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CIGRE/CIRED/UIE JWG C4.110, Voltage dip immunity of equipment in installations

scope and status of the work by May 2007.

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***Abstract*— This paper presents the status of the work in C4.110, a joint working group by CIGRE, CIRED and UIE. The scope of the working group is to gather technical knowledge on the immunity of equipment, installations and processes against voltage dips, and to use this knowledge in the further development of methods and standards. The activities of the working group are divided in seven "chapters", where the work has started in three chapters: "equipment and process performance", "voltage dip characteristics" and "economics and probabilities".**

Keywords-power quality, electromagnetic compatibility, voltage dips, equipment immunity.

I. INTRODUCTION

A joint working group on voltage dip immunity of equipment is supported by CIGRE, CIRED, and UIE. The scope of the working group is to gather technical knowledge on the immunity of equipment and processes against voltage dips and to use this knowledge in the further development of methods and standards.

The working group was formed during the autumn of 2005 and started its activities early 2006. Two meetings were held during 2006 and two in 2007. Further meetings are scheduled for October 2007 and March 2008. Starting from a core of about 10 people, the group has been growing steadily and currently consists of 40 persons: 22 regular members and 18 corresponding members. The members have the following background: 13 network operators; 10 academics and consultants; 6 industrial customers; 5 equipment manufacturers; 3 regulators and 3 persons with extensive experience on immunity testing of equipment. For more information, the reader is referred to the working-group website [1].

II. SCOPE OF THE WORKING GROUP

The results of the work will be delivered in the form of a technical report, in January 2009. This report will provide guidelines for power companies dealing with customers, equipment manufacturers and other interested parties, and give recommendations for future IEC standardization. To organize the work on this difficult but interesting subject, it was decided to split up the activities into a number of "chapters" that should later correspond to the chapters in the working-group report.

1. Introduction.

2. Voltage dip characteristics

This paper does not necessarily represent the opinion of the working group, but is an interpretation of the current status of the discussions within the working group.

3. Equipment and process performance.

4. Characteristics for testing.

5. Economics and probabilities.

6. Equipment and process dip immunity objectives.

7. Conclusions.

The activities (chapters) are shown in a systematic and chronological way in Figure 1.

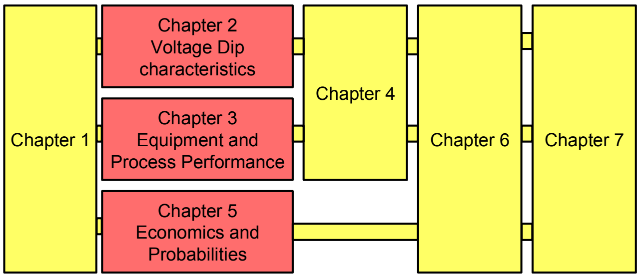

Figure 1, Activities within the working group organised in the form of chapters.

Work has started on three of the five main chapters. Chapter 2 will give a detailed description of individual voltage dips, with emphasis on those characteristics that may possibly be relevant for the performance of equipment and processes. Chapter 3 will summarize the knowledge within the working group on the performance of equipment and processes during voltage dips. Chapter 5 will evaluate the economic tradeoffs that must be made whenever voltage dip immunity levels are selected, first considering available voltage dip statistics (on their number and characteristics), then considering economic impact of dips with various characteristics, and finally considering the economic cost of making equipment immune to dips with various characteristics. The activities (especially) in this chapter will be coordinated with the work in our sister group C4.107 [2].

At a later stage, in Chapter 4, the results from Chapter 3 will be used to narrow down the information from Chapter 2 towards those characteristics that are identified as the most relevant for the assessment of equipment and process sensitivity to voltage dips. The results from Chapter 4 will, together with the results from Chapter 5, provide the input for Chapter 6.

III. Voltage Dip Characteristics

The main aim of this chapter is to provide a detailed description of voltage dips. Particular attention will be given to the potential impact of various voltage dip events on customers' equipment and processes - any dip characteristic that may potentially influence existing or future equipment will be included in this chapter.

The characterization and analysis of various types of voltage dip events, as well as the further assessment of their impact on equipment/process sensitivity, is a complex, time consuming and cumbersome process. This is a simple consequence of the large number of characteristics, parameters and factors that may have an influence on the ultimate response of a specific piece of equipment, or process, to voltage dip events.

