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Voltage-dip immunity: statistics and need for further work

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Abstract. This paper presents the main results from CIGRE/CIRED/UIE working group JWG C4.110 and an overview of the need for further work identified by this working group. The paper goes into more details of the voltage-dip statistics collected by the working group and on methods to present the results from voltage-dip surveys.

Key words

Power quality, electromagnetic compatibility, power transmission and distribution, voltage dips, distributed generation, equipment immunity

1 Introduction

Voltage dips (also known as "voltage sags") are short-duration reductions in voltage magnitude. Their duration is typically between a few cycles of the power-system frequency and a few seconds. The interest in voltage dips is mainly due to their impact on end-user equipment. Industrial processes may malfunction or shut down due to a voltage dip resulting in significant financial losses.

Voltage dips are due to short-duration increases in current magnitude, whereas voltage dips due to short circuits and earth faults are of most concern for customers.

International Joint Working Group (JWG) C4.1110 sponsored by CIGRE, CIRED and UIE has addressed a number of aspects of the immunity of equipment and installations against voltage dips and also identified areas were additional work is required. The work took place between 2006 and 2009 and resulted in a technical report to be distributed via CIGRE and UIE [1].

This paper summarizes the results and need for further work as formulated by the working group. Results are summarized in Section 2; the need for further work in Section 3. Section 4 presents the statistical results obtained from a global voltage-dip database. This section also gives recommendations on how to present the results from large voltage-dip surveys.

2 Results from C4.110

A) A description of voltage dips

A detailed description of the different properties and characteristics of voltage dips has been created. This description divides the voltage waveform into pre-dip, during-dip and recovery segments. Special emphasis has been placed on the three-phase character and the occasional non-rectangular character of voltage dips.

Based on this detailed description a summary of voltage-dip characteristics has been created that should be used by equipment manufacturers and researchers as a checklist during the development of new equipment.

For voltage dips in three-phase systems a classification is accepted based on the number of phase-to-neutral voltages that show a significant drop in magnitude. The three types of dips (Type I, Type II and Type III, see Figure 1) correspond to a significant drop in magnitude for one, two or three phase-to-neutral voltages, respectively.

B) Equipment and process immunity

An overview has been presented of the immunity of different types of equipment against voltage dips. The impact of voltage-dip characteristics (magnitude, duration and others) on equipment immunity is illustrated in a quantitative way.

A useful new concept has been introduced, "*process-immunity time*", where a distinction is made between equipment failure and process failure. This distinction allows better economic assessment of the impact of dips on industrial installations. A methodology has been developed for analysing an entire process, and finding a process immunity time for each individual device or section of that process.

C) Testing and characterization

Guidelines are given for characterizing dip immunity of equipment. The immunity of equipment should be presented as a "*voltage tolerance curve*", which is one simple way for equipment manufacturers and users of their equipment to communicate about dip immunity.

Characterization as well as compliance testing of single-phase equipment should include only two dip characteristics: residual voltage (magnitude) and duration. Based on the presently available knowledge, there is insufficient justification to perform additional tests covering characteristics such as phase-angle jump and point-on-wave.

For characterization testing of three-phase equipment, it is recommended that the equipment immunity be presented by voltage tolerance curves for each of the three types of dips (Type I, II and III). It may not be practical to exactly reproduce these dip types during the tests. In many cases approximations need to be made to allow the use of available test equipment. It was however not possible for the working group to argue for or against any of the methods due to lack of information.

Compliance testing of three-phase equipment should include tests for Type I, II and III dips. The statistical data obtained shows that a significant number of dips are of Type III (balanced dips). However due to a lack of data about the economic consequences of including Type III dips in the compliance testing, no recommendations are given regarding the form in which Type III dips should be included in compliance testing.

D) Economics

The economics of voltage-dip immunity have been described in a qualitative way. A distinction is drawn between dip immunity of individual installations, and dip immunity requirements that are placed on all equipment through standards. The economics of dip immunity at individual installations are well understood, but for a specific installation the data may not always be available.

So far, the economics of setting global standards for equipment dip immunity are still not understood. The work done by JWG C4.110 has resulted in a high-level description of the economics involved. An important conclusion from this was that economics play an important role in selecting the appropriate voltage-dip immunity, both for individual installations and for immunity requirements that impact all equipment.

E) Immunity classes and application

A number of voltage dip immunity classes and associate curves have been introduced. These classes will further simplify communication between equipment manufacturers and equipment end-users about dip immunity. These classes further allow equipment end-users a sufficient level of choice in selecting equipment. Test levels (combinations of duration and voltage magnitude; for each of the three types of dips) are proposed for each class.

