, installed in the electric power systems, has enabled network operators to acquire more information about the quality of the supply voltage and to provide appropriate information to the customers. Nowadays, different PQ monitors are available for this purpose. Some PQ monitors measure RMS values, while others record digitalized waveforms of voltage and current signals sampled at high frequency.

The CIGRE/CIRED guidelines recommend that PQ should be permanently monitored in the HV and MV networks. In the Netherlands, voltage dips have been monitored in the HV networks since 2006/07, and annual reports have been published. Since then, PQ monitors have been introduced in the MV networks, and even more monitors are installed during 2014 to 2015 for continuous voltage dips measurements in the MV networks. As also recommended in the CIGRE/CIRED guidelines, permanent PQ measurements are mostly done on the MV side of the transformer in the HV/MV substations, which is considered as the most optimal monitoring location.

Voltage events (voltage waveforms with high time resolution) collected from 53 monitoring locations over different years of measurement period are used in this work. With this monitored data, phase-to-ground voltages are monitored in the MV networks while the end-users are essentially influenced by voltage dips associated to the phase-to-phase voltages. The characteristics of phase-to-phase voltages as a function of time are obtained for each event from the waveforms of phase-to-ground voltages. In this way, the effect of propagation on the number and severity of voltage dips at the customer terminals will be taken into account. Figures 2, 3, and 4 are typical examples of monitored voltage events showing the variations on the voltage characteristics at the point of monitoring point (a) and at the end-user equipment terminals (b). It can be seen that voltage dips due to single-phase faults in MV networks with isolated system grounding are hardly experienced by the end-users. The magnitude of voltage dips caused by two-phase faults in the MV network is slightly shallower (even in the most affected phase) at the customer terminals than at the monitoring point. Balanced three-phase dips, however, are transferred to the customer terminals without significant changes on the characteristics.

3.2 | Assessing and presenting voltage dips

The voltage during a voltage dip is assumed to be a constant RMS value, and this simplified approach is usually considered during the analysis to obtain statistical data. However, in reality, voltage dips are often complex in shape, and the RMS value varies during the dip. When evaluating the dip parameters from the recorded waveforms of voltage events, the following considerations are made in this work:

- The RMS voltage characteristics of events are used to detect if each voltage event is qualified for a dip. As recommended by the IEC 61000-4-30, RMS voltage characteristics as a function of time of the voltage events are obtained using the half-cycle sliding window method. Regarding the data used, phase-to-ground voltages are monitored in the MV networks while the end-users are essentially influenced by voltage dips associated to the phase-to-phase voltages. The characteristics of phase-to-phase voltages as a function of time are obtained for each event from the waveforms of phase-to-ground voltages. In this way, the effect of propagation on the number and severity of voltage dips at the customer terminals will be taken into account. Figures 2, 3, and 4 are typical examples of monitored voltage events showing the variations on the voltage characteristics at the point of monitoring point (a) and at the end-user equipment terminals (b). It can be seen that voltage dips due to single-phase faults in MV networks with isolated system grounding are hardly experienced by the end-users. The magnitude of voltage dips caused by two-phase faults in the MV network is slightly shallower (even in the most affected phase) at the customer terminals than at the monitoring point. Balanced three-phase dips, however, are transferred to the customer terminals without significant changes on the characteristics.
- An event, in a polyphase system, is considered as a voltage dip when the remaining voltage at least in one of the phase-phase voltages is below 90% of the nominal and at least in one of the phase-phase voltages is above 5% of...
the nominal voltage for a duration between ½ cycle and 1 minute.\textsuperscript{1,2} In case of polyphase events, unbalanced faults can lead to dips in two or three phase-phase voltages with different drops in magnitudes and durations. As recommended in the standards,\textsuperscript{1,2} \textit{phase-aggregation} and \textit{time-aggregation} are applied such that: the magnitude of the lowest phase-phase voltage during the dip is used as the voltage dip magnitude, and the time between the first instant the RMS voltage of any phase-phase voltage drops below the dip start-threshold to the instant that the RMS voltages of all phase-phase voltages rise just above the dip end-threshold is considered as the voltage dip duration.