Although the voltage during a dip will be the dominant cause of changes in the equipment behavior, the equipment may also be influenced by the voltage before the dip and by the voltage during the recovery of the system after the event resulting in the dip. Accordingly, the description of the voltage dip introduces a number of so-called "*segments*": periods of time during which the voltage magnitude and the properties of the voltage waveform are more or less constant.

a) The *pre-event segment*, related to the voltage magnitude and waveform before the event resulting in the dip (e.g. before the fault).

b) One or more *during-event segments*, related to the voltage magnitude and waveform during the event resulting in the dip (e.g. during the fault).

c) The *voltage recovery segment*, related to the voltage magnitude and waveform after the event resulting in the dip (e.g. after fault clearing).

It is further emphasized in the description that the transition, for example, between pre-event voltage and during-event voltage does not occur instantaneously. Therefore so-called "*transition segments*" are introduced next to the above mentioned "*event segments*".

The voltage-dip description used in this chapter consists of:

- Number of transition segments, duration of event segments.
- Properties of the transition segments.
- Properties of the event segments.

As the voltage magnitude and waveform do not show large or fast changes during an event segment, the commonly-used tools like rms, DFT and symmetrical components give a trustworthy result. Properties of the event segments have been discussed in many reports and papers and include:

- Voltage magnitude;
- Voltage phase angle;
- Duration;
- Waveform distortion;
- Unbalance.

During a transition segment the magnitude and/or waveform of the voltage show fast changes. The standard analysis methods can no longer be used. Properties of transition segments include:

- Point-on-wave;
- Rate of change of voltage;
- Oscillation frequency and damping.

- Difference in switching or fault initiation instant between the different phases.

The characteristics of the pre-event segment are related to voltage magnitude, voltage waveform distortion and three-phase unbalance, present immediately before the occurrence of a voltage dip. In most of the practical cases, the voltage before the dip is in a quasi-stationary state, so that characteristics over relatively long periods may be used.

Characteristics of the voltage recovery segment for a voltage dip due to a fault are strongly influenced by the recovery of the system and the load after the dip. Examples at different time scales include higher current taken by induction-motor load; high in-rush current for electronic equipment; recharging of capacitor banks; and transformer saturation upon voltage recovery.

An example of the use of event segments and transition segments is shown in Figure 2 for a measured voltage dip. The dip was recorded in a distribution network due to a fault at subtransmission level. The recording shows the initial non-symmetrical fault developing into a three-phase fault and being cleared by the circuit breakers at the two line terminals at different instants.

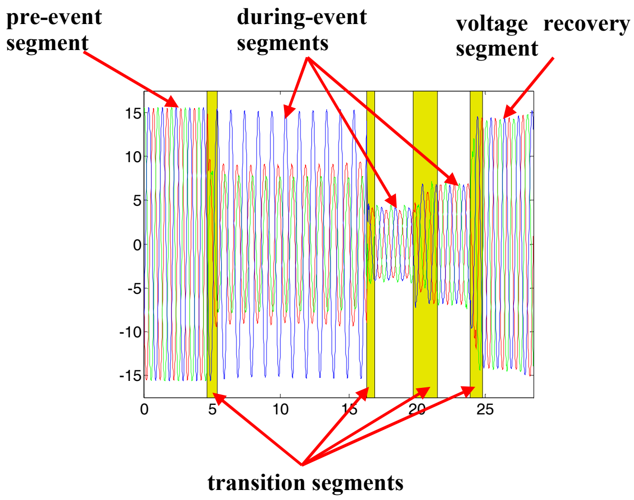

Figure 2, Example of the division of a voltage dip recording into event segments and transition segments.

It should be noted that most voltage dips are of a more simple character than the one shown in Figure 2. Most dips due to a fault show only two transition segments, corresponding to fault initiation and fault clearing. Most dips due to motor starting or transformer energizing show only one transition segment, corresponding to the switching instant.

Within this chapter both simple dip events (one or two transition segments) and more complex events (three or more transition segments) will be presented. Examples of more complex events are multistage dips caused by developing faults, dip sequences due to automatic reclosing operations, and simultaneous occurrence of combinations of dips, interruptions and swells. These composite dips usually represent a series of individual dip events occurring either in different phases or at different but nearby moments in time. Although composite, they should be treated as one inclusive event, as the impact of a series of events on equipment/process performance may be very different from the impact of each individual event in the established series.

Finally, a “check-list” of relevant dip characteristics will be provided for the benefit of all parties interested in the presented analysis. Such a checklist may be used for fast and transparent assessment of equipment and process sensitivity to voltage dips, e.g., during all stages of equipment and process design. By considering this checklist in the early stages of the development and design of new equipment, future immunity concerns may be avoided.

