Voltage dip immunity aspects of power-electronics equipment

Recommendations from CIGRE/CIRED/UIE JWG C4.110

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***Abstract*—This paper presents some of the results from an international working group on voltage-dip immunity. The working group has made a number of recommendations to reduce the adverse impact of voltage dips. Specific recommendations to researchers and manufacturers of power-electronic equipment are: considering all voltage dip characteristics early in the design of equipment; characterize performance of equipment by means of voltage-dip immunity curves; and made equipment with different immunity available.**

***Index Terms*—Power quality, electromagnetic compatibility, power distribution networks.**

I. INTRODUCTION

VOLTAGE dips, also known as voltage sags, are short-duration reductions in the magnitude of the voltage typically lasting 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) C4.110 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 [1] that is distributed via both CIGRE and UIE.

This paper summarizes the results of the working group in Section II. Some of the results are discussed in more details in Section III, IV and V. Section III presents a detailed description of voltage dips. Section IV gives recommendations for immunity testing of equipment and for the exchange of information of equipment immunity between the equipment manufacturer and buyer. Section V presents equipment immunity classes and an equipment immunity label.

II. OVERVIEW OF RESULTS FROM C4.110

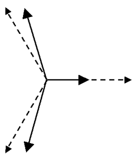
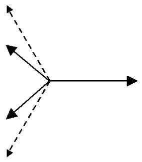
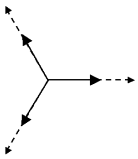
A. *A description of voltage dips*

A detailed description of the different properties and characteristics of voltage dips is included in the final working-group report. 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 recommended 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 Table I) correspond to a significant drop in magnitude for one, two or three phase-to-neutral voltages, respectively.

TABLE I
THE THREE DIP TYPES INTRODUCED TO REPRESENT MAGNITUDE AND PHASE UNBALANCE.

 Type I	 Type II	 Type III

The origin of these three types of voltages dips and the way they change when propagating from the fault location to the terminals of equipment being impacted is described in the working-group report.

B. *Equipment and process immunity*

An overview is presented in the working-group report 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 analyzing 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. Typical categories contributing to assessment of financial consequences of equipment failure are identified and briefly described.

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.

Finally the group proposed a methodology (shown as a block diagram in Fig. 1) for making investment decisions in improving process resilience to voltage dips. It is basically an optimization process which consists of several stages, briefly discussed below.

1. Establish the equipment or process immunity threshold/requirement based on process immunity time.
2. Estimate the annual number of process failures with and without mitigating solution.
3. Calculate the annual financial losses resulting from process failures with and without considered solution.
4. Estimate the cost of a mitigation solution taking into account all relevant associated costs depending whether the solution is network level solution, process level solution or improved equipment immunity.
5. Take into consideration other benefits and/or drawbacks resulting from application of particular solutions (e.g., additional benefits that may arise from applying a particular solution which were not directly reflected in improvement of process immunity to voltage dips).
6. Make investment decision based on comparison of financial implications resulting from steps 4, 5 and 6.

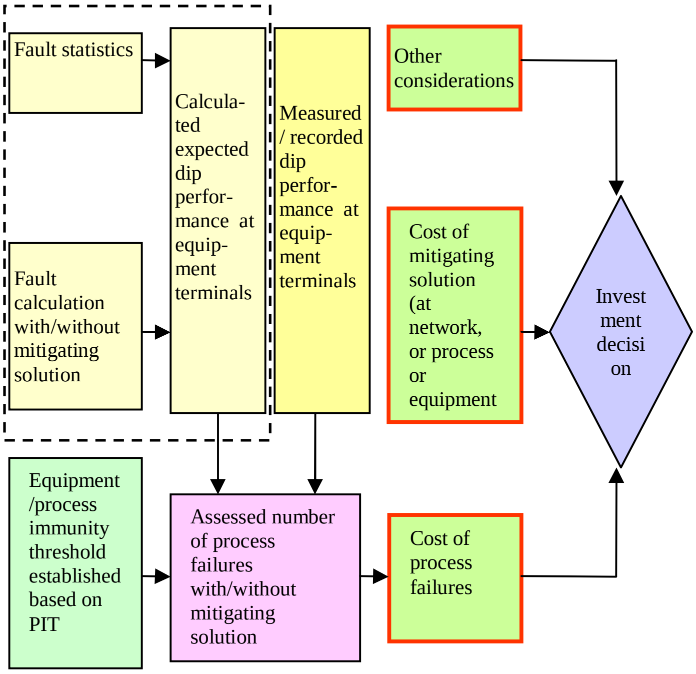


Fig. 1. Investment analysis process

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.