- Voltage events with the same common cause may comprise several dips within a short time interval. For instance, Figure 5 illustrates an event consisting of six dips within 5-second measurement window of the phase-to-ground voltages which are not seen in the phase-phase voltages. Another multi-dip event possibly caused by the reclosing action of protection device is shown in Figure 6. In this case, both phase-to-ground and phase-phase voltages comprise four dips characterized by different parameters. It can be recalled that dips affecting only one phase-to-ground voltage are not seen in the phase-phase voltages. If an equipment or a process fails for the first dip, the successive dips most likely will occur before the equipment or process recovers in such a short period.

PQ devices may also record recursive events, occurring within a short time interval, separately when the measurement window is short to capture all dips in one waveform. In either case, counting each dip separately would have a significant impact on regulation as they can considerably affect the total number of voltage dips despite the fact that the impact on end-user equipment is usually very similar to a single event. In this work, all dips affecting phase-phase voltages and occurring within 1 minute are aggregated and counted as a single dip for the regulatory purpose, and the event is represented by the parameters of the most severe dip obtained based on the voltage sag energy index method.\textsuperscript{34} Applying this method to the multi-dip event shown in Figure 6B, Table 2 indicates that the first dip has the
The highest voltage sag energy index, and it is the most severe dip. This voltage event can, therefore, be represented by the corresponding parameters (i.e., magnitude having 45% of nominal voltage and duration of 120 ms).

Various types of voltage dips have different impact on customer equipment or installations even though they have the same magnitude and duration.\textsuperscript{35,36} Depending on the number of (one, two, or three) affected phase-phase voltages, voltage dips are classified as $L_{001}$, $L_{011}$, and $L_{111}$ dips. In this way, the effect of different types of disturbances can be related to their impact on single-phase and three-phase equipment or installations. In this paper, voltage events monitored from 53 MV substations for 4 years are considered for obtaining the average dip profile. Taking the propagation of voltage dips and aggregation of multiple-dips into account, single event indices of each substation are combined into annual site indices, and the average annual occurrence of each dip type over all monitoring locations is shown in Table 3.

As can be seen from Table 3, a customer in the LV network would experience, on average, about 8.5 dips per year, and the share of $L_{001}$, $L_{011}$, and $L_{111}$ dips to the average number of voltage dips is about 32%, 22%, and 46%, respectively. Even though more dips caused by the phase-to-ground faults are measured at the monitoring points, they can hardly propagate to the end-user terminals. On the other hand, voltage dips caused by three-phase faults are unaffected during the propagation to the end-users and constitute a higher proportion. From the analysis, it is observed that more than 85% of the dips at the customer terminals have magnitude of the remaining voltages above 70% of the nominal voltage and more than 95% of these dips have durations less than 1 second. It is also noticed that using aggregation with multiple-dips over all monitoring locations reduced the average numbers of dips from 10 to about 8.5 per year—a reduction by 15% (more detail can be found in Weldemariam\textsuperscript{37}).
| Remaining Voltage, % | (a) Average Values for L₀₀₁ Dips | (b) Average Values for L₀₁₁ Dips | (c) Average Values for L₁₁₁ Dips |
|---------------------|----------------------------------|----------------------------------|----------------------------------|
|                     | Δt ≤ 0.2 | Δt ≤ 0.5 | Δt ≤ 1 | Δt ≤ 5 | Δt > 5 | Δt ≤ 0.2 | Δt ≤ 0.5 | Δt ≤ 1 | Δt ≤ 5 | Δt > 5 | Δt ≤ 0.2 | Δt ≤ 0.5 | Δt ≤ 1 | Δt ≤ 5 | Δt > 5 |
| 90 > u ≥ 80         | 1.67     | 0.00     | 0.02   | 0.02   | 0.00   | 0.34     | 0.00     | 0.02   | 0.00   | 0.00   | 0.25     | 0.20     | 0.17   | 0.02   | 0.00   |
| 80 > u ≥ 70         | 0.51     | 0.02     | 0.02   | 0.00   | 0.00   | 0.35     | 0.08     | 0.02   | 0.00   | 0.00   | 0.31     | 0.03     | 0.00   | 0.04   | 0.00   |
| 70 > u ≥ 40         | 0.19     | 0.04     | 0.08   | 0.00   | 0.00   | 0.45     | 0.04     | 0.19   | 0.02   | 0.00   | 2.26     | 0.05     | 0.14   | 0.04   | 0.00   |
| 40 > u ≥ 5          | 0.02     | 0.00     | 0.06   | 0.00   | 0.00   | 0.13     | 0.04     | 0.12   | 0.00   | 0.00   | 0.21     | 0.07     | 0.07   | 0.00   | 0.00   |
| 5 > u               | 0.04     | 0.00     | 0.00   | 0.00   | 0.00   | 0.02     | 0.00     | 0.06   | 0.02   | 0.00   | 0.00     | 0.00     | 0.04   | 0.00   | 0.00   |
| Total               | 2.67     |          |        |        |        | 1.91     |          |        |        |        | 3.90     |          |        |        |        |
3.3 | Impact of voltage dips