Finally, a systematic methodology, based on the "*voltage-dip immunity label*", has been introduced for selecting electrical equipment to ensure a required level of dip immunity for an industrial process.

3 Further work

Some of the future work indentified by the working group is presented in this section. Some of this is most appropriate for academic studies. In other cases practical work is needed or new working groups might have to be formed.

A) A description of voltage dips

The description of voltage dips is based on dividing a dip into transition segments and event segments. The characteristics of event segments are well understood and described in detail in the technical brochure. However, further work is needed on the characteristics of transition segments.

A basic methodology is needed for quantifying voltage-dip characteristics. One challenge is to develop methods for automatic detection of transition segments. Commonly-accepted methods are also needed for quantifying the proposed characteristics of event and transition segments. These methods, when they become available, should be used to obtain statistics about these new characteristics. Statistics on voltage-dip unbalance (Type I, Type II or Type III) are needed as a basis for discussions on equipment immunity requirements, and are important information for end-users when selecting equipment. Statistics on phase-angle jump and point-on-wave may be useful at a later stage.

The summary of voltage-dip characteristics (known informally as the "*checklist*") is aimed at providing equipment developers with a method for anticipating dip-related immunity problems at an early stage. Feedback is needed from equipment developers regarding the usefulness of such a checklist. If the list is useful, similar checklists could be developed for other types of power-quality disturbances.

B) Equipment and process immunity

More information is needed on the impact of repetitive dips (e.g. due to reclosing into a sustained fault) on equipment immunity. Potential equipment damage due to repetitive dips should be investigated. Further work is also needed to quantify the impact of the pre-dip voltage and of the source impedance.. Also restart mechanisms and restart time for equipment need to be determined.

A new activity should be started, composed predominantly of end-users, to quantify the process-immunity time for different types of industrial processes. The results of such a study would assist, indirectly, to quantify the economic losses due to voltage dips. More generally, it is still not known what level of immunity is typical of a well-designed industrial installation.

C) Immunity testing and characterization

Fundamental work is needed to estimate the error made by applying test vectors that are a simplification of reality. Although the analysis of the voltage-dip database has shown that some test vectors are closer to reality than others, there is no simple set of test vectors that can reproduce the range of voltage dips that occur in reality. Guidelines to initiate such a study are included in the technical brochure. The economic consequences of prescribing a specific set of test vectors should also be considered. This holds especially for compliance testing, and, to a lesser extent, for characterization testing.

The occurrence of multiple dips within a short period of time (e.g. due to reclosing into a sustained fault) was recognized and discussed at length within the working group. However due to lack of available data, no recommendation could be given. Further work should be conducted, in which manufacturers would provide information on the impact of multiple events on their equipment and network operators would provide information on the occurrence of multiple events. There is especially concern due to reports about damage to equipment because of multiple voltage-dip or short-interruption events.

No clear conclusion was reached about including Type III dips in compliance testing. Although Type III dips should be included in the compliance testing, further work is needed to determine appropriate immunity objectives. The economic consequences of including Type III dips in the compliance testing should be better understood and considered. Close cooperation with equipment manufacturers is needed here as well.

D) Economics of voltage dip immunity

During several of the discussions the lack of economic data prevented the working group from reaching a conclusion or making a recommendation. This especially concerns the economic consequences of decisions that impact all equipment, such as dip immunity standards. A considerable amount of further work is needed. The results of such work are an essential foundation for setting standards-based dip immunity requirements.

E) Statistics

The global data base created by the working group is the first of its type and it will be a very good base for further enlargement and contributions. By adding data from more countries and systems, the data will become more globally representative. It is important that the data is sufficiently representative for equipment in industrial installations as well as for all equipment. The former is important, among others, for the discussion on which immunity requirements to place on industrial equipment. A representative set of data for voltage dips as experienced at the equipment terminals is important input to the discussion on what are appropriate immunity requirements that all equipment should comply with.

Other applications for voltage-dip statistics, than the global voltage-dip database, should be found that would justify gathering and processing large volumes of voltage-dip statistics.

F) Dip immunity classes and application

The immunity requirements for five equipment classes were chosen using the available information about the economic consequences of the selection made. The curves should obviously be seen as one of many possible choices. Others are encouraged to continue this work and to come with alternative immunity requirements based on more information. The working group especially encourages equipment designers to suggest less expensive alternatives.

