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SENSITIVITY OF ELECTRICAL EQUIPMENT TO VOLTAGE SAGS AND SHORT INTERRUPTIONS: RECOMMENDATIONS FOR TESTING

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***Summary*: General testing procedures for testing different types of electrical equipment against various types of voltage sags and short interruptions are proposed and described in this paper. The recommendations for testing are discussed with respect to a number of sag and interruption parameters, non-ideal voltage supply characteristics, type of equipment, operating/loading conditions of the equipment and multiplicity of the malfunction criteria of the equipment. Presented analysis is illustrated using the examples of equipment sensitivity identified in tests.**

Key words:
Power quality
Voltage sags
Short interruptions
Sensitivity of equipment
Testing of equipment

1. INTRODUCTION

Testing is probably the simplest and the most efficient way for the assessment of equipment sensitivity to various power quality disturbances. Monitoring and computer simulations are two alternative approaches, but they have some significant drawbacks. Although most closely related to the actual conditions of the equipment utilisation and operation, monitoring is extremely time-consuming, as it relies on the recording of the disturbances, which are random and infrequent events. Furthermore, the results of monitoring are often site- and/or process-specific. As a consequence, additional efforts are necessary in order to generalise and use the results of monitoring for the full and reliable assessment of equipment sensitivity. Computer simulations, as the second alternative to testing, may indeed provide fast and convenient means to characterise and study various power quality disturbances and their influence on equipment operation. However, simulations are only as precise and reliable as are the used models of the equipment and system components. Even the most complex and the most realistic models cannot include all factors of influence. Specifically, from the equipment sensitivity point of view, the results obtained in both, monitoring and simulations should always be validated against the results obtained in testing.

During the tests against the sags and interruptions, the equipment is usually connected to a specially constructed device, which at the equipment terminals should produce "synthetic" voltage waveforms, closely resembling actual disturbances with the desired characteristics. This device is commonly known as the voltage sag generator (VSG). In tests with the VSG, electrical equipment is exposed only to a limited set of disturbances, and only a finite number of characteristics and parameters of these disturbances (and other influential factors) is taken into account. The main reason for such a limitation is that tests cannot include all variations from the ranges of possible values of disturbance characteristics that may be present at the place of equipment utilisation. Therefore, set of applied testing conditions and list of disturbances used in tests should be carefully selected and arranged. On the one hand, the results of testing should provide sufficient information about the impact that *any* disturbance may have on equipment operation, allowing assessment of equipment sensitivity in the general case. On the other hand, applied testing procedures should allow standardised, time-efficient and reproducible testing of the equipment. (E.g., testing of three-phase equipment against polyphase sags and interruptions with all possible combinations of three phase voltage magnitudes will be extremely time-consuming. Therefore, a set of discrete values of three-phase voltage magnitudes, which, with appropriate step, covers a whole range from 0% to 100% of the nominal voltage should be adopted and applied in tests.)

Testing of equipment to voltage sags and short interruptions can be conducted in two ways: a) in controlled laboratory environment (e.g., [1]), and b) "in-field", at the place of equipment operation, within its operating environment (e.g., [2]). In both cases, testing is related to reproduction (i.e., simulation) of the real voltage disturbances, using the VSG. In-field testing is usually related to the assessment of the sensitivity of a particular process, in which several pieces of electrical equipment are involved. The results of the in-field tests are often additionally influenced by the specific characteristics of the process, electrical, mechanical and other interconnections and mutual interactions of equipment within the process, as well as by the other process-related aspects and factors of influence. Although the in-field testing can be arranged and "precisely tailored" with respect to each particular application, this type of testing usually does not produce as specific information about the equipment sensitivity as the laboratory testing. The results obtained in in-filed tests often cannot be directly applied to the individual pieces of equipment utilised in other processes. As the more general and in essence independent on the end-user applications, testing of electrical equipment in the controlled laboratory conditions will be considered in the further text.

Although during the laboratory testing the equipment under the test is taken to the laboratory, the equipment should be tested with its minimum functional configuration and, if possible, together with its dedicated protection and communication circuits and peripheral/auxiliary devices directly controlled by the equipment. In order to allow comprehensive and reliable assessment of the equipment sensitivity, laboratory testing of equipment should be planned and adapted in accordance with both, the general requests (related to e.g., the use of the consistent, time-efficient and repeatable test procedures), and specific features and characteristics of the tested equipment. One of the effects of power quality disturbances in actual power systems is permanent damage of equipment, which is even more likely to happen if equipment is exposed to detailed and repetitive tests in the laboratory. Therefore, several pieces of the tested equipment should be readily available at the testing site.

The authors' previous experimental [1], [3], [4] and theoretical results [5]–[7] are in this paper used for the proposal of the general testing procedures, which can be applied for testing of different types of equipment (single-phase and polyphase) to various types of voltage sags and short interruptions (single-phase and polyphase, rectangular and non-rectangular, symmetrical and asymmetrical). Described testing procedures also include tests with non-ideal power supply conditions, different operating/loading conditions of equipment and consider application of multiple malfunction criteria of equipment.

2. POWER QUALITY STANDARDS AND TESTING OF EQUIPMENT TO VOLTAGE SAGS AND SHORT INTERRUPTIONS

Standards related to testing of electrical equipment to voltage sags and short interruptions, as a majority of other power quality standards, are almost exclusively concerned with only two parameters of these disturbances: root mean square (rms) value of voltage magnitude, and duration. Standard [8], for example, describes voltage sag as a "…two-dimensional electromagnetic disturbance, the level of which is determined by both voltage (i.e., rms voltage magnitude) and time (i.e., duration)". Existing standards consider such a "two-dimensional" characterisation as the sufficient, and seldom mention any other sag/interruption characteristic. Some of the standards even explicitly instruct that all other information about the sags and interruptions (e.g., sag shape, phase shift, point on wave, etc.) as the possible additional sag "dimensions" should be neglected. Standard [9], for example, states that the information about the phase shift and point on wave values: "… are not typically available in the sag environment data. Therefore, for compatibility evaluation (i.e., for the assessment of the equipment sensitivity) it is recommended that phase shift and point of initiation should not be considered."

None of the current power quality standards considers the possible influence of a phase shift on equipment sensitivity during the tests. Similarly, none of the existing standards specifies assessment of the influence of point on wave of disturbance ending on equipment sensitivity.

In existing standards, testing of electrical equipment is always related to a reproduction of a simple rectangular ("one-stage", or "one-step") voltage sags and short interruptions. Other sag/interruption "shapes", e.g., two-stage voltage sags, or voltage sags caused by starting of large motors, or combinations of sags and interruptions are, at the best, just mentioned. Practical instructions about quantification and characterisation of non-rectangular sags are not given, nor how to assess their effects on equipment operation. In actual power systems, however, voltage sags and short interruptions are seldom rectangular one-stage events.

One important aspect of existing standard for testing of electrical equipment is that they completely neglect the presence and possible influence of non-ideal voltage supply characteristics. Current standards recommend that voltage waveforms used in test should be ideal sine waves at nominal frequency. Allowed steady state deviations from the ideal voltage supply conditions in e.g., pre-sag and post-sag voltage magnitude, frequency, and harmonic contents (e.g., [10]) are not considered. These deviations, however, can not be simply ignored, as they are very often present in e.g., industrial plants, where equipment operates in a particularly harsh electrical environment. Furthermore, none of the existing power quality standards considers the influence of the simultaneous occurrence of several disturbances (e.g., cumulative effects of both voltage magnitude and harmonic contents variations).

Current power quality standards related to testing of electrical equipment mainly discuss testing of single-phase equipment to (single-phase) voltage sags and short interruptions. For testing of a three-phase equipment, current standards describe only two test procedures. The first one is "phase-by-phase" testing, in which only one phase of the three-phase equipment is exposed to sags and interruptions [11], [12]. Rated/nominal conditions are in all aspects maintained in two other, unsagged phases. After the testing of one phase, the same tests should be repeated (with the same conditions) two more times, for two other phases. In this case, related standards do not give precise instructions how to represent equipment sensitivity if different responses were identified for different phases (adopt response of the most sensitive phase, or average of tested phases, or show the results for all three phases). In the second procedure [12], three-phase equipment should be tested with the same sag/interruption duration and magnitude applied to all three phases simultaneously. In both standards, these two procedures are indicated as *sufficient* for the assessment of the sensitivity of the three-phase equipment. However, even if both procedures are applied in testing, sensitivity of three-phase equipment will be assessed against only two types of disturbances: single-phase sags and interruptions, and symmetrical three-phase sags and interruptions. Additionally, existing recommendations for testing of three-phase equipment do not include phase shift and points on wave of initiation and ending as the possible parameters of influence.

The simple truth, however, is that the sensitivity of the equipment cannot be fully and precisely assessed if *any* of the influential factors is excluded from the analysis, or not included in tests. Therefore, it can be generally concluded that current standards and recommendations for testing of electrical equipment to voltage sags and short interruptions are inadequate, and should be improved, extended and reformulated in order to include additional characteristics, parameter and conditions of influence. There are two main reasons why the information about the other sag/interruption characteristics should not be simply disregarded. First, sensitivity of the certain types of equipment is influenced by other sag/interruptions characteristics (e.g., by phase shift and/or point on wave, [1]). Second, the recent advances in monitoring equipment allow recording of both, rms and instantaneous voltage waveforms during the sags and interruptions, from which information about all relevant (i.e., influential) characteristics can be extracted and used for the analysis/characterisation of sags and interruptions, and for further investigation of their influence on equipment operation in tests.