3.3.1 | Equipment dip immunity

Industrial and commercial customers often have equipment that are sensitive to voltage dips. The performance of the supply system is often represented by the magnitude and duration of voltage dips whereas the equipment sensitivity is represented by the voltage-tolerance curves. Depending on the severity of dips, electrical devices may malfunction, fail prematurely, or not operate at all. In many manufacturing processes, a defect of only a few vital pieces of equipment may result in a complete or partial shutdown of production which in turn leads to huge financial losses.

Industrial standards, like SEMI F4713 and ITIC, and international standards IEC 61000-4-11/3411, are available providing guidelines to manufacturers and users for developing products with specific requirements and for performing product compliance tests. Equipment complying with the voltage-tolerance curves must be able to ride-through and continuously operate without interruption during conditions identified in the areas above the respective curves. However, not all standards contain mandatory requirements and a wide range of equipment exhibiting different sensitivities against voltage dips are used in industries. In practice, different brands of the same equipment type, and even different models of the same equipment brand, can have different sensitivities to voltage dips. This makes it difficult to develop a single standard that defines the immunity of process equipment.

In order to simplify the selection and ordering process of equipment, and to easily conduct immunity tests on limited number of test points, the CIGRE/CIRED/UIE JWG C4.11 proposed five equipment immunity classes whose voltage-tolerance curves against balanced and unbalanced voltage dips are shown in Figure 7. According to this proposal, Class A provides the highest level of equipment dip immunity, and Class D specifies a basic level of equipment dip immunity. Voltage dip immunity Class B and Class C are in between the two, while Class E covers equipment immunity falling into none of the other classes. Considering equipment dip immunity with the highest and basic levels, the immunity curves for Class A and Class D could be considered to set up boundaries defining the responsibilities between the parties involved in the network, and for building a voltage dip regulation proposal.

3.3.2 | Dip impact on aggregated customers

Industrial processes are usually composed of several equipment, and many customers of different category are connected to the MV distribution networks. The effect of voltage dips on the combined customers is, therefore, more complicated in practice than the equipment dip immunity requirements specified by some industrial and national/international standards. Besides, the effect of different types of (balanced and unbalanced) voltage dips on three-phase equipment and installations is not well considered in the standards.

An approach for estimating the impact of voltage dips on the aggregated customers connected to the MV distribution networks is proposed in Weldemariam et al. The approach considers the change of power for the customers measured between the pre-dip and post-dip event. Based on the weighted average of the relative loss of power for the aggregated customers, the estimation method is extended to obtain WFs representing the system severity indices for various types of voltage dips, and the obtained severity WFs are used for building a proposal on voltage dip regulation. The following points are considered when obtaining the WFs for making the voltage dip regulation proposal for the regulatory purpose:

- For each phase-phase dip at the MV side of the HV/MV substations, the absolute loss of power for the aggregated customers in each feeder is estimated based on the change of power before and after the dip event. An example
of voltage dip event caused by a short-circuit fault occurring in a feeder and its impact on the customers in different feeders is shown in Figure 8. As can be seen in Figure 8A, the during-dip power is significantly larger than the pre-dip power, and the power reduces to zero when the feeder is interrupted after the fault is cleared. In Figure 8B-D, the during-dip power of the respective feeder is less than the pre-dip power, and the resulting effect of the dip event on the aggregated customers in these feeders is in the loss loads (Figure 8B) and loss of DGs (Figure 8C-D). In the same way, the effect of the dip event on the customers of other feeders is categorized as a loss of loads or loss of DGs.