III. A DESCRIPTION OF VOLTAGE DIPS

Although all voltage dip events are characterized by a short duration reduction in voltage magnitude, voltage dips come in a wide variety of different types, where individual dips can have rather different characteristics. Consequently, dips with different characteristics can impact equipment in very different ways. The two basic characteristics to quantify the severity of a voltage dip are its “*residual voltage*” and its “*duration*”, as defined in IEC 61000-4-30 [2]. The working group proposes to go beyond IEC 61000-4-30 in two specific ways:

- ✓ The three-phase character of voltage dips should be considered. Therefore, a classification into three general types of dips is proposed, based on the number of phase-to-neutral voltages that show a significant drop in magnitude.
- ✓ The time-dependent behavior of voltage dips should be considered. Therefore, it is proposed to describe dips as events consisting of a number/series of transition segments and event segments.

A typical example of a voltage dip measured in a three-phase system is shown in Fig. 2. The figure illustrates the alternative approach proposed termed “*dip segmentation*”. The method is based on the analysis and separation of a dip event into the distinctive parts called “*dip segments*”, which include both pre-dip and post-dip parts of a dip-related event, while during-dip part is divided into “*during-event segments*” and “*transition segments*”.

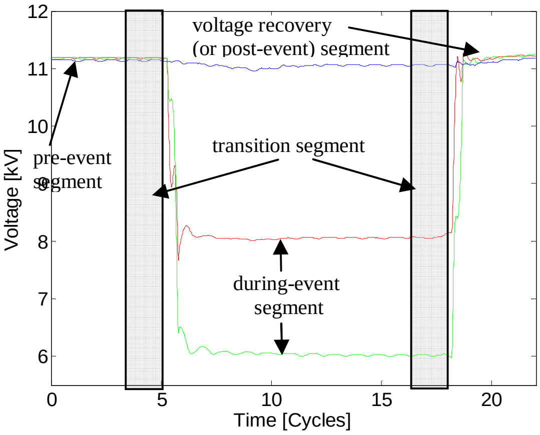


Fig. 2. An example of a typical voltage dip - rms voltage plot, with indicated event and transition segments

The segmentation method was originally developed for automatic analysis of voltage-dip recordings [3] but it has applications beyond that. The dip segmentation method allows for an improved assessment of standard and commonly used dip characteristics, incorporating, at the same time, several usually neglected characteristics and aspects of dip events into the analysis. This should allow better understanding of all relevant factors and parameters that may have an impact on sensitivity of different types of equipment, helping the end-users, designers and manufacturers of electrical equipment to quantify, test and compare performance of their equipment in a consistent, transparent and reproducible manner, particularly with respect to prescribed tolerance limits.

Voltage dips come in many different forms, a typical example was shown above, but many dips differ from this. It is very important to consider this when making equipment immune to voltage dips. A detailed description of these non-typical dips is given in the working-group report. Here we will only briefly summarize this.

- ✓ Dips due to motor starting and transformer energizing are characterized by a sudden drop in voltage followed by a slow recovery. Dips due to transformer energizing are associated with a high level of odd and even harmonic distortion.
- ✓ The recovery of the voltage after a fault may take rather long, resulting in an extended recovery segment sometimes associated with a high level of odd and even harmonic distortion due to transformer energizing.
- ✓ Multiple transition segments can be due to developing faults and due to delayed fault clearing at one side of a transmission line.
- ✓ Voltage dips do not occur evenly or randomly spread throughout the year, but show a clustering in time. During periods of adverse weather more dips occur than during normal weather. Multiple dip events may also occur due to automatic reclosing actions after a fault.

A. *Summary of Voltage-Dip Characteristics*

A summary of voltage dip characteristics, which can be used as a “check-list” for a quick assessment of equipment and process sensitivity to voltage dips during all stages of equipment and process design, is also given in [1]. It is expected that by considering this check-list at the early stages of the development and design of equipment, at least some of the future dip immunity concerns and problems may be avoided; see Table II, and Appendix A.