IV. Equipment and Process Performance

In order to harden processes against voltage dips, a good understanding of the process under consideration is of extreme importance. Processes can be divided into two big groups. Some processes are perfectly capable to operate without supply voltage for a small period of time (e.g. chemical plants). Some processes on the other hand are interrupted at the occurrence of a voltage interruption or a voltage dip (e.g. extrusion, steel and paper mills). For these processes, the knowledge of the individual equipment behavior under dip conditions is required to take the correct measures to harden the process.

A. *Equipment Performance*

Therefore, this chapter starts with a review of equipment behavior as obtained from different sources. The impact of a voltage dip on direct on line induction motors, synchronous generators, transformers, adjustable speed drives, contactors, PLC’s, PC’s, large rectifier units and lighting systems is discussed.

For each type of equipment, different hardware components, different topologies and control algorithms are implemented by different manufacturers. The discussion of equipment performance is therefore kept rather generic. For direct on line induction motors and synchronous generators, their behavior and impact on the supply system during and after the dip is discussed. For contactors and equipment containing power electronics, best case and worst-case rectangular voltage tolerance curves are presented, based on the current technology of tested pieces of equipment.

The equipment parameters and tripping mechanisms responsible for the high sensitivity of the equipment are discussed with great care. Knowledge of these parameters often indicates what type of mitigation technique is best suited to immunize the equipment. For example, the dip behavior of a contactor with ac control voltage depends on the point on wave of dip initiation. If a dc control voltage is used, flux is constant and the voltage tolerance curve changes drastically. As an example, Figure 3 shows the current state of the art of ac contactors with ac control coils. Worst case, best case and most likely voltage tolerance curves are presented. For single-phase equipment, the ITIC curve [4] is plotted as a reference. It can be seen in this example that not all contactors satisfy the ITIC curve.

To harden processes with sensitive equipment, voltage tolerance curves for the specific type of equipment are required. For each type of equipment, a checklist of relevant dip characteristics (introduced in chapter 2) will be provided. This checklist may be used for fast and transparent assessment of equipment sensitivity during all stages of equipment and process design. In chapter 4, "characteristics for testing", different methods to determine the actual tolerance curves of a specific piece of equipment will be discussed. Time consuming testing procedures of equipment and the use of simulation software to gather information are discussed.

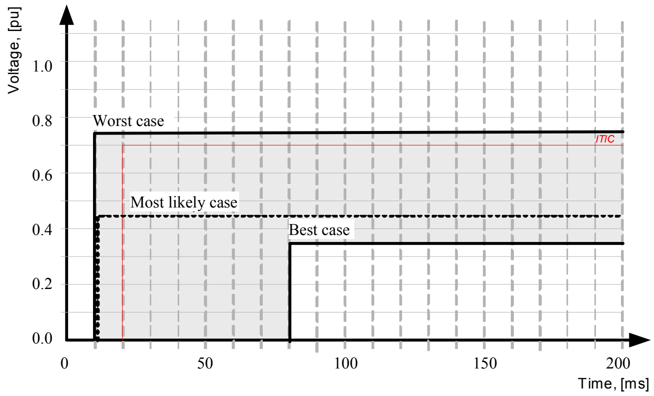

Figure 3, Voltage tolerance curves for ac contactors with ac control coil, worst, best and most likely case.

B. *Process Performance*

The second part of the chapter discusses process behavior. For typical processes, the process immunity time (critical time) is given. The process immunity time is defined as the total time that equipment within the process can be isolated from the power supply, including the time to restore, without unacceptable adverse impact on the process. For example, for a motor load "isolated" means the deceleration during a voltage dip, and the "restore" time is the time to re-accelerate the motor after the voltage has recovered.

Knowledge of the process immunity time is required to select the correct hardening technique. For a process with a time constant of several seconds, the voltage dip sensitive equipment may be stopped in a controlled manner at voltage dip detection and restarted as soon as the voltage has recovered without noticeable impact on the process. Another example is the coordinated re-start of direct on line induction motors after a voltage dip in order to avoid a voltage collapse due to the high currents during reacceleration. If the impact of each motor on the process is known, the most critical ones can be started first.

C. *Design of Installations*

Finally, the chapter will propose a flowchart that can be used for the systematic detection of critical processes and the critical pieces of equipment within these processes. For typical processes, values for the process immunity time will be presented as a guideline when determining process sensitivity.

