EVALUATING VOLTAGE DIP IMMUNITY OF INDUSTRIAL EQUIPMENT

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INTRODUCTION
Industrial process equipment may be affected by a variety of different power supply disturbances. Voltage dips are perhaps the most important because they are more common than complete interruptions to the supply. Various standards have been developed to help utilities define the expected voltage dip performance [1] and to help industrial customers evaluate the economic impacts of these events on their operation [2].

This paper describes testing procedures for evaluating equipment sensitivity to voltage dips. Testing procedures are specified in IEC standards 61000-4-11 [3] and 61000-4-34 [4]. These standards are useful in that they provide a consistent method of evaluating equipment sensitivity to voltage dips. However, the approaches recommended may not provide enough information to understand the equipment performance in real world applications. Therefore, the focus of this paper is to describe real world voltage dip characteristics and relate these characteristics to appropriate tests that could help estimate the likelihood of equipment malfunction in actual applications.

The results include three important contributions:
1. The standards that define equipment immunity requirements and equipment immunity testing for voltage dips are described. These include the SEMI F47 standard [5] in the semiconductor industry, and IEC standards 61000-4-11 (less than 16 amps) and 61000-4-34 (greater than 16 amps).
2. Approaches for testing equipment to evaluate sensitivity to voltage dips are described. Testing recommendations are provided in the IEC standards and are also outlined in the SEMI F42 [6] for semiconductor industry equipment. Categories of voltage dips are described along with their likelihood of occurrence from various benchmarking projects. These categories of voltage dips are compared with the recommended approaches for testing in the standards and the limitations of the recommended approaches are identified. Additional testing approaches that can provide a more complete picture of expected performance are presented.
3. An example of actual voltage dip immunity testing results is presented to illustrate the importance of voltage dip characteristics and to illustrate methods of characterizing equipment performance.

TESTING OF EQUIPMENT IMMUNITY TO VOLTAGE DIPS
Several test methods exist to evaluate the voltage dip immunity of industrial equipment. By generating synthetic events, these methods can determine the behaviour of equipment that is potentially sensitive to dips. Such testing should give information about the expected behaviour of the equipment to real-life dips. Different methods are available to generate these dips including transformer-switch type arrangements and amplifier based systems.

Generally, there are two different types of testing protocols:
1. Generating a predetermined number of standard dips for which the equipment performance is tested. For each test the EUT (equipment under test) either fails or passes.
2. Determining the equipment immunity curve by testing the EUT to the point of malfunction.

Within these two basic approaches, there are a wide variety of voltage dip characteristics that can be considered as part of the protocol. These include the magnitude vs time characteristics, the phase angle variations during the dip, the number of phases affected, the point on wave for initiation of the dip, and the source impedance. [7]

REQUIREMENTS OF A TESTING PROTOCOL
Equipment immunity testing is not an aim by itself, but part of improving (or ensuring) the compatibility between industrial equipment and the power supply. A detailed procedure for this evaluation was developed and documented in IEEE Standard 1346 [2]. The procedure requires understanding the expected voltage dip performance of the supply system, the immunity of equipment and processes in the facility, and the economic impacts of disruptions to the process. With this information, decisions about improving equipment immunity and implementing power conditioning solutions can be made based on traditional engineering economics decisions.

As part of this process, the testing protocol should help provide the information regarding the equipment and process immunity to the real world voltage dips that can occur. The protocol should result in information about performance that can be compared with the results from actual monitoring and also with stochastic prediction methods. Both for use in stochastic prediction of performance and for repeatability of the actual test results, the testing protocol must use a set of voltage dips with standard characteristics.

For comparison with the results from stochastic-prediction methods it is important that the standard dips have a physical significance. This is the only way in which their frequency-of-occurrence can be estimated through stochastic-prediction methods. There may be good reasons for using other than
such dips as standard dips in a testing protocol. However, choosing characteristics that do not have a physical basis will limit the use of the testing protocol to improve the compatibility between equipment and supply.

For comparison with the results from monitoring programs it should be possible to classify the recorded waveform in such a way that they can be grouped into the same standard dips as used in the testing protocol. It should be possible to correlate the majority of measured dips with one of the standard dips in the testing protocol. In this way, the measurement results reinforce stochastic prediction methods.