TABLE II
A SUMMARY OF VOLTAGE DIP CHARACTERISTICS

Characteristics of pre-event segments
Actual/expected values of pre-event: voltage magnitudes, voltage phase angles, harmonics and other waveform distortions, voltage magnitude/phase angle unbalances and frequency variations
Characteristics of during-event segments
Dip magnitude, dip duration, dip shape, dip voltage magnitude unbalance, dip phase shift (phase-angle jump), dip phase angle unbalance, dip waveform distortion and transients.
Characteristics of transition segments
Dip initiation, point-on-wave of dip initiation, phase shift at the dip initiation, multistage dip initiation, dip ending, point-on-wave of dip ending, phase shift at the dip ending, multistage dip ending, rate-of-change of voltage, damped oscillations
Characteristics of voltage recovery (post-event) segments
Voltage recovery, post-fault dip (prolonged voltage recovery), post-dip phase shift, multiple dip events (dip sequences), composite dip events

IV. EQUIPMENT TESTING

As was shown in the previous section, describing a voltage dip requires more than just residual voltage and duration. It has not yet been possible to study the impact of all dip characteristics on the performance of equipment, but several of the characteristics have been shown to impact equipment in a significant way. For a complete assessment of the compatibility between a device and the power system, all the characteristics mentioned in Section III should be included in the testing of new equipment. This is obviously not practical: it would make the testing of equipment unnecessary expensive. Also are many of the characteristics mentioned in Section II ill-defined at the moment which makes it difficult to define reproducible tests.

The working group has made a clear distinction between "compliance testing" and "characterization testing". The former is defined in standards, should be of limited scope, and should be fully reproducible. The latter is a form of communication between the equipment manufacturer and the customer about the immunity of the equipment against voltage dips at its terminals. There is less need for standardized tests and reproducibility; also would it be acceptable to use simulation results when these are considered sufficiently reliable.

The working group gives the following recommendations to equipment manufacturers concerning characterization testing:

- ✓ The voltage-tolerance curve should be used to present the immunity of equipment;
- ✓ The results of the test should be based on clear definitions of two main malfunction criteria: "*performs as intended*" and "*fails to perform as intended*".
- ✓ Different curves should be given for Type I, Type II and Type III dips. Test vectors for the three dip types are discussed in the working-group report.
- ✓ The dips used for the characterization testing should have zero phase shift for single-phase equipment. For three-phase equipment, the phase shift is defined by the test vectors.
- ✓ The dips used for the testing of single-phase equipment should start at a voltage zero-crossing with positive gradient. For testing three-phase equipment, a consistent reference voltage should be chosen (typically, one phase-to-neutral or phase- to-phase voltage) and each dip should start at a zero-crossing of the reference voltage.
- ✓ The pre-dip and post-dip voltage waveform should be equal to rated voltage magnitude and rated frequency, with low harmonic distortion. Crest factor and total harmonic distortion of pre-dip and post-dip voltage waveforms during the test should be recorded.

The consideration of the phase-angle jump and the need for exact reproduction of the vectors for unbalanced (Type I and Type II) dips was discussed at length within the working group. In order to justify the requirement of additional tests and of an exact reproduction of unbalanced voltage dips, a criterion was introduced by the group. Information of the voltage-dip immunity of equipment is needed to assess the compatibility between equipment and the power system. The expected number of equipment maloperations per year due to voltage dips, is a commonly-used measure to quantify the compatibility. Adding additional information about voltage-dip immunity is only justified where it allows for a better estimation of the expected number of equipment maloperations.

Such an assessment was made for phase-angle jumps, and the conclusion was that it was at this moment not justified to require such information from equipment manufacturers. What contributed to this conclusion is the lack of data on the actual phase-angle jumps as they occur in reality. Even a standardized method for calculating the phase-angle jump of a voltage dip is lacking.

A similar conclusion was drawn where it concerns the way in which the voltage magnitudes and phase angles should be reproduced for the testing of three-phase equipment during unbalanced dips. It is recommended to reproduce the vectors shown in Table I where possible (for example during simulations), but alternative methods should be accepted where this is not practical or too expensive.