V. ECONOMICS AND PROBABILITY

Whereas chapters 2 and 3 address individual dips and individual installations; chapter 5 takes a more global look at dips and installations. A number of questions are asked to support the setting of immunity requirements in standards such as IEC 61000-4-11 [5] and IEC 61000-4-34 [6].

A. *Economics of Immunity Requirements*

Among others, the following information is needed to set immunity requirements:

- The frequency of occurrence of voltage dips with different dip characteristics, for customers all over the world.
- Equipment mal-function, damage and process interruptions due to voltage dips with different characteristics, and the economic consequences of these.
- Costs of voltage-dip immunity requirements, including mitigation measures in installations, mitigation measures in the grid, costs of immunity testing and immunity requirements, and adverse side effects of mitigation measures.

The working group is aware of the huge complexity of the economics of voltage dips, and is also aware that it will not be possible to get all this data within their three-year mandate. However, available information will be gathered and best guesses will be given from this information.

B. *Voltage Dip Statistics*

In order to get the expected performance of already existing and new equipment it is essential to know the voltage-dip performance of the supply at the equipment terminals. The performance is presented by using graphs with remaining voltage and duration; an example is shown in Figure 4. This allows us to compare the performance with requirements set by SEMI [3], ITIC [4] or IEC [5][6] and with tolerance curves as in Figure 3. To obtain a complete picture of the supply performance it is essential to consider the three-phase character of the system and to include that most dips are associated with unbalanced voltages. One way of considering this in the statistics is by presenting different curves, as in Figure 4, for different types of unbalanced dips.

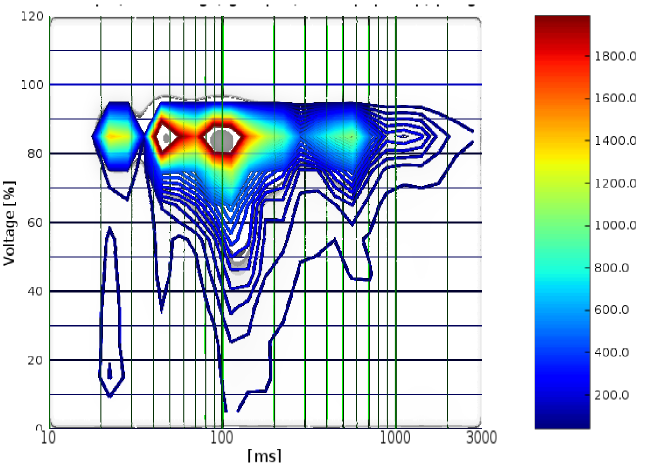

Figure 4, Example of presentation of voltage-dip performance of a system. (The vertical column on the right represents the number of dips recorded during the study.)

Measurement sites will be chosen as close as possible to the equipment terminals. Some data comes from permanent installed equipment at MV busbars, since this is the location that utilities most commonly use for power-quality monitoring. This data may be adjusted based on known transforms between the MV system and the equipment terminals, to obtain a reasonable approximation of dips at the equipment terminals.

All voltage measurements, including voltage dips, are made between pairs of conductors (although voltage dips are sometimes labeled with a single conductor name). To properly understand the voltage dip statistics, it is important to understand on which pair of conductors a voltage measurement was made. For example, on some common European MV networks, voltage is often recorded only between phase conductors since not very fast potential increases to earth are not transferred to the secondary side (primary is not grounded). In contrast, in low-voltage networks with neutral, measurements are often carried out between phase conductors and neutral.

VI. Liaison with Other Groups

Activities on voltage-dip immunity of equipment are ongoing in a number of other groups as well. In order to make use of the resources as efficient as possible, liaison between such groups is of utmost importance and an important part of the activities of this working group.

Through our parent organizations, CIGRE, CIRED and UIE, liaison with other groups within those organizations takes place. The most important liaison at the moment is the one with CIGRE/CIRED JWG C4.107. Joined working group C4.107 will develop a framework for evaluating the economic impact of adverse power quality. Costs due to voltage dips will be an important part of that work. A number of key persons in both groups are member of the other group as well.

Outside of our parent organizations, liaisons have been set up with CEER, IEEE and IEC.

The council of European Energy Regulators (CEER) aims among others at defining methods for regulation of power quality. Regulation of the number of voltage dips is seen as an important part of this. Recommendations by CEER have been published in two recent reports [7][8]. The latter report was aimed at obtained feedback from the stakeholders on this important subject. Our working group expressed its opinion on those parts of the report within the scope of the working group, especially concerning the concept of "*responsibility sharing curve*" as introduced by CEER. It was emphasized in the reply that the choice of responsibility sharing curve should be coordinated with equipment immunity requirements.