Once the impact of the dip event \((k)\) on the aggregated customers within each feeder is calculated, the losses of power in all feeders \((f_n)\) are combined using Equation 1 to evaluate the impact of the dip on all customers in the entire substation \((sub)\). It should be recalled that the loss of power due to the interrupted feeder is not included in the analysis. This is further explained in the previous works.\(^{36,44}\)

\[
\Delta P_{\text{sub,load}}^k = \sum_{i=1}^{n} \left( P_{f_i,\text{load,pre}} - P_{f_i,\text{load,post}} \right) \quad \Delta P_{\text{sub,gen}}^k = \sum_{i=1}^{n} \left( P_{f_i,\text{gen,pre}} - P_{f_i,\text{gen,post}} \right)
\]  

(1)

- The size and type of customers as well as the occurrence time of disturbances vary from location to location, and this may significantly affect the amount of absolute loss of power due to voltage dips that even have similar characteristics. To compare the correlation between the severity of voltage dips (characterized by magnitude, duration, and type) and their impact on the aggregated customers, the relative loss of power calculated using Equation 2 is considered for each phase-phase dip \((k)\). It is presented in Weldemariam et al\(^{36}\) that the relative loss of power for aggregated loads increases when the dip gets longer and deeper and even gets worse when more phase-phase voltages are affected by the dip.

\[
\Delta P_{\text{sub,load}}^k / \% = \frac{\sum_{i=1}^{n} \left( P_{f_i,\text{load,pre}} - P_{f_i,\text{load,post}} \right)}{\sum_{i=1}^{n} P_{f_i,\text{load,pre}}} \times 100 \quad \Delta P_{\text{sub,gen}}^k / \% = \frac{\sum_{i=1}^{n} \left( P_{f_i,\text{gen,pre}} - P_{f_i,\text{gen,post}} \right)}{\sum_{i=1}^{n} P_{f_i,\text{gen,pre}}} \times 100
\]  

(2)

- Considering the field measurement data from six substations measured for 4 years, system average dip severity indices (SADSI), representing the severity for various types of voltage dips shown in Table 3, are obtained from the weighted average of the relative loss of power for the aggregated customers due to voltage dips over all monitoring locations. The percentage SADSI value of \(N_{r,c}\) events within the \(r^{th}\) row and \(c^{th}\) column of a cell for each

![FIGURE 8](image-url)  

**FIGURE 8** Voltage dip caused by short-circuit fault in a feeder leading to the A, complete interruption of customers in the same feeder; B, 1.53 MW less load power in another feeder; C, 0.22 MW more load power (0.22 MW less DG power) in another feeder; and D, 6.86 MW less DG-power in another feeder.
type of dip is evaluated using Equation 3. When completing the values of percentage SADSI densities corresponding to the voltage dips represented in Table 3, missing values are interpolated, and WFs based on the 95 percentile of the SADSI (shown in Table 4) are proposed as voltage dips severity indices for estimating the economic impact on industrial customers.

\[
SADSI_{r,c}[\%] = \frac{1}{N_{r,c}} \sum_{k=1}^{N_{r,c}} \left( \frac{\frac{k}{P_{sub,pre}} \sum_{i=1}^{N_{i}} |P_{i,pre}|}{\Delta P_{sub,load} + \Delta P_{sub,gen}} \right) \times 100
\]

As can be seen from Table 4, depending on the magnitude and duration, dips can lead to the loss of 1% to 40% per-dip power of the aggregated customers, while dips can lead the loss of 4% to 67% of pre-power and 17% to 94% of pre-dip power of the aggregated customers, respectively. This is a good indication that distinct clusters should be considered for the different types of voltage dips when building the proposal of voltage dip regulation for the regulatory purposes.