V. EQUIPMENT IMMUNITY CLASSES

A. The need for a classification

To facilitate the specification of equipment and the discussion between end-users and manufacturers, the working group has proposed a new immunity classification for equipment into five classes, labelled A, B, C1, C2 and D. This classification is mainly based on a statistical evaluation of a worldwide database build with the voltage-dip obtained from network operators around the world. This analysis brings a meaningful value to the classification proposed. The classification takes also into consideration existing voltage-dip immunity standards such as IEC-61000-4-11, IEC 61000-4-34 and SEMI F47-0706. Finally, the economics of improving equipment immunity were not considered when choosing these immunity classes. As shown in Section II.D of this paper each situation is unique and has to be evaluated by the end-user. The selection of several classes, instead on one, was strongly influenced by the understanding that the economics of individual customers differ strongly.

To deal with the economic aspects, a complete methodology for process immunity is proposed in the working-group report and briefly summarized in Section II.D. In the future an evaluation of the immunity classes is needed; there it may be decided that some immunity classes are more viable or more useful then others.

B. The different classes

Each immunity class has two different immunity curves, one for type I and II voltage-dip, and another for type III voltage-dip. First of all, most voltage dips involve just one or two of the three voltage magnitudes in the three phase system. Such unbalanced voltage dips are, in most cases, less severe for three phase equipment. Therefore the working group recommends more strict immunity curves for unbalanced (Type I and Type II) voltage dips. Secondly, the statistical analysis performed by the group helped to determine that three phase voltage dips represent 20% of the voltage-dip in HV and MV networks and 11% of those in LV networks. This is relevant enough to consider: balanced dips cannot be just described as a rare phenomenon. Another justification for introducing immunity curves for balanced (Type III) dips comes from their impact on the behavior of the equipment or the process. These are often the most expensive cases for end-users.

The above reasoning resulted in the working group proposing the immunity classification shown in Fig. 3 and Fig. 4. The classes can be described as follows:

- Class A : Highest level of equipment immunity
- Class B : High level of equipment immunity
- Class C1 : Medium level of equipment immunity (as per IEC-61000-4-11/34)
- Class C2 : Medium level of equipment immunity (as per SEMI F47-0706)
- Class D : Low level of equipment immunity

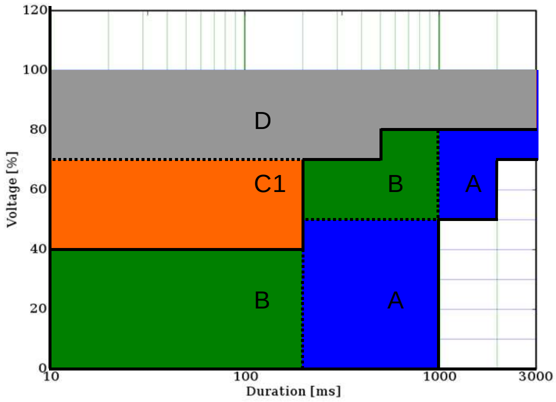


Fig. 3. Equipment Immunity Classification for unbalanced (type I and II) voltage dips

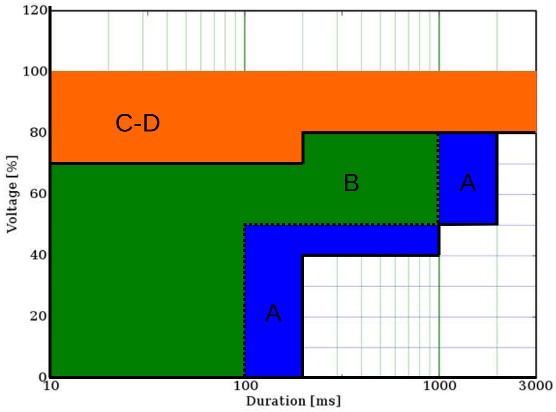


Fig. 4. Immunity classification for balanced (type III) voltage dips

C. Voltage-dip Immunity Label :

The voltage-dip immunity label is a combination of the proposed immunity classification and the selected equipment performance criteria. This gives the opportunity to better specify any individual device or process equipment in a cost-effective way. The three criteria for equipment performance are:

- **Full operation**: the equipment performs at full rated operation within technical specifications.
- **Self-recovery**: the equipment performance comes temporarily outside of its specifications; the equipment recovers automatically without operator intervention.
- **Assisted-recovery**: the equipment performance comes outside of its specifications; operator intervention is needed for the equipment to continue its normal operation.

These criteria express how the equipment is expected to behave when it faces a voltage dip inside the immunity classification area. The evaluation of the process immunity time (PIT) will have a direct impact on the selection of equipment performance criteria.