Multiple case studies, covering a range of production process types, would help to evaluate the methods proposed for selecting electrical equipment. Especially the detailed use of the process immunity time needs to be evaluated.

G) Renewable sources of energy

The immunity of small and large-scale generators based on renewable sources of energy is discussed intensively at many platforms. The term "fault-ride-through" is often used, somewhat as a synonym for "voltage-dip immunity". The main discussion concerns setting requirements on the immunity by the network operator. The issue should however be treated more widely and include at least the following three aspects:

- ✓ The number of unnecessary trips should be limited. The economic impact for many types of generation is small as the units will reconnect again after some minutes, depending on local regulations. However, with industrial combined-heat-and-power (CHP) and possibly also with future domestic CHP, the restart time may be long and expensive.

- ✓ The unit should trip with a high probability when the part of the grid to which the unit is connected, is disconnected from the rest of the grid. This is to prevent “uncontrolled islanding operation” and the protection against this is called “anti-islanding protection” or “loss-of-grid protection”.

- ✓ The unit should remain connected with a high probability for any fault of other event impacting large numbers of units. This is referred to as “fault-ride-though” and normally any fault at transmission level and every serious shortage of generation and considered.

The trade-off between these three aspects is rarely discussed however and there are often contradicting requirements on fault-ride-through and anti-islanding detection. Voltage-dip statistics, like the ones presented in this paper, should be used as one of the inputs for such a trade-off.

4 Presentation of voltage-dip statistics

A) Voltage-dip contour chart

The voltage-dip statistics have been presented by means of a number of so-called voltage-dip contour charts. A contour chart is a graphical representation of a two-dimensional function on a flat sheet of paper. In our case the representation is of a function of the residual voltage (*V*) and duration (*T*) of the dip. The function value is the number of dips per year with duration longer than *T* and residual voltage less than *V*. Once the function is defined, the contour chart connects points with an equal function value, in this case with an equal number of voltage dips per year.

Several examples of voltage-dip contour charts are shown below. For example, in Figure 2 there were about 2 events per year where the voltage was below 67% of nominal for more than 100 ms. There were also about 2 events per year where the voltage was below 90% of nominal for more than 300 ms.

Two important advantages of the contour chart can be mentioned. The underlying function is has its maximum on the upper left of the chart and decreases from there along both axes. This enables easy interpolation between curves. The second advantage is that the curve can be applied immediately to coordinate the supply performance and the equipment performance. Hence, the term “voltage-dip coordination chart” being used for the combination of the equipment voltage-tolerance curve and the contour chart. The contour chart has been introduced first in IEEE 493 [2] and is also explained further in [3] and in an annex with [1].

B) Balanced and unbalanced dips

In a three-phase system, it is important to consider the three-phase character of the system when characterizing voltage dips. The existing power-quality monitoring standard, IEC 61000-4-30, only uses the lowest of the three voltages to characterize the event. Studies of the impact of voltage dips on three-phase equipment have however clearly shown that this is insufficient to describe the impact of the event on equipment (see Chapter 3 of [1] for an overview).

The classification of three-phase voltage dips recommended by JWG C4.110 is a modified version of the one presented first in [4], and shown in Figure 1.

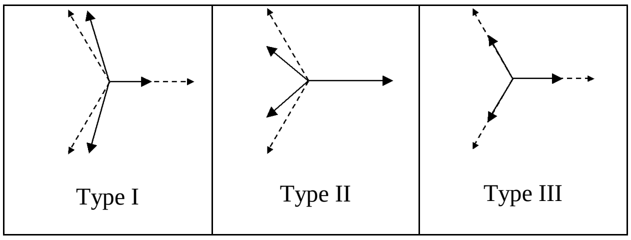

Figure 1. The three dip types introduced to represent magnitude and phase unbalance.

In words the three dip types are defined as follows:

- ✓ Type I is a dip with the major drop in one of the phase-to-neutral voltages. The other two phase-to-neutral voltages show at most a minor drop or even an increase.

- ✓ Type II is a major drop in two of the phase-to-neutral voltages.

- ✓ Type III is a drop about equal in all three phase-to-neutral voltages.

Each recorded voltage dip has to be classified as either Type I, Type II, or Type III and the residual voltage and duration have to be calculated. This is the data that is used for further analysis and representation of the results. Different methods exist for determining the dip type and for extracting a suitable value of the residual voltage for each dip type [5][6].