4 | VOLTAGE DIP REGULATION PROPOSALS

In this section, proposals based on equipment dip immunity levels and on dip severity WFs are described for defining different clusters of voltage dips. Also, a method to put the expected number of dips for the regulatory purpose is described.

4.1 | Equivalent dip immunity-based approach

Considering the voltage-tolerance curves for equipment with the highest (Class A) and basic (Class D) dip immunity levels, three clusters can be made for balanced and unbalanced voltage dips as shown in Table 5. The three clusters and the responsibilities of different parties to voltage dips in the different clusters can be briefly described as follows:

- Cluster A (A\(_{12}\) for unbalanced and A\(_3\) for balanced dips) covers areas above the curves for the basic level of dip immunity (Class D). Voltage dips in this cluster (A\(_{12} = A_1 + A_2\), and A\(_3\)) have little impact on end-users, and the customers should make their equipment or installations tolerate the dips in this area. Equipment manufacturers should also ensure that their equipment are immune to these dips.
- Cluster C (C\(_{12}\) for unbalanced and C\(_3\) for balanced dips) covers areas below the curve for the highest level of dip immunity (Class A). Voltage dips in this cluster (C\(_{12} = C_1 + C_2\), and C\(_3\)) are the most severe dips. Voltage dips in this area may not be acceptable, and the network operators should work to prevent the number of dips from exceeding the limit set based on previous years.
- Cluster B (B\(_{12}\) for unbalanced and B\(_3\) for balanced dips) covers areas between the curves for the basic and highest level of dip immunity. Due to the various levels of immunity classes covered in cluster B (B\(_{12} = B_1 + B_2\), and B\(_3\)), a certain number of dips in this area may be accepted, and voltage dips in this area can be limited. The network operators have the responsibility to reduce voltage dips in this area to the extent that the mitigation options are feasible. Equipment manufacturers should also make sure that different classes of products are available to cover this area.

With this clustering approach, the number of voltage dips in each cluster of the L\(_{001}\), L\(_{011}\), and L\(_{111}\) dips can be calculated from the respective dip profiles shown in Table 3. The different types of voltage dips belonging to similar clusters (eg, A\(_1\), A\(_2\), and A\(_3\)) have similar effect on end-user installations. Due to this, such clusters can be combined to reduce the number of clusters into three general categories (A, B, and C) for setting limits on the amount of voltage dips for the regulatory purpose. The number of voltage dips from all dip types belonging to similar clusters can be added together using Equation 4,

\[
A = A_1 + A_2 + A_3
\]
\[
B = B_1 + B_2 + B_3
\]
\[
C = C_1 + C_2 + C_3
\]
| Remaining Voltage, % | (a) WFs for L_{001} Dips, % Duration, s | (b) WFs for L_{011} Dips, % Duration, s | (c) WFs for L_{111} Dips, % Duration, s |
|---------------------|----------------------------------------|----------------------------------------|----------------------------------------|
|                     | $\Delta t \leq 0.2$ | $\Delta t \leq 0.5$ | $\Delta t \leq 1$ | $\Delta t \leq 5$ | $\Delta t > 5$ | $\Delta t \leq 0.2$ | $\Delta t \leq 0.5$ | $\Delta t \leq 1$ | $\Delta t \leq 5$ | $\Delta t > 5$ | $\Delta t \leq 0.2$ | $\Delta t \leq 0.5$ | $\Delta t \leq 1$ | $\Delta t \leq 5$ | $\Delta t > 5$ |
| $90 > u \geq 80$    | 1 | 3 | 5 | 5 | 5 | 4 | 18 | 26 | 27 | 27 | 17 | 31 | 36 | 39 | 44 |
| $80 > u \geq 70$    | 3 | 12 | 15 | 15 | 15 | 11 | 25 | 27 | 30 | 31 | 27 | 35 | 38 | 42 | 48 |
| $70 > u \geq 40$    | 8 | 25 | 28 | 29 | 29 | 27 | 36 | 37 | 38 | 41 | 40 | 41 | 44 | 53 | 60 |
| $40 > u \geq 5$     | 18 | 33 | 37 | 38 | 39 | 42 | 48 | 55 | 58 | 61 | 49 | 53 | 58 | 78 | 85 |
| $5 > u$             | 20 | 33 | 38 | 39 | 40 | 45 | 53 | 63 | 66 | 67 | 52 | 58 | 66 | 87 | 94 |
TABLE 5  Clustering based on immunity levels for Class A and Class D equipment against—(a) unbalanced dips, (b) balanced dips