3. CLASSIFICATION OF FACTORS THAT MAY HAVE INFLUENCE ON EQUIPMENT SENSITIVITY

Full and reliable assessment of equipment sensitivity to various voltage supply disturbances is a complex, time consuming and cumbersome process. This is a consequence of the large number of factors that may have an influence on the equipment response to various voltage disturbances. All these factors (i.e., characteristics, conditions and parameters) can be, with regards to their nature and origin, divided into three following general categories [7]:

i. Voltage supply related electrical characteristics
ii. Equipment specific electrical characteristics
iii. Other, non-electrical characteristics

All types of equipment are neither influenced by the factors from all three categories, nor by all factors from the same category. Depending on the type of the equipment, the effects of some factors for full ranges of their possible values might be so small that they can be neglected during the assessment of equipment sensitivity. The most reliable approach in deciding what factors can be neglected and what cannot is the direct testing of equipment. Therefore, the complete list of important sag/interruptions characteristics and parameters (largely exceeding those considered in current power quality standards and recommendations) that should be controlled and varied in tests is described in the further text.

3.1. Voltage supply related electrical characteristics

Although the voltage supply characteristics during the disturbance have a dominant effect on the equipment behavior, the sensitivity of the equipment may be influenced by both, voltage supply characteristics present before the occurrence of the disturbance, and voltage supply characteristics after the end of the disturbance. Therefore, voltage supply related characteristics, which are considered here as purely electrical, could be further divided into three following sub-categories: a) pre-disturbance voltage supply characteristics, b) during-disturbance voltage supply characteristics, and c) post-disturbance voltage supply characteristics. In the following sections, they will be all discussed from the equipment testing point of view.

Pre-disturbance voltage supply characteristics

The characteristics of a voltage supply are generally specified by the explicit mandatory regulations (e.g., [10]). They however, may still vary both, inside and outside allowed limits and tolerances. If there are "steady-state" variations in the voltage supply prior to disturbance, this may influence the equipment response during the disturbance. Depending on the nature of these variations and equipment characteristics, their influence on the equipment sensitivity ranges from a negligible to a significant, and can be two-fold: some variations in the pre-disturbance voltage supply may increase the equipment sensitivity, and again other may decrease the equipment sensitivity. The most common non-ideal pre-disturbance voltage supply characteristics are related to the voltage magnitude and frequency variations, as well as to the presence of the harmonics and unbalance (i.e., voltage waveform deviations). When several variations in pre-disturbance voltage occur simultaneously, their influence will be complex and composite.

Figure 1 illustrates one example of the significant influence of the non-ideal pre-disturbance voltage supply characteristics on the sensitivity of personal computer to voltage sags and short interruptions. Figure 1a and 1b show the individual effects of the voltage magnitude variations (±10% of nominal voltage) and harmonic contents variations (3^{rd} harmonic with 0^{o} and 180^{o} phase angle), respectively. Cumulative effects of the simultaneous variations in both the voltage magnitude and harmonic contents are shown in Fig. 1c.

During-disturbance voltage supply characteristics

Voltage supply characteristics during the disturbance are, actually, disturbance characteristics. As far as the voltage sags and short interruptions are concerned, the most important during-disturbance characteristics are: type of sag/interruption, shape of sag/interruption, magnitude of sag/interruption, duration of sag/interruption, points on wave of sag/interruption initiation and ending, and during-sag phase shift.

Sag/interruption magnitude

In existing power quality standards, voltage magnitude of sags and interruptions is almost exclusively defined and characterised using the rms values of the phase (phase-to-neutral), or line (phase-to-phase) voltages. (Note: The information about the phase voltages is generally preferred to information about the line voltages, as the concept of the line voltages does not make any sense for phase-to-neutral connected single-phase equipment; additionally, line voltages can be accurately calculated (or "reconstructed") if phase voltages are known; calculation of the phase voltages from the line voltages is not possible in the general case, as line voltages do not contain zero-sequence voltage component.) The rms values, however, are calculated or measured from the corresponding instantaneous voltages recurrently, using the preceding 1-cycle, or ½-cycle values of the instantaneous voltages [13]. If the ideal sine waves with the nominal frequency (and different amplitudes/magnitudes) are used in tests with electrical equipment, the rms sag/interruption magnitude can be exactly correlated with the corresponding instantaneous voltage in all cases, except when applied instantaneous voltage is shorter than ½ cycle (the shortest possible duration for which rms value of a periodic quantity can be calculated is ½ cycle).

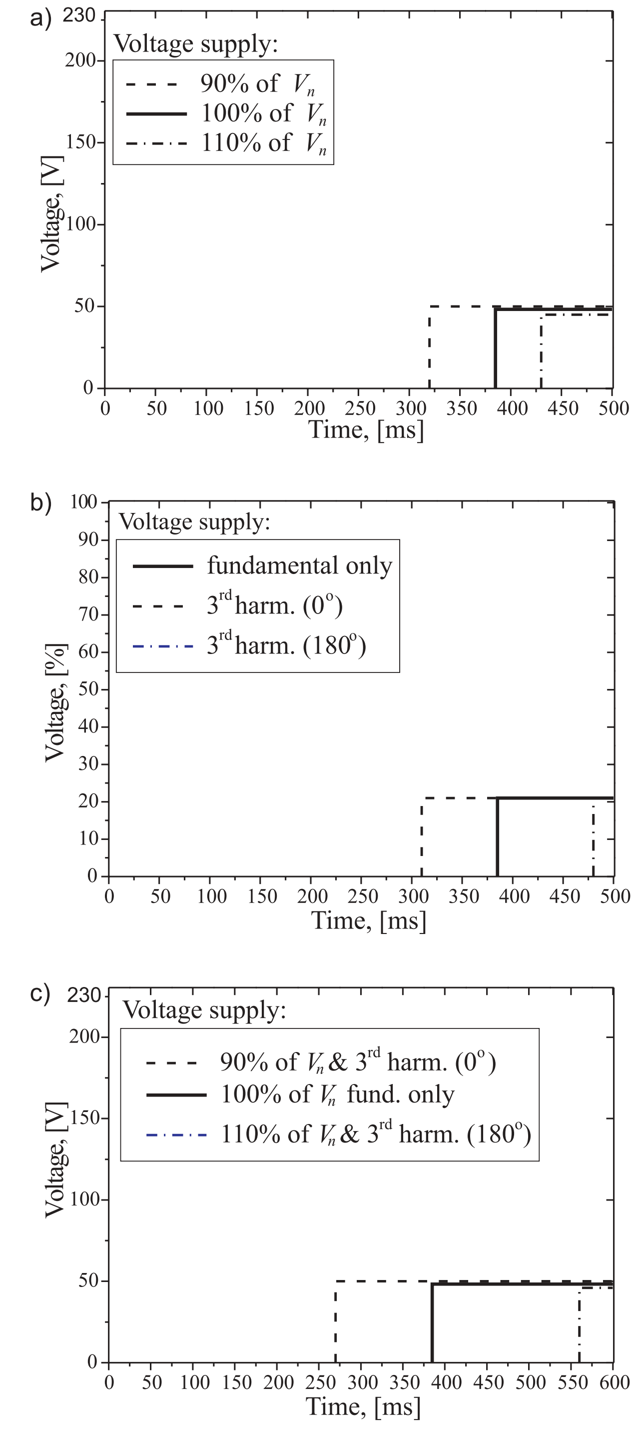

Fig. 1. Individual and cumulative effects of the variations in the pre-disturbance voltage supply characteristics on the sensitivity of the personal computer to voltage sags and short interruptions [3]: a) individual effects of ±10% voltage magnitude variations; b) individual effects of the 3rd harmonic with 20% THD; c) cumulative effects of variations from a) and b)

The sensitivity of some types of equipment, however, is so high that they may malfunction even for sags or interruptions shorter than ½ cycle (see Fig. 2). Therefore, the magnitude of sags and interruptions applied in tests should be adjusted using the amplitude value of the instantaneous voltage sine wave produced by the VSG, i.e., not using the rms voltage values. (Note: In tests with single-phase equipment, one voltage magnitude/amplitude should be controlled; testing of three-phase equipment is more complicated, as there are three voltage magnitudes that should be simultaneously controlled.) Because of the classification problems (in existing power quality standards, sags and interruptions are always defined as the voltage reduction event longer than ½ cycle), sags and interruptions shorter than ½ cycle are termed as the "undervoltage transients" [1].

Figure 2 also illustrates the standard way for representation of equipment sensitivity, the so called "voltage-tolerance curve" of equipment. During the testing of the contactor from Figure 2, discrete values of during-disturbance voltage magnitude were adjusted by the VSG and applied at the contactor's terminals. After adjusting the desired value for magnitude (applied during-disturbance voltage magnitude values covered the whole range from 90% (100%) of the nominal voltage down to 0%), the duration of the corresponding sag/interruption was prolonged until the malfunction of the contactor occurred, or up to a few seconds, if there was no malfunction. With this information at disposal, obtained results for contactor sensitivity are then arranged and illustrated graphically in Figure 2, forming voltage-tolerance curve of contactor. This curve displays duration of disturbance along the horizontal axis, and during-disturbance voltage magnitude along the vertical axis, illustrating the equipment response to disturbances with a particular magnitude and duration. Voltage-tolerance curve of tested contactor divides duration-magnitude plane in two areas, clearly showing which sags and interruptions result in malfunction of contactor, and which do not. In general case, the equipment behaviour cannot be described and characterised by a single voltage-tolerance curve. This is particularly true for three-phase equipment, whose sensitivity cannot be expressed with regards to only one sag magnitude—all three phase voltage magnitudes influence response and behaviour of three-phase equipment. Moreover, if there is any additional parameter that has influence on equipment sensitivity, new voltage-tolerance curve will be obtained for each value of that parameter.