EXISTING VOLTAGE DIP IMMUNITY TESTING STANDARDS

Existing standards for testing equipment voltage dip immunity focus primarily on verifying a minimum immunity requirement for equipment response to voltage dips. IEC Standard 61000-4-11 [3] is for equipment below 16 amps. Usually, these will be single phase devices where the testing is fairly straightforward because multiple phase dips are not an issue and phase shift is usually of secondary importance. The most important consideration in this case is the actual immunity characteristic that is required. The immunity test levels from 61000-4-11 and 61000-4-34 are compared with the immunity requirements from SEMI F-47 in Figure 1.

Testing three phase equipment is more complicated. Both IEC 61000-4-11 [3] and IEC 61000-4-34 [4] cover single-phase and three-phase equipment in a similar way, but the former only applies to equipment up to 16A per phase, whereas the latter covers larger equipment. Preferred test levels and test characteristics are defined for different classes of equipment. A recommended approach for testing the equipment both phase-to-neutral and phase-to-phase is provided. Three-phase equipment with neutral connection shall be subjected to three phase-to-neutral and three-phase-to-phase dips, whereas three-phase equipment without neutral shall be subjected only to three phase-to-phase dips. However in reality the equipment will experience the same dips. Further no testing is required for dips due to two-phase and three-phase faults (although the allowance is made for product standards to add additional requirements, it is unlikely that product standards will introduce tests not covered by the basic testing standard) and the vectors defined for phase-to-phase testing do not have a physical basis (see Figure 2). The problem is illustrated with an example from actual testing in the next section. We will also come back to the physical basis in a later section.

Figure 1. Immunity testing levels from IEC 61000-4-11 and 61000-4-34 compared with immunity requirements in SEMI F-47.

Figure 2a. Vectors recommended by IEC [3] [4] for phase-to-neutral testing of three-phase equipment.

Figure 2b. Vectors recommended by IEC [3][4] for phase-to-phase testing of three-phase equipment. Note that the vectors in method A are preferred, the vectors in method B are acceptable, and the vectors in method C are not acceptable.

VOLTAGE DIP TESTING OF AN ADJUSTABLE SPEED DRIVE

An Adjustable Speed Drive (ASD) is selected as an example industrial load for testing because it is very common in many industrial facilities, is often part of processes sensitive to voltage dips, and is a three phase load that illustrates the importance of the voltage dip characteristics on the device immunity.

During a voltage dip or momentary interruption, the diodes in an ASD rectifier bridge will not conduct if the peak line voltage drops below the dc bus voltage. While the ASD is still controlling the motor and its load, energy is drawn from the dc-bus capacitors, which will cause the dc-bus voltage to decrease. If the dc-bus voltage falls below the ASD’s undervoltage trip point before the line voltage returns, then the control circuit will respond according to the drive’s program, typically shutting down the drive [e.g. 8].

Using a typical 5 hp (3.5 kW) ASD, tests were conducted to determine how the drive would respond to voltage dips that were generated using different test methods. The tests were conducted with the drive loaded to 81 percent of full load, with an input voltage of 400V rms phase-to-phase, 50 Hz. The voltage sag generator used is compatible with SEMI F47-0200, SEMI F42-0200, and the proposed IEC 61000-4-34 standards.
Set in its default configuration with no ride-through features enabled, the drive was setup to trip when the minimum dc bus level was reached. Phase-to-phase and three-phase voltage sags were applied. For the phase-to-phase voltage sags, three different methods were used described in the IEC documents as method A, B, and C. A three-phase symmetrical voltage dip test was also conducted, referred to herein as a method D voltage dip. For harmony with the IEC documents, a voltage dip is characterized by the remaining (residual) voltage during an event, not by the decrease in rms voltage.

All voltage dip tests were conducted with a duration of 200 milliseconds, which is a common duration point for both the SEMI F47-0200 standard and the IEC standards. The voltage dip level for testing began at 90 percent of nominal for each test configuration and was reduced by 5 percent for each successive event until the drive tripped due to a low voltage on the dc bus. A summary of the test results is shown in Table 1. For reference, the nominal dc bus voltage was measured at 555Vdc peak prior to the voltage dip events.