| Remaining Voltage, % | (a) Clusters for L_{001} and L_{011} Dips | (b) Clusters for L_{111} Dips |
|----------------------|------------------------------------------|--------------------------------|
|                      | Duration, s                               | Duration, s                      |
|                      | Δt ≤ 0.2  | 0.2 < Δt ≤ 0.5  | 0.5 < Δt ≤ 1  | 1 < Δt ≤ 5  | Δt > 5  | Δt ≤ 0.2  | 0.2 < Δt ≤ 0.5  | 0.5 < Δt ≤ 1  | 1 < Δt ≤ 5  | Δt > 5  |
| 90 > u ≥ 80          |           |                 |                |              |        |           |                 |                |              |        |
| 80 > u ≥ 70          | A_{12}    |                 |                |              |        |           |                 |                |              |        |
| 70 > u ≥ 50          |           |                 |                |              |        |           |                 |                |              |        |
| 50 > u ≥ 40          |           |                 |                |              |        |           |                 |                |              |        |
| 40 > u ≥ 5           |           |                 |                |              |        |           |                 |                |              |        |
| 5 > u                |           |                 |                |              |        |           |                 |                |              |        |
where the subscripts 1, 2, and 3 represent the dip types $L_{001}$, $L_{011}$, and $L_{111}$, respectively. For the various types of dips, the average occurrence of voltage dips within the different clusters over all monitoring locations is summarized in Table 6. On average, the number of measured voltage dips in cluster A, B, and C is 3.98, 4.25, and 0.25 dips per year, respectively. It can also be seen from Table 6 that equipment with minimum immunity level of Class D would negligibly be affected by the majority (~84%) of the $L_{001}$ dips while the same equipment would trip to more than 58% and 76% of the monitored $L_{011}$ and $L_{111}$ dips, respectively.

For both network operators and customers, the frequency and probability of voltage dips occurring every year are useful for estimating the quality of the supply voltage and costs incurred due to this level of power quality. It is observed that the frequency and severity of voltage dips vary from location to location and time to time. Using the average number of dips for regulatory purposes may underestimate the expected occurrence of voltage dips to some locations, and it can also overestimate the expected occurrence of dips in other locations. Assuming the occurrence of voltage dip events is random and consecutive events are independent of each other, the probability of occurrence of events occurring in a fixed period of time, with a known average rate, can be predicted using the Poisson’s distribution function. The probability mass function in the Poisson’s distribution is given by Equation 5,

$$P(X = k) = \frac{\lambda^k}{k!} e^{-\lambda}$$

where $P(X = k)$ is the probability that exactly $k$ dips occur in a fixed period of time, $k$ is the amount of voltage dips occurring in that particular period of time, $\lambda$ refers to the average voltage dips per the specified period, and $e$ is base of natural logarithm.

Due to the limited amount of voltage dips especially in cluster C (ie, 0.25 dips/year), direct application of the Poisson’s distribution function might lead to unrealistic values when setting the limits. It is possible that a high number of dips can occur in 1 year, and few (or no) dips occur in the next year. Because of changes in the network, the regulator may consider to update the limits based on the dip occurrences in several years (eg, during the last 4 years), and this can also improve the practical application of the Poisson’s distribution function with the available data.

Considering the voltage dip occurrences in the last 4 years, the numbers of dips in clusters A, B, and C are about 16, 17, and 1, respectively. Using the Poisson’s distribution function, it is shown in Figure 9 that the number of dips in cluster A, B, and C for the 95% of the time in the last 4 years can be limited to 23, 24, and 3, respectively. According to this approach, 24 and 3 dips in the previous 4 years for cluster B and C can be considered as the maximum limits beyond which the quality of the supply voltage is insufficient.