It should be noted that the sets of voltage magnitude values recommended for testing of electrical equipment in existing power quality standards differ significantly. For example, standard [12] considers only very few discrete values of voltage magnitude and duration which should be used in testing: 0%, 40% and 70% of the nominal voltage for the magnitude, and ½, 1, 5, 10, 25 and 50 cycles for duration. If testing is performed only with these recommended values (marked by "**x**" in Fig. 2), the sensitivity of the contactor could be assessed roughly as less than 10ms for short interruptions, somewhere between 20ms and 100ms for sags with magnitude 40% of the nominal voltage, and not sensitive to sags of 70% of the nominal voltage. Only the most recent standard [11] recommends testing of (single-phase) electrical equipment with incremental changes in voltage magnitude, not larger than 5% and using the whole range from 0% to 100% of the nominal voltage.

Duration of the sag/interruption

Existing power quality standards explicitly instruct that the duration of voltage sags and short interruptions should be calculated/determined using the rms value of the during-

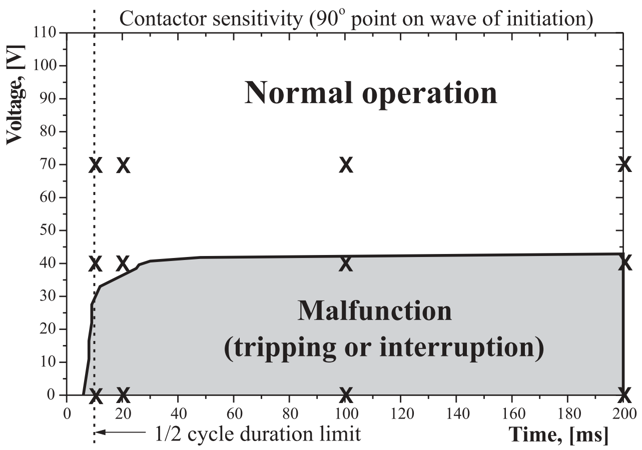

Figure 2. The sensitivity of the ac coil contactor to voltage sags, short interruptions and undervoltage transients (sags and interruptions shorter than ½ cycle), [1]

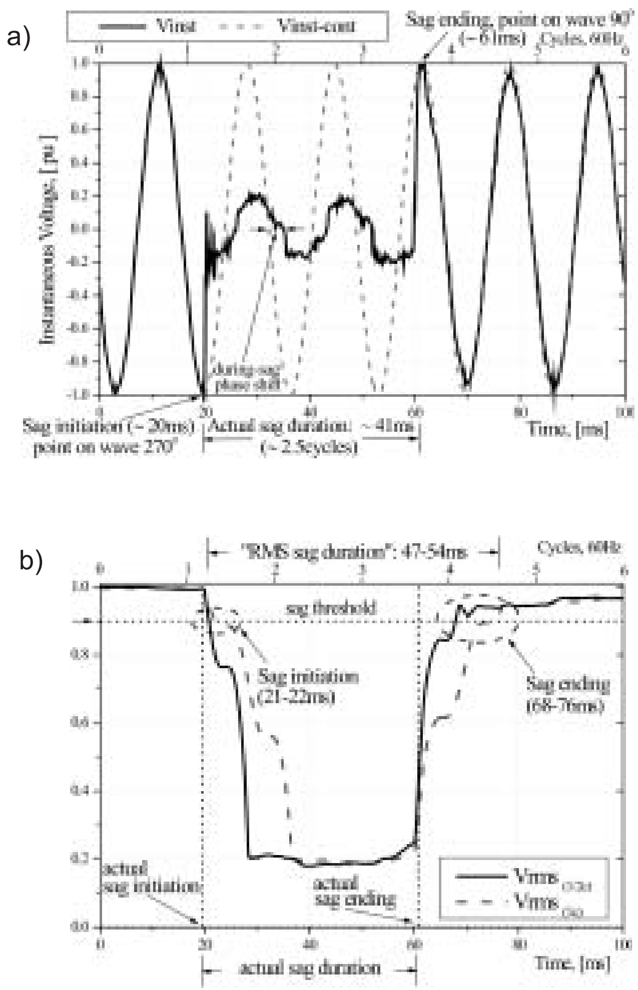

Fig. 3. Recorded rectangular single-phase voltage sag (numerical values adopted from [14]): a) sag duration determined by instantaneous voltage; b) sag duration determined by rms voltage

disturbance voltage. After establishing so-called „magnitude thresholds" of sags and interruptions (the most common values are 90% of the nominal/declared voltage for sag threshold, and 10% for interruption threshold), standards define duration of the sags and interruptions in a three-phase power supply system as the time difference between the moment at which at least one of the three rms voltages falls below the corresponding sag/interruption threshold, and the moment at which all sagged/interrupted rms voltages rise above it. In tests, however, the duration of the applied voltage sags and short interruptions will be most likely determined as the time difference between the instant at which disturbance starts and the instant at which disturbance ends. In other words, these two instants (initiation and ending of disturbance) are related to the instantaneous voltage waveform, not to the rms voltage. As a consequence, durations of the sags and interruptions measured or recorded in actual power systems will differ from the durations of sags and interruptions applied in tests. This is illustrated in Fig. 3.

Instants of sag initiation and sag ending determine duration of sag as approximately 2½ cycles, or 41ms, as one 60 Hz cycle in Fig. 3 lasts 16.67ms. For sag magnitude threshold of 90% of the nominal voltage, and depending on the window size used for calculation of the rms voltage (1-cycle or ½-cycle), corresponding "rms durations" of the sag from Fig. 3 are 47ms and 54ms, respectively. This approach (i.e., the use of the rms voltage values and sag magnitude threshold) results in an error of 15% and 32%, respectively, compared to the *actual* sag duration. Therefore, results obtained in tests and results obtained in measurements should always be carefully correlated and interpreted. The use of the instantaneous voltage waveforms for determination of the during-disturbance magnitudes and durations has another advantage: the instants of initiation and ending are then exactly correlated with the corresponding points on wave of disturbance initiation and ending.

Phase shift during the sag/interruption

Standard analytical representation of the instantaneous (time-dependant) voltages in both single-phase and polyphase alternating current (ac) power supply systems is through the complex numbers, or complex time-varying functions, also known as phasor quantities. In this approach, instantaneous sinusoidal voltage waveforms are expressed through a more convenient phasor representation, which in polar form has two parameters: magnitude and phase angle. Any change of the actual instantaneous voltage can be calculated and expressed analytically through the corresponding changes in voltage magnitude and voltage phase angle. If the information about the changes in either of them is not available, the actual voltages cannot be calculated accurately, and their effects on equipment operation cannot be assessed. Changes in voltage phase angles during the disturbance are commonly known as the phase shift, and are associated with the majority of sags and interruptions caused by short circuit faults. In the further text, phase shift of the phase (line-to-neutral) voltages will be assumed.

The influence and effects of during-sag phase shift on equipment sensitivity will depend on type of equipment (single-phase or three-phase) and connection of equipment ("wye" or "delta"). Electrical equipment normally connected between the phase and neutral conductors ("wye"), will "see" only phase voltages, and the impact of the phase shift will be determined (and limited) by the sole influence of changes in voltage waveform phase angles. The impact on phase-to-phase (“delta” or line-to-line) connected single-phase and three-phase equipment is more complex and more influential. In this case, phase shift (of phase voltages) has influence on both, the magnitudes and phase angles of the line voltages through which voltage sag affect this equipment.

During-disturbance phase shift is the only voltage sag characteristic which does not exist (cannot be defined) in the case of the short interruption, when voltage magnitude is reduced to zero, or very close to that value. Therefore, phase shift should be adjusted and controlled by the VSG only in tests against voltage sags.

Continuous or discrete changes in voltage phase angles (i.e., phase shifts) are associated with the majority of voltage sags. Regardless of the nature of these changes, phase shift can be expressed as the difference between the phase angles of the pre-sag and during-sag instantaneous voltage waveforms This is shown in Figure 3a, where the continuation of the instantaneous pre-sag voltage is plotted by a dashed line, in order to allow easier identification of the during-sag phase shift value. During the tests, however, it is usually sufficient to control and adjust only phase shift at the sag initiation and phase shift at the sag ending (independently in each phase, in the case of the three-phase equipment testing). Phase shift at the sag initiation and phase shift at the sag ending (in one phase) should be equal, but with the opposite sign (if one is positive, the other is negative). With this approach, during-sag phase shift is constant and equal to the adjusted value of the phase shift at the sag initiation. The simplest way to carry out such a testing with the VSG, is to generate two sine waves: one sine wave is related to both, pre-sag and post-sag voltage waveforms (it has nominal magnitude/amplitude), and the other is related to during-sag voltage waveform (its magnitude/amplitude is sag magnitude). The difference in phase angles of these two sine waves at the moment of transition from the pre-sag to during-sag instantaneous voltage waveform will determine phase shift at the sag initiation; the difference in phase angles at the moment of transition from the during-sag to post-sag instantaneous voltage waveform will determine phase shift at the sag ending.

Points on wave of sag/interruption initiation and ending

As their names suggest, points on wave of initiation and ending of sags and interruptions are phase angles of the instantaneous voltage waveform applied in tests at which voltage starts and ends to experience (sharp) reduction in voltage magnitude. More precisely, point on wave of initiation corresponds to the phase angle of the instantaneous pre-disturbance voltage at which (main) transition from the pre-disturbance test voltage to the during-disturbance test voltage is initiated. Similarly, point on wave of ending corresponds to the phase angle of the instantaneous post-disturbance voltage at which (main) transition from the during-disturbance test voltage to the post-disturbance test voltage is finished.