One noticeable result from this testing is a large difference in the minimum value of the drive dc bus voltage as a result of the phase-to-phase test methodology used. The dc bus voltage during the dip is mainly determined by the highest phase-to-phase voltage [7,8]. For method A the highest phase-to-phase voltage is not affected by the dip, whereas it is lowest for method D. Figure 4 shows the minimum values during the voltage sags along with the measured peak dc bus value during normal operation at 400Vac, 50 Hz.

Voltage dips of 60% and 70% of nominal lead to tripping the ASD for Methods C and D, respectively. As voltage dip susceptibility is a leading concern of drive users and drive manufacturers, many manufacturers allow adjustments of the drive control parameters such as trip level and restart functions. Implementation of a testing standard that may not require these features to be enabled in order to pass the test criteria may lead to failures in actual field applications. Based on these lab test results as well as other tests performed on drives in a semiconductor plant environment, the phase-to-phase test methods recommended in IEC 61000-4-34 will result in overly optimistic results (ignoring multiple phase dips).

This test illustrates the importance of including two and three phase voltage dips as part of a testing protocol if the equipment immunity levels are to be characterized in a way that will help estimate the actual likelihood of disruption in the facility.

<table>
<thead>
<tr>
<th>Example Dip Vector Diagram</th>
<th>DC Bus Waveform at Lowest %Vdip Test Point</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>%Vdip=0%, 0.2 sec Min DC Bus = 465Vdc</td>
<td>Drive Does Not Trip even for Total Interruption where %Vdip=0%</td>
</tr>
<tr>
<td>(B)</td>
<td>%Vdip=0%, 0.2 sec Min DC Bus = 367Vdc</td>
<td>Drive Does Not Trip even for Total Interruption where %Vdip=0%</td>
</tr>
<tr>
<td>(C)</td>
<td>%Vdip=60%, 0.2 sec Min DC Bus = 355Vdc</td>
<td>Drive Trips at %Vdip=60%</td>
</tr>
<tr>
<td>(D)</td>
<td>%Vdip=70%, 0.2 sec Min DC Bus = 348Vdc</td>
<td>Drive Trips at %Vdip=70%</td>
</tr>
</tbody>
</table>

Figure 4. Minimum dc bus values during the voltage dip tests (refer to Table 1 for test conditions).

A DIP CLASSIFICATION BASED ON PHYSICAL PHENOMENA

An approach is needed with a limited number of standard dips that can be used in a testing protocol. A dip classification that is based on physical phenomena can be used to select the standard dips for testing:

- Voltage dips due to motor starting. Balanced dips, characterised by a lowest voltage and a recovery time constant.
- Transformer-energizing dips. Unbalanced dips, characterised by a lowest voltage, an unbalance, a recovery time and even-harmonic distortion.
- Voltage dips due to faults. These form the majority of severe dips and even the majority of shallow dips at
many locations. These dips are the focus of the dip immunity testing standards and also the focus of this paper. A classification into specific types of dips has been proposed [9]. This classification can be used as a base for a testing protocol, where types B and E are not important for equipment without neutral connection (i.e. for the majority of three-phase equipment). The classification provides the basic characteristics of the voltage dips – magnitude and phase shift during the dip. Future considerations may address secondary characteristics, such as unequal clearing times on the three phases and post-fault recovery that can be of extended duration in some circumstances.

Table 2 illustrates the voltage dip types proposed [9]. Most real-world voltage dips can be approximated by the characteristics of the seven voltage dip types given in the table. Once equipment immunity is understood for these different types of dips, the immunity characteristics can be compared with stochastic predictions of the actual voltage dip performance at the site in each of these categories. These stochastic predictions can be developed using both measurements and simulations (based on a knowledge of system characteristics and expected fault types on the system).

Table 2. Voltage dip types proposed for testing of equipment immunity so that results can be compared with stochastic predictions of performance.