The Liaison with IEC especially concerns Subcommittee TC 77A, working group WG6 (immunity of equipment against low-frequency conducted disturbances). This working group published a call for comments on the maintenance of standard document IEC 61000-4-34 [6]. Two specific questions were asked on which our working group officially replied.

Liaison is further taking place with IEEE, especially where it concerns two important activities: IEEE P1668 and P1346. The newly formed working group P1668 will review existing standards on equipment immunity against voltage dips and is expected to result in a guide or recommended practice for immunity levels of equipment and for testing of equipment against voltage dips. IEEE Std.1346 [10], which was published in 1998, played an important role in making network operators and their customers aware of voltage dips and, even more important, of the possibility of addressing voltage-dip issues in a systematic way. Currently an update of the document is planned.

VII. Remaining Chapters

The work currently ongoing within the working group consists to a large extent of the gathering and reporting of existing knowledge and data. The two remaining main chapters, Chapter 4 and Chapter 6, will build on the gathered knowledge and data to obtain recommendations on equipment immunity and testing.

A. Characteristics for Testing

Work on Chapter 4 will commence soon. The starting point of the work will be the checklist of voltage dip properties resulting from Chapter 2. Using the knowledge on equipment performance gathered in Chapter 3, the list will be significantly narrowed down to a list of characteristics to be included during the testing of equipment. An important distinction will thereby be made based on the aim of the tests.

Compliance testing is based on international standards or local regulations and is to be performed by an accredited test lab. Such tests are by nature expensive as the results shall be trustworthy and reproducible. The definition of such tests is the realm of IEC 61000-4-11, IEC 61000-4-34, and the various product standards. The number of tests and the complexity of the tests should not be more than absolutely necessary; however the results of the tests should give a reasonable prediction of the performance of the equipment in reality.

Equipment performance tests are also performed by manufacturers as part of the design and manufacturing of equipment. These tests are aimed among others at providing customers with information on the performance of the equipment during dips. Such tests may be performed by the equipment manufacturer or by the customer under any circumstances deemed appropriate. The resulting curves may for example be part of the technical specification of the equipment. These tests are sometimes referred to as "*characterization tests*".

This chapter will give recommendations to standard-setting organizations on the dip characteristics to be included in compliance testing. Recommendations and guidelines will be given to equipment manufacturers and users of sensitive equipment concerning characterization testing.

B. Immunity Objectives

The final main chapter of the report, Chapter 6, will give recommendations on immunity of equipment and installations against voltage dips. The material gathered in the other chapters will form the basis for the discussions within this chapter. The recent discussions on responsibility sharing within CEER (see Section VI) will make the outcome of this chapter even more important than originally envisaged.

Work on this chapter is not expected to start before March 2008.

VIII. Status of the Activities

The activities within the working group have been divided into a number of "chapters" that should later correspond to the chapters in the final report. Work is currently ongoing within three different chapters and significant progress has been made during the first year of activities.

Existing knowledge has been gathered on the description of voltage dips (Chapter 2) and on equipment immunity (Chapter 3). Most of the knowledge concerning Chapter 2 has been written down and will be edited during the coming months. The main remaining task in Chapter 2 concerns the change in characteristics when a dip propagates through the system towards the equipment terminals.

The existing knowledge on equipment performance, for Chapter 3, will be reported within the coming months. The data gathering process will however continue even after that so that the final report contains the most up to date information. The work on the immunity of complete installations has resulted in an interesting approach where the emphasis has shifted from the equipment behavior to the process behavior. New concepts for describing process behavior will be discussed with different types of industry during the coming months. An important spin-off from this part of the work will be a set of guidelines for the design of installations

Within Chapter 5 (Economics and probabilities) data on voltage-dip performance is currently being developed. Detailed dip statistics have been obtained from 6 countries and discussions are ongoing with a few more countries. The dip data are obtained in the form of lists of residual voltages (rms values) for the three phase-to-phase voltages. The further processing of the data is done within the working group to ensure consistency. This approach also enables us to make changes in the way of processing, to choose additional characteristics, and to study the impact of the processing method.

The work on the economic part of Chapter 5 has started with a discussion on the cost items that need to be considered when deciding on equipment test methods and immunity requirements. The working group is aware that hard global data on the various costs will be extremely difficult to obtain. The activities during the coming months will concentrate on gathering the available information and on making educated guesses where no hard data is available.

Acknowledgment

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