In existing power quality standards, point on wave of ending is completely neglected. Point on wave of initiation is, to some extent, acknowledged, but only in procedures related to testing of the single-phase electrical equipment.

Furthermore, available recommendations for testing single-phase electrical equipment to sags and interruptions with the point on wave of initiation as a parameter are limited in scope. Standard [12], for example, concludes that testing of equipment “…can start and stop at any phase angle” (preferably at 0^o), and suggests testing for additional angles only if they are “…considered critical by product committees or individual product specifications”. If so, a range from 0 to 360^o (in steps of 45^o) is recommended for such additional testing. Other standards mostly suggest that tests should preferably be performed at 0^o point on wave of initiation of the voltage waveform [11], [15]. Similarly, compatibility guidelines in [9] include “point on wave tolerance” in a list of optional criteria that may be posed to the equipment supplier during the review of equipment specification. The reference states that for the equipment testing: “…the sag should be switched in and out during the voltage zero crossing”.

Generally, when the same process or device seems to respond differently to voltage sags having the same magnitude and duration, the reason for such an inconsistent behaviour is most likely to be the influence of some of additional sag characteristics (beside the sag magnitude and sag duration). Figure 4 illustrates significant influence of point on wave of sags and interruptions initiations on the sensitivity of an ac coil contactor. Depending on the point on wave of initiation values of two otherwise completely identical sags or interruptions, the sensitivity of the contactor changes in a range from a few milliseconds (for 90^o point on wave of initiation, voltage-tolerance curve $V(90^o)$) to more than 80ms (for 0^o point on wave of initiation, voltage-tolerance curve $V(0^o)$). In fact, for the contactor illustrated in Figure 4, it can be concluded that the point on wave of initiation has *dominant* influence on contactor sensitivity.

Probably the most common and most notable influence of the point on wave of sag/interruption ending on equipment operation is related to the occurrence of a high in-rush current during the reinstatement of the nominal power supply conditions after the sag/interruption ending. Figure 5 shows an example, where two voltage sags with different points on wave of sag ending (i.e., with different durations) were used for testing of personal computers in [3].

Different points on wave of ending of two otherwise completely identical sags in Fig. 5 influence completely different responses of the tested computer. Voltage sag with 0^o point on wave of ending (Fig. 5a) does not have any notable influence on computer operation. Very high peak-inrush current (10 times greater than the rated current), however, occurs for sag with 90^o point on wave of sag ending (Fig. 5b). This high in-rush current influenced activation of both 4A and 6A C class automatic fuses (minimum 10A fuse is necessary for normal operation), clearly demonstrating that particular point on wave of ending values influence malfunction of computer.

Sag/interruption shape

Majority of power quality standards divide voltage sags and short interruptions with respect to their shape in only two general categories: rectangular sags/interruptions, and non-rectangular sags/interruptions. Of these two, rectangular shape is much simpler for description, characterisation

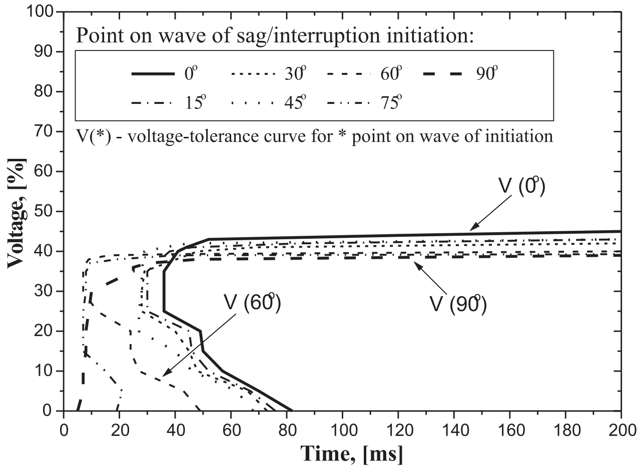

Fig. 4. The influence of different points on wave of sag/interruption initiation on sensitivity of ac coil contactor (no phase shift), [1]

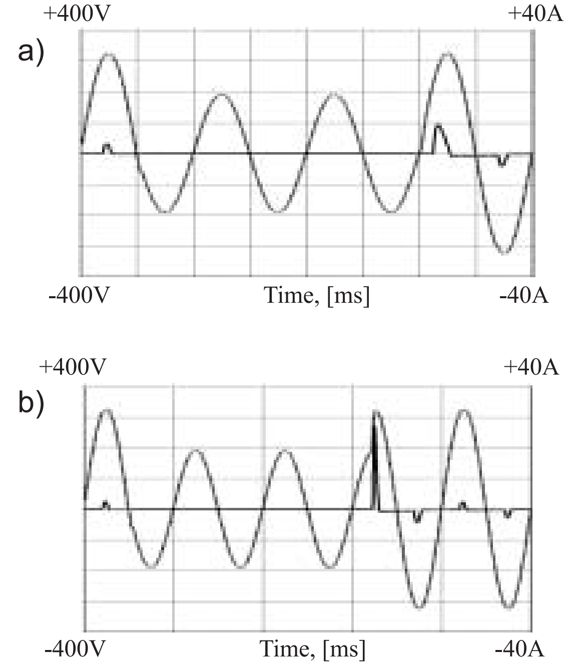

Fig. 5. Illustration of the influence of the point on wave of sag ending on the equipment performance (dotted line—input voltage, solid line—input current, adopted from [3]): a) 0^o point on wave of sag ending; b) 90^o point on wave of sag ending

and reproduction in testing, as it assumes that the voltage magnitude during the voltage reduction event is constant. This allows exact description of the during-event voltage magnitude with the only one, constant value. All other sag/interruption "shapes", e.g., two-stage or multistage sags, or voltage sags caused by the starting of large motors, are categorised as "non-rectangular". In the case of the non-rectangular sags and interruptions (or their combinations, e.g., event starts as a sag and develop further in a short interruption), during-event voltage magnitude is a function of time, and cannot be described with a single and constant value. Exact description of the non-rectangular voltage sags and short interruptions (and their reproduction in tests) is therefore more complicated, as the information about the time-dependent changes in during-event voltage magnitude should be provided in this case. In order to overcome this situation, standards [8], [9] and [16] propose (over)simplified analysis, in which non-rectangular sags and interruptions are replaced with their rectangular "equivalents". These standards recommend the use of the lowest experienced voltage magnitude during the non-rectangular event as the during-event magnitude of the corresponding equivalent event. Although in essence conservative, this approach may result in (significant) overestimation of the influence of non-rectangular sags and interruptions.

The shape of the sags and interruptions is basically determined by their causes. Both abnormal and specific aspects of normal operation of the power system and to it connected load might cause voltage sags and/or short interruptions. These sags and interruptions will have rectangular shape only if all characteristics of the corresponding cause (e.g., short-circuit fault) are constant in time *and* if dynamic nature of the system and load responses to the cause/disturbance can be neglected. These three-way interactions (between the system components, loads and the cause of the event) start at the moment of event initiation, and may last even after the primary cause of the event is removed. For example, if short-circuit fault is initiated in a (weak) system with a large, directly connected motors, resulting sag at the location of interest will be two-stage non-rectangular sag, with two distinctive parts. Sag characteristics of the first part are determined by the characteristics of the short-circuit fault (e.g., fault type and fault impedance) and system/load "response" to fault. When the primary cause of the sag (i.e., short-circuit fault) is cleared, reacceleration of the motors is responsible for the second part of the sag. Due to the inherent dynamic nature and characteristics of the system/load (transient) response to both small and large disturbances, non-rectangular sags and interruptions are far more frequent and more likely to occur than rectangular sags and interruptions. Furthermore, equipment response to non-rectangular sags and interruptions can not be, in general case, identified or determined from the information about the equipment responses to rectangular sags and interruptions. Therefore, sags and interruptions with non-rectangular shape should be also included in the analysis and applied in tests with electrical equipment.

Sag/interruption type

Most generally, distinction between the different types of sags and interruptions can be made regarding the number of sagged/interrupted phases and presence of asymmetries. With this approach, voltage sags and short interruptions can be divided into single-phase sags and interruptions (one phase has rms voltage magnitude below the sag/interruption threshold, other two phases have magnitudes above it), two-phase sags and interruptions (two phases have rms voltage magnitudes below the sag/interruption threshold, the third phase has magnitude above it), and three-phase sags and interruptions (all three phases have rms voltage magnitudes below the sag/interruption threshold). Polyphase sags and interruptions then can be divided into symmetrical (all sagged/interrupted phases have equal rms voltages), and asymmetrical sags and interruptions (at least two sagged/interrupted phases have different rms voltages).

When exposed to voltage sag or short interruption, equipment response can be assessed only if the type of the event is known. Single-phase equipment will respond according to the actual voltage of the phase to which it is connected. Three-phase equipment, on the other hand, will respond with regards to all three phase voltages. In testing of electrical equipment, however, the type of the event (single-phase, two-phase or three-phase, symmetrical or asymmetrical) does not have any meaning for single-phase equipment, as only single-phase sags and interruptions will be applied in tests with the single-phase equipment. In tests with the three-phase equipment, however, all three phases are available (and should be used) for application of single-phase and polyphase symmetrical and asymmetrical sags and interruptions. Clear and simple classification of voltage sags and short interruptions (i.e., their "per-phase description") is therefore crucial for both, efficient and reproducible testing of three-phase electrical equipment.