C) Performance for a single site

The performance of a single site is represented by means of three voltage-dip contour charts; one for each type of dip. These voltage-dip contours are shown in Figure 2, Figure 3, and Figure 4 for the median-site from the global voltage-dip database to be discussed in the next section. Half of the sites in the database have more than the indicated number of dips per year; half of the sites have less than this number of dips per year.

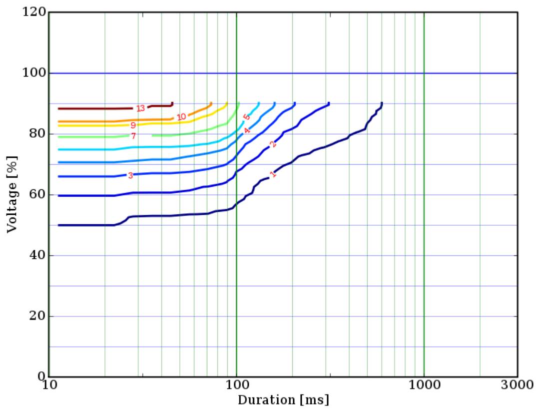

Figure 2. Number of Type I dips per year for the median site.

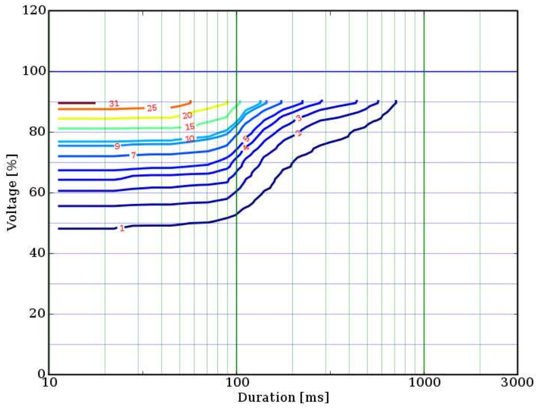

Figure 3. Number of Type II dips per year for the median site.

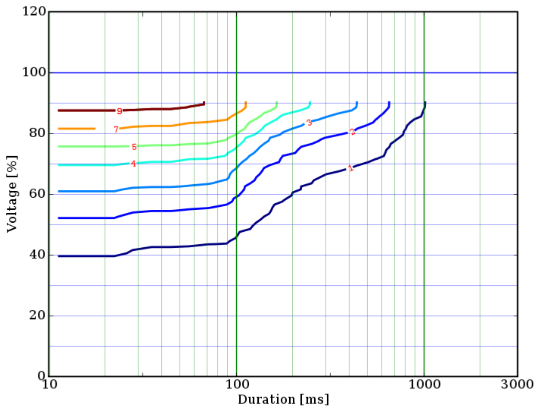

Figure 4. Number of Type III dips per year for the median site.

These voltage-dip contour charts, or equivalent voltage-dip tables, represent the supply performance for an individual site. The information in the charts can be used for the design of industrial installations. The individual information on Type I, Type II and Type III dips is important as equipment is often impacted in a different way by the different types.

D) Global voltage-dip database

Voltage-dip data has been collected from a number of countries spread over the planet: Canada; Portugal; United Kingdom; South-Africa; United States of America; Australia; and Spain. All data was combined into one single database, covering 1175 sites. These sites were next treated as one single system and the voltage-dip contour charts were calculated for a number of "reference sites" to present statistical information on the number of dips at different sites, using the "percentile method" used in statistics. For example a "75-% site" has been defined in such a way that 25% of the sites experience more dips than the 75-% site, whereas 75% of the sites experience less dips than the 75-% site. In the same way, a "25%-site", a "50% site" (the "median site" presented before), a "90% site" and a "95%-site" have been defined. Note that the ranking of the sites is by growing number of dips, as is common in statistics, although it may appear somewhat counter-intuitive for those not familiar with statistical methods. Thus, the 75% site does NOT represent 75% of the sites; neither does it represent 25% of the sites. Instead it can be interpreted as the borderline site when splitting all sites into the 75% best sites and the 25% worst sites.

E) Performance for a large number of sites

To describe the statistical performance of a large system, it is not sufficient to present the average or median values over all sites. Individual sites will likely have a different number of voltage dips per year than the average or median site. To represent the variation between sites, the voltage-dip contour charts for the before-mentioned reference sites should be given.

The number of Type II voltage dips per year is shown in Figure 5 through Figure 8 for the 25%, 75%, 90% and 95% sites. The 50% site was presented before. For a complete picture the same contour charts should be given for Type II and Type III dips. The reader is referred to the technical brochure [1] for the complete data.