### 4.2 Dip severity WF-based approach

Based on the system severity indices obtained from the relative impact of voltage dips on the aggregated customers connected to the MV networks, the method of WFs is applied here for building a voltage dip regulation proposal for the regulatory purpose. Using the voltage dips severity WFs shown in Table 4, the effect of voltage dips is classified as BIG, MEDIUM, or SMALL. This divides the dip table into three clusters described as follows:

- Voltage dips leading to the loss of less than 30% of the pre-dip power (or WF < 30%) for the aggregated customers are considered to be SMALL effect and clustered in A;
- Voltage dips leading to the loss of more than 50% of the pre-dip power for the aggregated customers (or WF > 50%) are regarded to be BIG effect and clustered in C; and
- Voltage dips leading to the losses between 30% and 50% of the pre-dip power (or 30 ≤ WF ≤ 50%) for the aggregated customers are considered to be MEDIUM effect and clustered in B.

| Dip Type | Number of Dips per Each Cluster | Total | Share |
|----------|---------------------------------|-------|-------|
|          | A  | B  | C  |       |       |
| $L_{001}$ | 2.24 | 0.43 | 0.00 | 2.67 | 31%   |
| $L_{011}$ | 0.79 | 1.08 | 0.03 | 1.91 | 22%   |
| $L_{111}$ | 0.95 | 2.73 | 0.22 | 3.90 | 46%   |
| Total    | 3.98 | 4.25 | 0.25 | 8.48 | 100%  |
Based on these criteria, three clusters (A_p, B_p, C_p), which also define the responsibility-sharing of different parties involved in the delivery and usage of power, are made for each type of dip “p” as shown in Table 7. According to this approach, a total of eight clusters are made out of the three types of voltage dips. Because of the small effect they have on end-users, L001 dips are not included in cluster C. On the other hand, cluster A covers very small area for L111 dips due to the fact that these dips have very significant effect on the aggregated customers. It can also be seen from Table 7 that areas of similar clusters considerably vary from one dip type to another, and this indicates the variation in the severity of various types of voltage dips which are even characterized by the same magnitude and duration.

Similar to the aforementioned approach, voltage dips in similar clusters (ie, having similar impact) can be combined to end up with three general clusters (A, B, and C) when setting the limits for the regulatory purpose. The number of voltage dips in each cluster of the L001, L011, and L111 dips can be calculated from the respective dip profiles shown in Table 3. For the various types of dips, the average occurrence of voltage dips within the different clusters over all monitoring locations is summarized in Table 8. Considering the dip data from all monitoring locations, clusters A, B, and C contribute about 52%, 43%, and 5% to the average occurrence of 8.48 dips per year. It can also be seen from Table 8 that the majority of the L001 (~98%) and L011 (~67%) dips have small impact on the customers while more than 80% of the L111 dips have medium to big impacts on the end-user installations.

The number of dips within a particular cluster can be all from any of the dip types, or they can be shared among all types. However, the total occurrence of events per cluster is important when setting limits on the number of voltage dips for the regulatory purpose. Because of the limited amount of voltage dips in cluster C (ie, 0.41 dips/year), the historic performance of the networks is again considered with this approach to apply the Poisson’s distribution function. Using the prescribed clustering approach and considering the occurrence of voltage dips in the last 4 years, the number of dips within the clusters A, B, and C are about 18, 15, and 2, respectively. Applying the Poisson’s distribution function, it can be seen from Figure 10 that the number of dips in each cluster for the 95% time of the last 4 years can be limited to 25, 21, and 4 dips, respectively. From this point of view, a maximum of 21 and 4 dips for cluster B and C in the previous 4 years can be considered as indicative limits for the network operator beyond which the quality of supply voltage at present is insufficient. From this, it can be said:

- voltage dips in cluster A have very little impact on customers’ equipment or installations, and end-users are expected to choose equipment that ride-through these dips. Therefore, there is no need for setting a limit on the number of dips in this group.
- voltage dips in cluster B and C can affect customer installations significantly. The network operators should take measures to reduce these dips where possible, and they should take responsibility to avoid the dips from exceeding the maximum limits. During periods when the number of dips exceed the objective reference values, there is an indication of alarming power quality problems and the network operators should investigate the problem.