Classification of sags and interruptions in only three general types assumes that not all combinations of three phase voltages during the sags and interruptions are likely to occur [6]. In this classification, it is assumed that sags and interruptions caused by different fault types propagate in power systems in such a way that during the fault at least two phase voltages will have equal voltage magnitudes. With this approach, asymmetrical two-phase sags and interruptions will have two sagged/interrupted phase voltage magnitudes equal. Similarly, asymmetrical three-phase sags and interruptions could have only two following characteristics: a) voltage magnitude in one sagged/interrupted phase is lower than the voltage magnitude of two other equally sagged phases, or b) voltage magnitude of two sagged/interrupted phases is equal and lower than the voltage magnitude of the third sagged phase. These two types of asymmetrical three-phase sags and interruptions are similar to "ordinary" single-phase sags and interruptions (for which two phases have nominal voltage) and "ordinary" two-phase sags and interruptions (for which one phase has nominal voltage).

Generalised single-phase sag/interruption, as an ordinary single-phase sag/interruption, has the minimum phase voltage in one phase, and two other phase voltages higher than the minimum one. However, generalisation means that, contrary to ordinary single-phase sag/interruption, generalised single-phase sag/interruption may have two other phase voltages also sagged. Similarly, generalised two-phase sag/interruption, as an ordinary two-phase sag/interruption, has the voltage in two phases equal and lower than the voltage in the third phase. Generalisation here means that, contrary to ordinary two-phase sag/interruption, generalised two-phase sag/interruption may have third phase voltage magnitude also sagged. With this approach, ordinary single-phase and ordinary two-phase sags and interruptions are special cases of the generalised single-phase and two-phase sags and interruptions.

According to the above description, following three types of generalised voltage sags and short interruptions can be established and used in testing of three-phase electrical equipment:

1. Three-phase symmetrical voltage sags, which have all three during-event phase voltage magnitudes equal, below the sag threshold and above the interruption threshold.
2. Generalised single-phase voltage sags, for which during-event voltage magnitude in one phase is between the sag and interruption thresholds, and lower than the during-event voltage magnitude in two other phases; two other phases have equal voltage magnitude, which should be used in tests as a parameter and adjusted either at the nominal value, or also below the sag threshold.
3. Generalised two-phase sags, for which two during-event phase voltage magnitudes are equal, between the sag and interruption thresholds and lower than the during-event voltage magnitude in the third phase; the voltage in the third phase should be used in tests as a parameter and adjusted either at the nominal value, or also below the sag threshold.

(Note: Similar classification applies to short interruptions. During the tests with generalised sags and interruptions, voltage magnitude in phase(s) used as a parameter should be changed in steps of e.g., 10% of the nominal voltage.)

One example of testing the three-phase equipment with sags and interruptions from the above described classification in three general types is illustrated in Figure 6.

Response of the equipment to any other sag or interruption (with arbitrary combination of three phase voltage magnitudes) can be estimated using the results of testing obtained with the above described three general types of sags and interruptions. For example, if 10% resolution is applied for voltage magnitude used as a parameter in testing with generalised single-phase and two-phase sags, equipment response to asymmetrical three-phase sags with phase voltage magnitudes of 28%, 53% and 68% of the nominal voltage can be estimated using the test results related to two sets of generalised single-phase sags obtained in tests with applied phase voltage magnitudes of 28%, 50%, 50% and 28%, 70%, 70%.

Post-disturbance voltage supply characteristics

This category of voltage supply related factors includes both, the individual sag/interruption characteristics and separate events/phenomena that may occur after the initial disturbance (the primary cause of the sag/interruption) was cleared. The example of the former is the post-sag phase shift, which may occur *after* the elimination of the sags caused by the short-circuit faults. After clearing the fault and re-establishing the steady-state power supply conditions, two "scenarios" can be discerned in the most general case. If the fault is self-extinguishing/transient, or if automatic reclosing operation was successful, system will completely return to its pre-disturbance conditions, and all changes in voltage phase angles will be cancelled. In the second "scenario", however, faulted part of the system and some system elements will be disconnected due to the action of the circuit breakers, and the post-fault (i.e., post-disturbance) voltage phase angles will differ from their pre-fault/pre-disturbance values. This difference between the pre-fault and post-fault phase angles (i.e., between the pre-sag and post-sag phase angles) is, actually, post-disturbance phase shift. The exam-

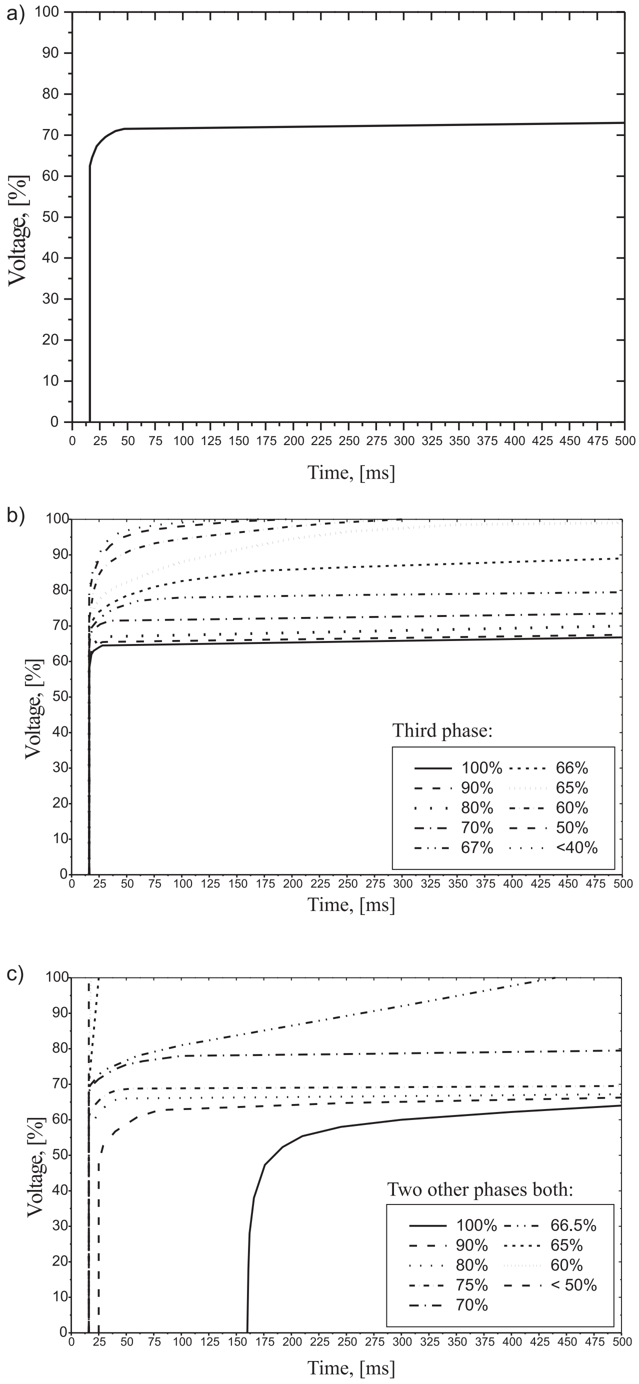

Fig. 6. Sensitivity of an ASD identified in tests with three general types of sags and interruptions, [4]: a) symmetrical three-phase sags and interruptions; b) generalised two-phase sags and interruptions; c) generalised single-phase sags and interruptions

ples of the post-disturbance events, on the other hand, include previously mentioned voltage sags and short interruptions caused by short-circuit faults in weak power supply systems with large and directly connected motors. Another example of post-disturbance events are occurrence of sequence of sags, due to the automatic reclosing operations of circuit breaker(s).

All post-disturbance characteristics and events, however, can be treated either as a set of separate disturbances (which starts with the initial event), or as an aggregate, multistage and most likely non-rectangular disturbance, which could be expressed as a single disturbance. The aggregation is performed in the case of the disturbances that after the initial event have one or more subsequent and continuous events. They can be completely described by one unique set of during-disturbance characteristics. If, however, the events following the initial disturbance are separated in time, they should be considered as a set of separate disturbances, and each of them, again, could be described with its own during-disturbance characteristics. With this approach, all post-disturbance voltage supply characteristics can be analysed and reproduced in tests as during-disturbance characteristics, related to either one unique (but composite disturbance), or to a set of several separate disturbances.

3.2. Equipment Specific Characteristics

When exposed to a disturbance in a voltage supply, equipment response can be also strongly influenced by some equipment specific factors. These factors can be divided in two general categories.

The first category is related to electrical characteristics that describe the mode of operation of the equipment during the disturbance. The factors from this category are usually related to loading and operating conditions of equipment, and can be expressed directly in terms of electrical or electromagnetic quantities and units (current, voltage, power, flux, etc.).

The second category of equipment specific factors is related to concrete manifestations of effects that voltage disturbance have on equipment operation, i.e., to conditions selected for measurement and quantification of the impact on equipment. They can be generally denoted as the equipment "malfunction criteria", and can be also (directly or indirectly) related to electrical quantities and units. For example, if disconnection/tripping of equipment and automatic restart of equipment are selected as two equipment malfunction criteria, manifestation of the first criterion is permanent disconnection of equipment from voltage supply. Temporary disconnection from the voltage supply and subsequent restarting are manifestations of the second criterion. Generally, any condition that represents degradation/loss of some of equipment functions may be selected as equipment malfunction criterion. Accordingly, if equipment during the disturbance can maintain particular function (expressed as corresponding malfunction criterion) within the allowed tolerances, normal operation of equipment should be assumed in that case.