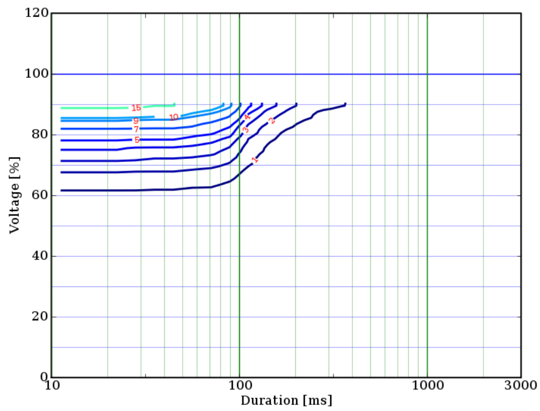

Figure 5. Number of Type II dips per year for the 25% site; 25% of the sites show less dips per year than this site.

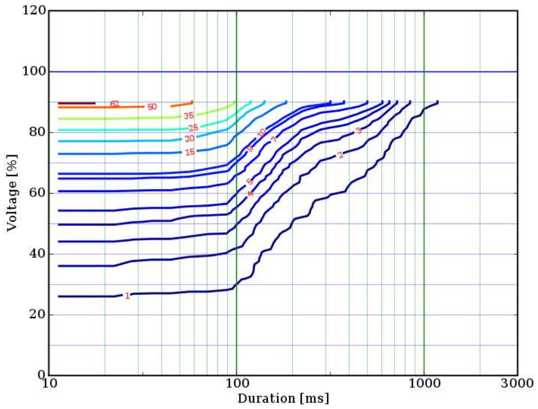

Figure 6. Number of Type II dips per year for the 75% site; 75% of the sites shows less dips per year than this site.

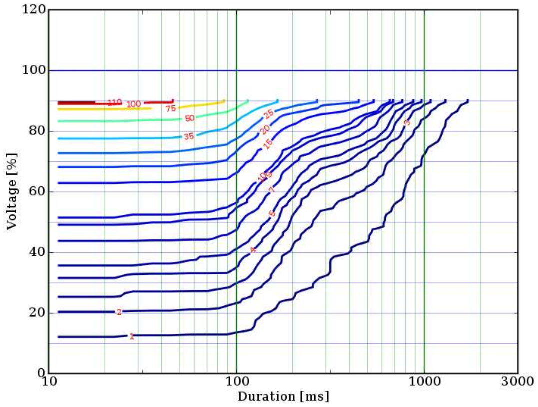

Figure 7. Number of Type II dips per year for the 90% site; 90% of the sites show less dips per year than this site.

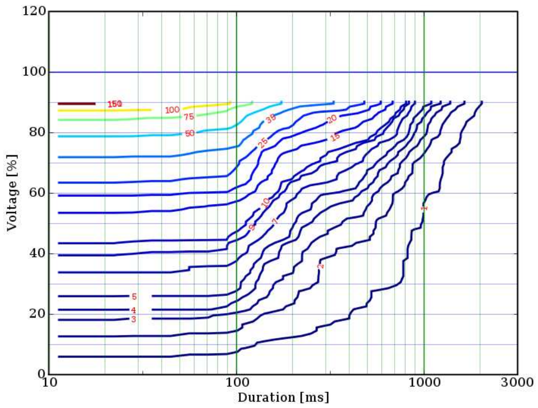

Figure 8. Number of Type II dips per year for the 95% site; 95% of the sites show less dips per year than this site.

5 Conclusions

Joint working group C4.110 has resulted in additional understanding and further information on voltage-dip immunity for equipment and installations. A detailed list of further work needed has been created. This includes development work as well as fundamental research more suitable for academic studies.

The results from a large voltage-dip survey should be presented in the form of a number of contour charts or equivalent. Such charts should be given for Type I, Type II, and Type III dips, for a number of statistical reference sites. The following sites are suggested: 25%, 50%, 75%, 90% and 95%, where the 25% site is defined such that 25% of the sites show less dips than this site, etc. We are aware that this would result in a total of 15 contour charts (3 dip types, 5 sites) whereas a trend has been to try and quantify the performance of a site or system with just a few numbers. Such numbers may have a role in benchmarking of sites or systems, but they do not give any useful information to the network operator and neither to the customers. The 15 contour charts are seen as a suitable compression of the data from a large survey.

A new working group (UIE Working Group 2) has been started, sponsored by the Union for Electricity Applications (UIE), which will, among others, disseminate the results from JWG C4.110 and initiate new work.

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