<table>
<thead>
<tr>
<th>Type</th>
<th>Voltages</th>
<th>Phasors</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$U_a = V^*$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_b = -\frac{1}{2}V^* - \frac{1}{3}jV^* \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_c = -\frac{1}{2}V^* + \frac{1}{3}jV^* \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td>B</td>
<td>$U_a = E_1$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_b = -\frac{1}{2}E_1 - \frac{1}{3}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_c = -\frac{1}{2}E_1 + \frac{1}{3}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td>C</td>
<td>$U_a = V^*$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_b = -\frac{1}{3}V^* - \frac{1}{2}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_c = -\frac{1}{3}V^* + \frac{1}{2}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td>D</td>
<td>$U_a = E_1$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_b = -\frac{1}{2}E_1 - \frac{1}{3}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_c = -\frac{1}{2}E_1 + \frac{1}{3}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td>E</td>
<td>$U_a = V^*$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_b = -\frac{1}{3}V^* - \frac{1}{2}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_c = -\frac{1}{3}V^* + \frac{1}{2}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td>F</td>
<td>$U_a = E_1$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_b = -\frac{1}{2}E_1 - \frac{1}{3}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_c = -\frac{1}{2}E_1 + \frac{1}{3}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td>G</td>
<td>$U_a = V^*$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_b = -\frac{1}{3}V^* - \frac{1}{2}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
<tr>
<td></td>
<td>$U_c = -\frac{1}{3}V^* + \frac{1}{2}jE_1 \sqrt{3}$</td>
<td>![Phasors]*</td>
</tr>
</tbody>
</table>

Dip type C is identical to method B in Figure 2 and Table 1 of this paper; type E is identical to method C; and type A identical to method D. The IEC Method A does not correspond with any dip type according to the classification.

Besides the basic voltage dip characteristics, it is also useful to consider the different dip durations that are possible for different fault locations:

- Dips due to transmission system faults. Both three phase faults and single phase faults should be considered, even though single phase faults are the most likely. Three-phase faults cause dips over a wider area, so that equipment will see a higher percentage of three-phase dips than the percentage of three-phase faults in the system. This especially holds for more severe events. Durations are generally short, which is the basis for the 200 msec test durations in the existing standards.

- Dips due to faults on distribution systems. Many faults on distribution systems turn into two phase or three phase faults, even if they start out as single phase faults. This makes inclusion of three phase faults even more important in the protocol. Also, the fault durations may be longer for distribution events (up to a couple seconds is not unusual).

It is also important for the testing protocol to take into account the characteristics of the equipment being evaluated. This is especially true for three phase devices that may have significantly different immunity characteristics for multiphase dips than for single-phase dips. IEC 61000-4-34 attempts to specify an approach of testing three phase devices with only single phase and phase-to-phase dips. As a result, the recommended test vectors in IEC-61000-4-34 may provide an incomplete and even distorted picture about the equipment immunity. The SEMI F47 and the related test protocol SEMI F42 also address single-phase and phase-to-phase dips. However, the recommended vectors for phase-to-phase testing are representative of two phase-to-ground faults (Method "C" in Figure 2b and in Table 1, Type E in Table 2) and result in more conservative estimates of equipment immunity.

**CONCLUSIONS AND FUTURE WORK**

Industry standards for testing voltage dip immunity provide a starting point for understanding equipment response characteristics. However, real world voltage dips can have characteristics significantly different than the test conditions and additional testing may be required to estimate actual performance in the real world environment.

The main issue in selecting an appropriate set of standard voltage dips for testing is the amount of detail and variations to be included. The more characteristics that are included, the more representative the tests will be of real world conditions. On the other hand, the number of variables quickly becomes unmanageable and compromises must be made. An approach must be developed that provides a realistic set of characteristics so that the practical use of the testing results is not limited.

The amount of detail needed requires two types of studies. At
first statistics are needed on the frequency of occurrence of the different dip types and the values for the different dip characteristics. Less frequent dip types will in general have less need to be included in a testing protocol. But the impact of the dip types and characteristics on equipment performance should also be considered in the decision. Dip types that have a severe impact on equipment should be included, even if they are not very common.

When evaluating electrical equipment that requires three-phase power, it is important to use a voltage dip test methodology that will supply meaningful results and lead to improved system compatibility. The example ASD testing described here illustrated the importance of including multiphase dips when considering the characteristics of some types of three-phase equipment.

REFERENCES