Equipment operating/loading conditions

Equipment behavior after the initiation of disturbance in voltage supply is primarily determined by the inherent characteristics of equipment, its nature and the way in which it converts supplied electrical energy into some other useful forms of energy (e.g., mechanical, thermal, or illuminating). Exactly these characteristics are the main reason for principal differences in responses between the different types of equipment. These differences are usually manifested as the difference in shapes of their voltage-tolerance curves and/or difference in number of factors that have influence on their sensitivity. Generally, when operating conditions of a parti-

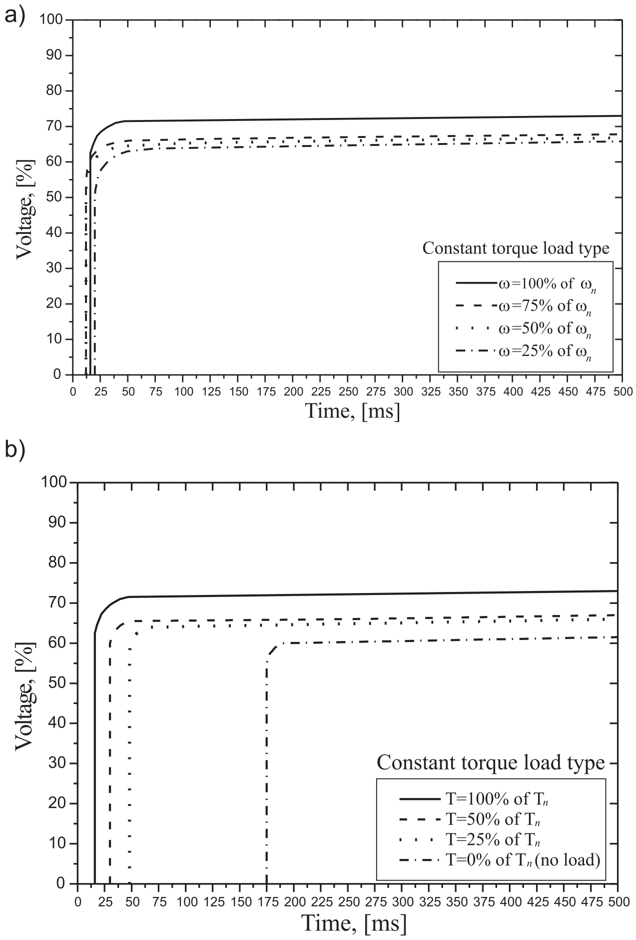

Fig. 7. The influence of the operating conditions of equipment on the sensitivity of an ASD to symmetrical three-phase sags and interruptions [4]: a) influence of different speeds on drive sensitivity; b) influence of different torque values on drive sensitivity

cular piece of equipment change, basic characteristics of equipment behavior and principal shape of its voltage-tolerance curves usually remain the same, but there are often quantitative variations. Therefore, in order to determine the ultimate response of equipment to a particular disturbance, different equipment operating conditions should be also included and varied in tests.

Factors from this category may be as trivial as the position in which equipment operates. This, for example, has significant influence on the response of the ac coil contactor [1]. The effect of gravity on the contactor is different for contactor laid on its back (with horizontal position of the front panel) and on its bottom (with vertical position of the front panel). Other important (and most common) factors of influence from this category are: equipment connection, settings of equipment internal protection systems, operating mode of equipment, and equipment loading conditions: load type, load current, load voltage, load torque, inertia constant of the load, etc. Besides the equipment itself, factors from this category also include actual working conditions of all external or peripheral load controlled or supplied by the equipment. Testing of electrical equipment, therefore, should be performed with at least basic configuration of equipment. This is of particular importance in so called "critical process applications", when degradation of some of the parameters/quantities controlled by the equipment during the disturbance cannot be tolerated, even though the equipment itself is not disconnected by the disturbance.

The influence of different operating conditions of equipment on its sensitivity to voltage sags and short interruptions is illustrated on example of an ASD in Figure 7. This example is of particular interest, as it is related to the testing of equipment configuration in which three different components are involved: the drive controls the speed of the motor, and motor controls/drives the mechanical load at its shaft.

Figure 7 illustrates significant influence of both, loading torque applied at the shaft of the motor, and operating speed of the motor on the overall sensitivity of the ASD to rectangular symmetrical three-phase voltage sags and short interruptions. The variations in drive's sensitivity illustrated in Fig. 7 are identified only after the corresponding equipment specific factors were included in tests.

Equipment malfunction criteria

The sensitivity of the equipment to various power quality disturbances can be measured and quantified only if a clear distinction between the normal operation of equipment and malfunction of equipment can be easily made. Thus, explicit definition and reliable identification of all equipment malfunction criteria of interest are both crucial for the assessment of equipment sensitivity in tests.

In [17] (part 161-01-21), susceptibility of equipment to a disturbance in voltage supply is defined as the inability of equipment to perform its intended functions without the degradation in the presence of an electromagnetic disturbance. Slight variation of that term is used here for the following definition of the malfunction criteria of equipment:

> Equipment malfunction criterion represents situation or condition in which equipment is no more able to perform at least one of its relevant functions, or terminates its ability to control the functions of dedicated/controlled equipment, or starts to execute unintended/adverse functions.

When equipment performs several, more or less independent and separate functions or tasks, the interruption/corruption of each of these functions/tasks may be used as an additional malfunction criterion. This assumes that the disconnection (or restarting) of the equipment is its basic malfunction criterion, which terminates equipment ability to perform all its tasks and functions. In the most general case, the equipment may have different voltage-tolerance curves ("sensitivity levels"), which correspond to different malfunction criteria. It might happen that a particular disturbance influences only some of the functions or tasks performed by the equipment, but there are other functions or tasks that equipment is still able to perform in the presence of that disturbance.

This is illustrated in Figure 8, which shows results obtained in tests of computer sensitivity to voltage sags and short interruptions. Typically, the sensitivity of the personal computers to voltage sags and short interruptions is expressed by a single voltage-tolerance curve, which corresponds to restarting/rebooting malfunction criterion. During the assessment of computer sensitivity in [3], restarting/rebooting of computer (basic malfunction criterion) was denoted as the “hardware” malfunction criterion. Tests with additional malfunction criteria, however, showed that a voltage sag or short interruption might cause interruption of some of the operations performed by the computer *without* the restarting/rebooting of the computer. Two additional malfunction criteria used in these tests were: a) lockup of a read/write operation, and b) blockage of the operating system. They are denoted as the “software” malfunction criteria, and, for some of the tested computers, these two additional malfunction criteria resulted in different voltage-tolerance curves that indicate higher sensitivity. The results of the testing of the computer whose sensitivity was already partially described by Figure 2 (related to basic/hardware malfunction criterion) are shown again in Figure 8, but this time together with the results of testing obtained with additional, software malfunction criteria.

If only the voltage-tolerance curve corresponding to a restarting (basic) malfunction criterion is used for the assessment of the overall computer sensitivity, the error in the assessment would not be conservative, because curves for other malfunction criteria suggest higher sensitivity to voltage sags. As Figure 8 shows, some sags and interruptions did not cause the restarting of the computer, but computer is nevertheless useless, because its operating system is blocked. Again, as mentioned previously, the use of only restarting/rebooting voltage-tolerance curve can be especially misleading when some critical process, “software-controlled” by the computer, is of a particular importance and interest.

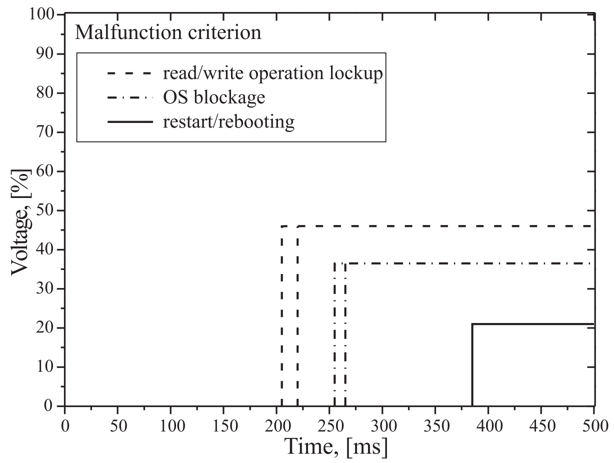

Fig. 8. The results of the sensitivity of a personal computer to voltage sags and short interruptions obtained in tests with multiple malfunction criteria [3]

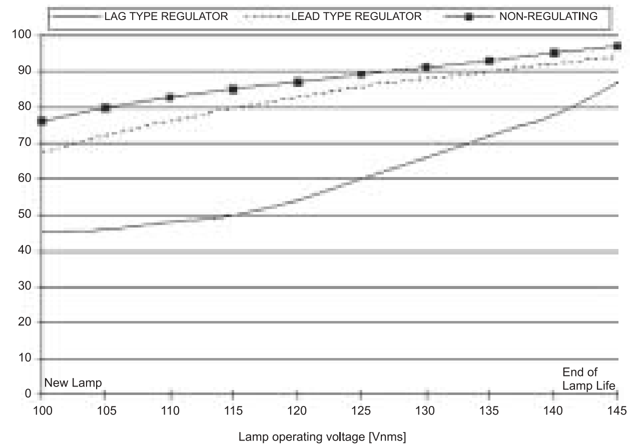

Fig. 9. Influence of ageing on sensitivity of high pressure sodium lamps to voltage sags [18]

3.3. Non-electrical Characteristics

The last category of the influential factors is related to various non-electrical characteristics that also may have an influence on equipment sensitivity to disturbances in voltage supply. Those characteristics are usually related to environmental or ambient conditions encompassing both, voltage supply and the equipment itself. Although each of non-electrical factors of influence ultimately affects the changes in some of the equipment electrical parameters (e.g., voltage, current, resistance, induced flux, etc.), these factors are usually measured and expressed in non-electrical units. Due to their non-electrical nature, they are considered here as the genuine non-electrical characteristics.