For example, if we specify a class C1 drive with self-recovery, then we expect the drive to be able to recover by itself either by catching up after the voltage dip or by going off-line and then back on-line by itself. If the PIT is long enough then that means, an automatically restarted is sufficient on this equipment when it face a Type I or II voltage-dip of 50% for 100 msec. For process with very tight power specifications then the criteria "full operation" is needed and technical range limits should also be define (ex.: speed range).

VI. CONCLUSIONS

The potential adverse impact of voltage dips on power-electronics equipment is beyond doubt. Equipment potentially impacted includes, among others, computers, consumer electronics, process-logic control, sensors and relays, adjustable-speed drives, solar panels and wind turbines. The working group has made a number of recommendations to various stakeholders to limit the adverse impact of voltage dips on equipment and on installations. The following recommendations are given to researchers, developers and manufacturers of power-electronic equipment:

- Voltage dips should be considered very early in the development of new equipment. This should not be limited to the tests prescribed in standards, but to all characteristics of voltage dips. The summary of voltage-dip characteristics given by the working group is recommended as a check list.
- The performance of equipment should be characterized by means of a voltage-tolerance curve for Type I, Type II and Type III voltage dips.
- Equipment with different voltage dip immunity should be made available. Possible voltage-dip immunity classes have been proposed by the working group.
- Further research is needed on the impact of different dip characteristics on equipment; research is especially encouraged for multiple events.
- Equipment manufacturers are encouraged to contribute to the development of voltage-dip immunity classes. Important input to the discussion is the cost associated with making different types of equipment more immune to voltage dips.

VII. ACKNOWLEDGEMENT

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VIII. REFERENCES

[1] CIGRE/CIRED/UIE JWG C4.110, Voltage dip immunity of equipment and installations, CIGRE Technical Brochure TB 412, April 2010. http://www.e-cigre.org or http://www.uie.org.

[2] Electromagnetic compatibility (EMC), Part 4: Testing and measurement techniques, Section 30: Power quality measurement techniques, IEC Standard 61000-4-30, International Electrotechnical Commission, 2003.

[3] E. Styvaktakis, M.H.J. Bollen, I.Y.H. Gu, Expert system for classification and analysis of power system events, IEEE Transactions on Power Delivery, Vol.17, No.2, April 2002, pp.423-428.

IX. APPENDIX A: OVERVIEW OF CHARACTERISTICS AND RECOMMENDATIONS FOR TESTING

The working group report includes a detailed description of voltage dips, with reference to their potential impact of equipment performance, as well as recommendations for the testing of equipment. Both the characteristics and the recommendations are summarized in Table III. For more details the reader is referred to the body of the text and to the working-group report.

TABLE III
SUMMARY OF VOLTAGE-DIP CHARACTERISTICS AND RECOMMENDATIONS FOR EQUIPMENT TESTING

VOLTAGE DIP CHARACTERISTIC	RECOMMENDATION FOR TESTING
Pre-event segment	
Characteristics of the pre-event segment	Nominal voltage, with low distortion
During-event segments	
Dip magnitude	Test variable (vertical axis)
Dip duration	Test variable (horizontal axis)
Dip shape	Rectangular
Dip voltage magnitude unbalance	Test for each case: Type I, Type II, and Type III
Dip phase angle unbalance	Test for each case: Type I, Type II, and Type III
Dip phase shift (phase-angle jump)	None for single-phase equipment tests. For three-phase equipment, test for each case: Type I, Type II, and Type III
Dip waveform distortion and transients	Test waveform should have low distortion
Transition segments	
Dip initiation	Not specified
Point-on-wave of dip initiation	Voltage zero-crossing of the reference voltage (choose one of the phase-neutral or phase-phase voltages as the reference).
Phase shift at the dip initiation	None for single-phase equipment tests. For three-phase equipment, test for each case: Type I, Type II, and Type III
Multistage dip initiation	Not tested
Dip ending	Not specified
Point-on-wave of dip ending	Not specified: determined by dip duration
Phase shift at the dip ending	Not specified: determined by phase shift at dip initiatioon and dip duration.
Multistage dip ending	Not tested
Rate-of-change of voltage	Not tested or specified
Damped oscillations	Not tested
Voltage recovery (post-event) segment	
Voltage recovery	Immediate
Post-fault dip (prolonged voltage recovery)	Not tested
Post-dip phase shift	None
Multiple dip events (dip sequences)	Not tested
Composite dip events	Not tested