## 5 | DISCUSSION OF RESULTS

Two methods, based on equipment dip immunity levels (method-1) and on system dip severity WFs (method-2), are described in this paper for classifying voltage dips into different clusters and setting limits on the number of voltage dips for the regulatory purpose. Comparing the two approaches, the following points can be noted:
| Remaining Voltage, % | (a) Clusters for L_{001} Dips | (b) Clusters for L_{011} Dips | (c) Clusters for L_{111} Dips |
|----------------------|-------------------------------|-------------------------------|-------------------------------|
|                      | Duration, s                  | Duration, s                   | Duration, s                   |
|                      | Δt ≤ 0.2 | Δt ≤ 0.5 | Δt ≤ 1 | Δt ≤ 5 | Δt > 5 | Δt ≤ 0.2 | Δt ≤ 0.5 | Δt ≤ 1 | Δt ≤ 5 | Δt > 5 | Δt ≤ 0.2 | Δt ≤ 0.5 | Δt ≤ 1 | Δt ≤ 5 | Δt > 5 |
| 90 > u ≥ 80          | A1               | A2               | A3               |                           |
| 80 > u ≥ 70          |                   |                   |                   |                           |
| 70 > u ≥ 40          |                   |                   |                   |                           |
| 40 > u ≥ 5           | B1               | B2               | C3               |                           |
| 5 > u                |                   |                   |                   |                           |

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Even though the same voltage-tolerance curves are considered in method-1 for equipment against the Type I (L001) and Type II (L011) dips, the equipment sensitivities can vary in practice. Besides, the sensitivity of processes and installations against voltage dips can be different from the equipment behavior during the same disturbance. Method-2, on the other hand, considers the impact of L001 and L011 dips on the customers separately, and this approach is more realistic for making different voltage dip clusters than method-1.

In this paper, the limits on the number voltage dips are proposed to be set and updated over a 4-year historical performance of the networks. According to this, the number of voltage dips set as a maximum limit for the combined clusters B and C using method-1 is close to the value obtained using method-2. Method-1 led to one dip lower in cluster C and three dips higher in cluster B over 4 years than the corresponding values in method-2. This is because the equipment with the basic and highest dip immunity levels, which are considered to define the responsibility-sharing curves in method-1, have the effect of increasing the area for cluster B and reducing the area for cluster C.

**CONCLUSION**

Two approaches for building a proposal to set up a regulatory framework regarding voltage dips in the MV networks are described in this paper. Different aspects including the frequency and severity of voltage dips occurring in the networks, the propagation of voltage dips, the classification of voltage dips, the aggregation of multiple-dips, and the effect of voltage dips are considered with each approach. Because of the limited number of voltage dips occurring yearly, the limits on the number of voltage dips are proposed to be set and updated based on historical performance of the networks over several years. With this, the variation of voltage dips due to the possible network modifications can also be considered in regulation.

The first approach considers the highest level and the basic level of equipment dip immunity classes for defining three clusters of balanced and unbalanced voltage dips. In the second approach, three clusters are defined for each type of dips based on the severity WFs which are obtained from the impact of voltage dips on the aggregated customers. In either case, the clusters are made to define the responsibility-sharing of different parties involved in the delivery and usage of power. Considering the variation of voltage dips over 4 years, the results obtained from the two methods are close to each other. However, the second approach (based on WFs) considers the sensitivity of all equipment and installations connected to the MV distribution networks and takes the impact of the three types of dips separately. This approach is, therefore, chosen over the first method (based on equipment dip immunity) for building the proposal on voltage dip regulation for the Dutch.
MV networks. For the network operators, this proposal can be important for evaluating the quality of supply voltage in the grid, and for investigating the source of the disturbance and improving the supply voltage when the value is below the indicative minimum requirement. For the customers, this is useful to make economic analysis on the required mitigation measures for reducing the expected economic damages due to voltage dips.

The number of years over which the voltage dips regulation should be updated is still a discussion for the grid operators. Some modifications might also be required by the DNOs to make the regulation in one table. Therefore, the proposed voltage dip regulation needs further discussions among different stakeholders before it is adapted in the national grid code. Further studies on the economic aspect will be required if any network modification to be made by the network operator can reduce the expected number of dips with a feasible investment.

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