The most common factors from this category are related to the non-electrical characteristics of the ambient in which both equipment and power supply system should operate: temperature, humidity, air pressure, altitude, the presence of vibrations, etc. If manufacturer’s technical specification of equipment explicitly declares that the operation of the equipment is influenced by such external non-electrical factors in steady-state operating conditions, it is likely that these factors will also influence equipment behaviour when equipment is exposed to voltage supply disturbances. However, if there is no other explicit information about them, or if they are not expected to be out of the specified ranges at the equipment exploitation location, the environmental conditions during the testing of electrical equipment should be adjusted inside the specified ranges and not changed in tests.

It should be noted, however, that this category of factors also includes ageing of the equipment. Ageing usually decreases the overall equipment performance and increases its sensitivity. Main reasons for that are: wearing of mechanical and other functional parts inside the equipment, dielectric and isolation stresses, amortisation, etc. Therefore, when effects of ageing are of specific interest in end-user applications, results of testing should be obtained in tests with both, new and old pieces of equipment, and then compared and adequately interpreted.

The example of the influence of ageing on equipment sensitivity is illustrated in Figure 9 [18]. Only the variation in the magnitude threshold with the age of different types of high-pressure sodium lamps is shown. It can be seen that at the beginning of their exploitation magnitude thresholds vary in the range from 45% to 75% of the nominal voltage (depending on the type of the ballast used). At the end of their exploitation, however, the sensitivity of lamps is so high that they all may malfunction (i.e., turn off) even if the reduction in voltage magnitude is only few percent below the nominal value. (Note that in such cases the voltage reduction would not be even characterised as a disturbance). In [18] is also reported that the ambient temperature also has an influence on the sensitivity of high-pressure sodium lamps to voltage sags and short interruptions.

4. CONCLUSIONS

Closer look at the current power quality standards related to testing of single-phase, and especially three-phase equipment proves that they are very limited in scope. Particularly from the practical applications point of view, existing recommendations for testing of electrical equipment have to be extended and/or improved.

In general case, equipment sensitivity cannot be simply described with only two disturbance characteristics (rms voltage magnitude and duration) and a single voltage-tolerance curve. Other disturbance characteristics may have significant influence on the sensitivity of various types of equipment. If those other characteristics are excluded from the analysis or tests, the assessment of the equipment sensitivity either cannot be done, or will provide only limited and sometimes even misleading information. Each value of each additional parameter or characteristic of influence will result in a new voltage-tolerance curve of equipment, meaning that instead of a single voltage-tolerance curve, a set of the voltage-tolerance curves have to be used for description/presentation of equipment sensitivity.

This paper tries to fill at least some of the gaps in current standards and recommendations for testing of electrical equipment to voltage sags and short interruptions. First, all factors that may have an influence on equipment sensitivity are divided in three general categories. Number of factors and characteristics of influence that are analysed and included in the proposed testing procedures largely exceeds those considered and described in existing standards and previously published literature. After that, all-inclusive comprehensive testing procedures are described. Testing procedures recommended in existing standards are carefully extended, in order to allow testing against newly introduced factors and parameters in a consistent manner and regarding the repeatability of tests. When there are neither instructions, nor previous attempts in available literature, completely new testing procedures are proposed and described. These testing procedures include testing of equipment with non-ideal voltage supply conditions, testing of equipment against non-rectangular voltage sags and short interruptions, and testing of three-phase equipment based on a new and simple classification of sags and interruptions in only three general types. Regarding the sag and interruption characteristics not included in existing standards, testing procedures proposed in this paper introduce, for the first time, tests with the during–sag phase shift and point on wave of ending. Whenever was possible, the proposed testing procedures are generalised and discussed with respect to various types of single-phase and three-phase equipment. Finally, the presented analysis and discussion is illustrated using the examples of different equipment previously tested in [1], [3] and [4].

Short and concise description of three "test algorithms" that can be used in testing with single-phase and three-phase equipment, as well as in tests with non-rectangular voltage sags and short interruptions are given in three separate appendices at the end of the paper.

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APPENDIX A: Testing of single-phase equipment to rectangular sags and interruptions

In order to ensure a high degree of repeatability, testing of single-phase equipment should be always conducted according to a well-defined procedure. One possible procedure for testing of single-phase equipment with rectangular voltage sags proceeds as follows:

1. Before the initiation of the disturbance, single-phase equipment should be connected to two terminals of the (single-phase) voltage sag generator (VSG). Initially, nominal voltage supply condition should be adjusted at the output of the VSG. After the normal operation of the equipment is confirmed (including all auxiliary/peripheral devices controlled by the equipment), selected loading and other operating conditions of equipment should be adjusted (initially, nominal/rated operating/loading conditions). Particular malfunction criterion of equipment should be identified and closely monitored during the tests.
2. Initial value of the point on wave of initiation should be adjusted (e.g., 0º on the voltage waveform).
3. Initial value of the phase shift should be adjusted (e.g., 0º).
4. Keeping constant the adjusted values of the point on wave of initiation and phase shift, voltage sags/interruptions should be applied in steps of 1% of the nominal voltage[1], starting from 0V. For each applied voltage magnitude, the duration of the event should be progressively increased, until the malfunction of equipment occurs, or up to a few seconds. The duration required for malfunction of equipment should be ascertained/verified by several (3-5) repeated measurements (for each adjusted magnitude, point on wave of initiation and phase shift). After each malfunction of equipment (identified using the corresponding malfunction criterion), a recovery time of minimum 5-10 seconds should be allocated before the next sag/interruption is applied.[2]
5. If pre-disturbance and post-disturbance voltage waveforms used in tests are identical, post-disturbance phase shift will be equal to zero. In that case, point on wave of ending will be determined only by adjusted point on wave of initiation and adjusted duration. In order to perform testing of equipment with respect to different point on wave of ending values, testing of equipment should continue *after* the equipment malfunction is identified for certain point on wave of initiation and duration in Step 4.[3] Tests with the prolonged duration should be applied, e.g., in steps of 1ms (corresponds to changes of point on wave of ending values in steps of 18º for 50Hz voltage supply). Testing with prolonged durations, corresponding to different point on wave of ending values, should continue until the malfunction of equipment occurs for all applied durations within the one full cycle/period.[4]
6. Initial value of the point on wave of initiation (Step 2) should be replaced with another value in the range from 0 to 360º, using the 15º step, and the measurements described in Step 4 should be repeated.[5]
7. Initial value of the phase shift (Step 3) should be replaced with another value from two ranges: a) from 0º to -90º (using the step of -15º), and b) from 0º to +90º (using the step of 15º), and the measurements described in Step 4 should be repeated.[5]
8. Initial loading condition of equipment selected in Step 1 should be changed with the next condition of interest, and testing procedure should continue again as described above.
9. The malfunction criterion of equipment selected in Step 1 should be changed with the next malfunction criterion of interest, and testing procedure should continue again as described above.
10. The nominal/ideal voltage supply characteristics adjusted in Step 1, should be replaced with selected individual and composite non-ideal voltage supply characteristics, and testing procedure should continue again as described above.[6]

In all cases, the during-disturbance voltage waveform at the output of the VSG should be the ideal sine wave with nominal frequency (50Hz) and adjusted disturbance characteristics. The only exception is testing with non-ideal supply characteristics, when during-sag voltage wave form can have the same characteristics (e.g. harmonic contents) as the applied pre-sag and post-sag voltage. Influence of non-electrical characteristics on sensitivity of tested equipment (as described in Section 4.3) may be also investigated for the range of selected values of interest (e.g., for different ambient temperatures).

In general case, the tests described above will produce families of voltage-tolerance curves, corresponding to different voltage supply conditions, different points on wave of initiation, different phase shifts, different malfunction criteria, different operating/loading conditions of equipment, etc.

APPENDIX B: Testing of three-phase equipment to rectangular sags and interruptions

The main difference between the tests with single-phase and three-phase equipment is, obviously, number of phases in which sags and interruptions (and their characteristics) should be initiated and controlled. Furthermore, testing of the three-phase equipment is more complicated, because in this case some "phase angle characteristics" of disturbance (e.g., points on wave of initiation and ending) have to be interpreted in a three-phase sense. One possible procedure for testing of three-phase equipment in accordance with the classification of sags and interruptions described in this paper proceeds as follows:

1. Before the initiation of the disturbance, three-phase ("wye" or "delta") equipment should be connected to three-phase VSG, with the nominal voltage supply condition initially adjusted at its outputs. After the normal operation of the equipment is confirmed (including all auxiliary/peripheral devices controlled by the equipment), selected loading and other operating conditions of equipment should be adjusted (initially, nominal/rated operating/loading conditions). Particular malfunction criterion of equipment should be identified and closely monitored during the tests.
2. One of three general sag/interruption types should be selected for testing (e.g., tests might start with the symmetrical three-phase sags and interruptions).
3. Initial value of the point on wave of initiation should be adjusted (e.g., 0^o on the voltage waveform), using one phase as the reference.
4. Initial values of the phase shift in each phase should be adjusted in accordance with the sag/interruption type selected in Step 2 (initially, phase shift can be set to 0^o in all three phases).
5. Keeping constant the adjusted values of the point on wave of initiation and phase shift in each phase, voltage sags/interruptions should be applied in steps of 1% of the nominal voltage[1], starting from 0V. In the case of the symmetrical three-phase sags/interruptions, this should be done in all three phases simultaneously (one phase is the reference phase). For generalised single-phase sags/interruptions, resolution of 1% should be applied to one (reference) phase, while voltage magnitude in two other phases is equal and used as a parameter (initially set to nominal voltage). For tests with generalised two-phase sags/interruptions, resolution of 1% should be simultaneously and equally applied to two phases (one of them is the reference phase), while voltage magnitude in the third phase is used as a parameter (and initially set to nominal voltage). For each set of adjusted during disturbance magnitudes, the duration of disturbance should be prolonged until the malfunction of equipment occurs, or, if there is no malfunction, up to a few seconds. The critical duration (required for malfunction of equipment) should be ascertained/verified by several (3-5) repeated measurements. After each malfunction of equipment (identified using the corresponding malfunction criterion), a recovery time of minimum 5-10 seconds should be allocated before the application of consecutive disturbances.[2]
6. If pre-disturbance and post-disturbance voltage waveforms used in tests are identical, post-disturbance phase shift will be equal to zero. In that case, point on wave of ending (in each phase) will be determined only by adjusted point on wave of initiation and adjusted duration. In order to perform testing of equipment with respect to different point on wave of ending values, testing of equipment should continue *after* the equipment malfunction is identified for certain point on wave of initiation and duration in the reference phase in Step 5.[3] Tests with the prolonged duration should be applied, e.g., in steps of 1ms (corresponds to changes of point on wave of ending values in steps of 18^o for 50Hz voltage supply). Testing with prolonged durations, corresponding to different point on wave of ending values, should continue until the malfunction of equipment occurs for all applied durations within the one full cycle/period.[4]
7. In testing with generalised two-phase and single-phase sags/interruptions, for which voltage in one and two phases, respectively, is used as a parameter, this parameter should be changed in steps of 10% from 0-100% of the nominal voltage, and measurements described in Step 5 should be repeated.[7]
8. Initial value of the point on wave of initiation (Step 3) in reference phase should be replaced with another value in the range from 0 to 360^o, using the 15^o step, and the measurements described in Step 5 should be repeated.[5, 8]
9. Initial values of the phase shift in each phase (Step 4) should be replaced with another values, depending on the applied sag/interruptions types. In tests with symmetrical three-phase sags/interruptions, the same conditions should be reproduced in all three sagged/interrupted phases, including the equally adjusted phase shift (range from 0^o to 90^o in steps of 15^o, and from 0^o to -90^o in steps of -15^o). In tests with generalised single-phase sags/interruptions, phase shift applied in reference phase is again from the ranges 0^o to 90^o in steps of 15^o, and 0^o to -90^o in steps of -15^o.[8] In tests with generalised two-phase sags/interruptions, phase shift applied in two equally sagged/interrupted phases should have the same absolute value (range from 0^o to 60^o), but opposite signs (one is positive, the other is negative, i.e., applied steps should be $+15^o$ in one phase, and -15^o in the other).[5, 9]
10. The voltage sag type should be changed to the next of the three general types and measurements as described from Step 3 further should be repeated.
11. Initial loading condition of equipment selected in Step 1 should be changed with the next condition of interest, and testing procedure should continue again as described above.
12. The malfunction criterion of equipment selected in Step 1 should be changed with the next malfunction criterion of interest, and testing procedure should continue again as described above.

13. The nominal/ideal voltage supply characteristics adjusted in Step 1, should be replaced with selected individual and composite non-ideal voltage supply characteristics, and testing procedure should continue again as described above.[6]

Notes:

[1] Applied step/resolution can be both, higher (e.g., 2% or 5% of the nominal voltage) and lower (e.g., 0.5% of the nominal voltage).

[2] If equipment needs more time to obtain adjusted operating/loading conditions, that should be allowed.

[3] It may happen, that a particular point on wave of ending value produces high in-rush current (which may activate overcurrent protection of equipment), but the next point on wave of ending value does not.

[4] If identified, appropriate discussion and analysis of the influence of different point on wave of ending values should be included in the test report.

[5] If necessary, lower step (±10º, or ±5º) may be used as well.

[6] Non-ideal voltage supply characteristics may include, for example, up to ±10% variation in voltage magnitude, up to ±2% variation in frequency, different harmonic contents (both, individual harmonics and harmonic spectrum) with different phase angles with respect to fundamental component, and with different total harmonic distortions (THDs); in the case of the waveform deformations (different harmonic contents), definition and adjusting of the voltage magnitude and phase shift should be carefully described and interpreted, e.g., using the fundamental component of the applied pre-disturbance/post-disturbance voltage waveform.

[7] Applied step/resolution can be both, higher (e.g., 20% of the nominal voltage) and lower (e.g., 5% of the nominal voltage). If 10% resolution is applied for adjusting voltage magnitude in one or two phases used as a parameter in tests with generalised two-phase and generalised single -phase sags/interruptions, set of eleven voltage-tolerance curves will be obtained for both types of generalised sags/interruptions (see [4], [6]).

[8] As the points on wave of initiation and ending in (each phase) define/determine the duration of applied sags and interruptions in individual phases, there are two possible ways for testing of three-phase equipment against polyphase sags and interruptions: a) with the same durations of individually sagged/interrupted phases, and b) with different durations of individually sagged/interrupted phases. If the same duration is applied, sags and interruptions in individual phases will be initiated and finished simultaneously. The same range as in the case of single-phase equipment testing (i.e., from 0º to 360º in steps of 15º) should be used for point on wave of initiation values in the reference phase. Applied durations and points on wave of initiation will determine points on wave of ending in the reference phase. As the initiation and ending of sags and interruptions is simultaneous in all sagged/interrupted phases, points on wave of initiation and ending there will be shifted by 120º, with respect to points on wave of initiation and ending in the reference phase. If tests with different durations are applied, that should be performed with respect to instantaneous currents and voltages of the tested equipment, which should be monitored. Points on wave of initiation and ending in one phase should be again used as the reference, but initiation and ending of sags and interruptions in other sagged/interrupted phase(s) should not be done simultaneously. Instead, sags and interruptions should be initiated and finished *after* the initiation/ending in the reference phase. If the initiation of sags and interruptions in phases other than the reference phase does not correspond to two voltage waveform half-cycles with positive gradients), point on wave of initiation should be adjusted at the first zero crossing of the instantaneous voltage that occur after the initiation in the reference phase. The ending of sags and interruptions in other phases should be adjusted at the first zero crossing of their instantaneous currents that occur after the ending in the reference phase. In that way, the basic principles of the initiation and clearance of polyphase faults will be closely reproduced in tests (with respect to, e.g., operation of single-pole circuit breakers, which will clear faults in individual phases at their current zero crossings.

[9] Additionally, phase shift maybe also introduced in one or in two phases whose voltage magnitude is used as a parameter in tests with generalised two-phase and single-phase sags/interruptions, respectively. This, however, may produce additional sets of voltage-tolerance curves of tested three-phase equipment.

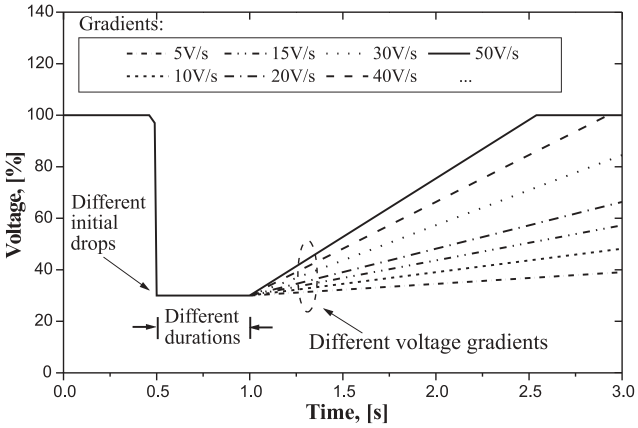

Fig. C.1. General shape of non-rectangular sags and interruptions applied in tests

APPENDIX C:
Testing of single-phase and three-phase equipment to non-rectangular sags and interruptions

One possible testing procedures related to reproduction of non-rectangular voltage disturbances that closely resemble sags and interruptions caused by the starting of large motors, or sags and interruptions caused by short-circuit faults in weak systems with large directly connected motors is illustrated in Figure C.1. General shapes of these two types

Table C.1 Tabular format for representation of equipment sensitivity to non-rectangular voltage sags and short interruptions.

Initial drop to	0% of the nominal voltage					10% of the nominal voltage					…
Voltage gradient	**Duration of the flat part**					**Duration of the flat part**					
	0ms	50ms	100ms	200ms	…	0ms	50ms	100ms	200ms	…	…
5 V/s											
10 V/s											
15 V/s											
20 V/s											
30 V/s											
40 V/s											
50 V/s											
…											

of non-rectangular sags and interruptions will have the following main characteristics/parts: a) initial drop in voltage magnitude, b) duration of the flat part, and c) gradient of voltage recovery. (Note: For voltage sags caused solely by the starting of the large motors, there may not be a flat part, i.e., the duration of this stage could be equal to zero.)

Various initial voltage drops, durations of the flat part and voltage recovery gradients should be considered in tests. During the testing of single-phase equipment, this general type of non-rectangular sags and interruptions should be reproduced in one phase. For tests with three-phase equipment, the same conditions should be reproduced in all three phases simultaneously, as influence of the motor (re)acceleration is the same in all three phases (i.e., the voltage recovers gradually and equally in all three phases). Point on wave of initiation may be varied (range from 0^o to 360^o, step of 15^o), but, generally, phase shift may be assumed to be equal to zero (in all phases) during these sags and interruptions.

Instead of the graphical representation using the voltage-tolerance curves, tabular format should be used for representation of equipment sensitivity to applied non-rectangular voltage sags and short interruptions. Table C.1 illustrates one example for presentation of equipment sensitivity. Each cell of the table should indicate one of two possible outcomes when equipment is exposed to a particular non-rectangular sag/interruption with corresponding characteristics: a) normal operation of tested equipment, or b) malfunction of tested equipment, in which case time of equipment malfunction should be entered in corresponding table cell.