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Fabs can ride through voltage sags with

power-quality targets

OVERVIEW Interruptions and brief disturbances in utility power during semiconductor manufacturing can result in significant loss of revenue, productivity, production yields, and product quality. Concerns about power quality are growing with the movement of wafer fabrication to developing regions, such as China and elsewhere in Asia, which historically suffer from poor infrastructure. Efforts to create highly automated fabs, known as "lights-out factories," are also driving interest in systems that can ride through power glitches without completely shutting down tools or production lines. This article examines how power quality, especially voltage sag events, affects semiconductor manufacturing and how industry standards and guidelines for tool immunity to those events affect the design of power supplies.

The semiconductor industry, recognizing its vulnerability to disturbances in electrical power and voltage sag events, has established several standards to address the responsibility of utilities, wafer-processing facility designers, and chip-equipment manufacturers to prevent the loss of product or deterioration of product quality. These disturbances can influence sensitive processes, leading to equipment malfunction or shutdown, but the SEMI Power Quality and Equipment Ride-Through Task Force has defined specifications for tool immunity to voltage sag events, providing targets for facility and utility systems.

The working definition used for power quality is the faithfulness of the voltage at the point of common coupling to maintain a sinusoidal waveform at rated voltage and frequency. In three-phase systems, the degree to which the phase currents and voltages are balanced must also be included in the notion of power quality [1].

Power-quality problems include harmonic interference, load imbalance, poor voltage regulation, voltage flicker, transient over-voltages, voltage swells and sags, and brownouts, as well as momentary and sustained interruptions. Many indices and measures exist to describe power quality — for example, total harmonic distortion for harmonic interference, and magnitude and duration for voltage sags.

The definition of a voltage sag is a decrease in RMS voltage to between 10% and 90% of nominal voltage for periods from a half cycle up to a minute, whereas a momentary interruption is a decrease in RMS voltage to <10% of nominal voltage [2].

A voltage sag is caused by a fault condition either within the manufacturing facility itself or somewhere on the electric utility grid, in which case it is referred to as a remote fault. Remote faults are the most common cause of voltage sags. In one study, 83% of disruptive voltage sags were traced to remote faults and another 8% were listed as probable only because the exact time of the faults was not absolutely certain [3]. The fault condition is most likely a result of lightning, but may also be caused by wind, contamination of insulators, animals, or accidents [4]. The starting of large motors can also lead to a voltage sag, although sag magnitudes due to motor starts are usually not severe enough to cause equipment malfunction [5].

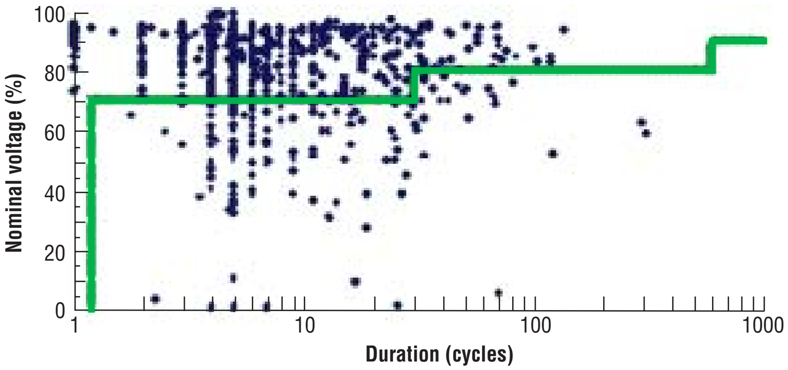

Figure 1. Scatter plot of data from SEMI power-quality survey; the CBEMA 96 curve is overlaid on the plot for reference.

Power-quality surveys

Several major power-quality surveys have been conducted in the last 15 years in an attempt to describe the electrical environment in which electrical and electronic equipment typically operates. It was found that short-duration, shallow sags are the most prevalent events at large US industrial sites [6]. A study conducted by a SEMI task force at 15 global semiconductor sites confirmed the general findings of earlier surveys, which reported on general industry US sites. The voltage sag events recorded during this study are illustrated in Fig. 1. The Computer Business and Equipment Manufacturers

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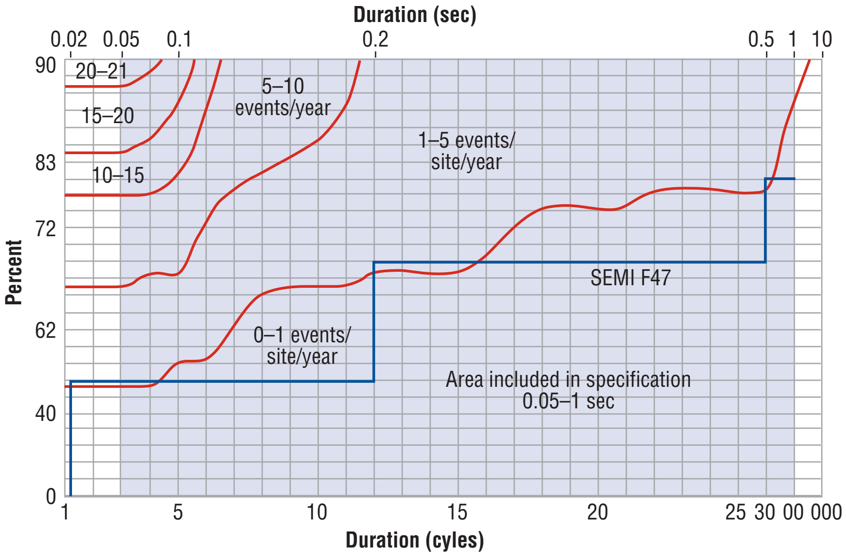

Figure 2. Contour plot of expected number of events/site/year compiled from data from SEMI power-quality survey.

Association (CBEMA) made the first attempt in the late 1970s to determine the appropriate response of computer equipment to voltage sags. The CBEMA 96 curve, updated in 1996, also known as the Information Technology Industry Council (ITIC) curve, is overlaid on the SEMI scatter plot for reference.

It was found that 15% of the recorded events fell below the CBEMA 96 curve and that the average number of events below the CBEMA 96 curve/site/year was 5.4. The expected number of events/site/year is presented as a contour plot in Fig. 2. A second curve, proposed by the SEMI task force and enacted in the SEMI F47 "Specification for Semiconductor Processing Equipment Voltage Sag Immunity" standard, extended the lower end of the CBEMA 96 curve to track the contour line in Fig. 2 that represents an average of one event/site/year. The CBEMA 96 curve applies to single-phase voltage incidents. The SEMI survey found that 68% of voltage sag measurements were triggered by one-phase voltage and another 19% were triggered by two phases [7]. Therefore, in the case of three-phase equipment, the F47 standard applies to two-phase (phase-to-phase) and single-phase (phase-to-neutral) voltage incidents [8].

Industry standards

Utilities are addressed in SEMI F50 "Guide for Electric Utility Voltage Sag Performance for Semiconductor Factories." Semiconductor-factory electrical service involves a number of aspects that are enumerated in F50. These include, but are not limited to, connection to the highest available voltage feeder lines and reduction of system susceptibility to environmental conditions (lightning, trees, accidental damage, etc). The specification identifies the utility as an active and ongoing partner with the semiconductor factory owner.

SEMI F49 "Guide for Semiconductor Factory Systems Voltage Sag Immunity" makes suggestions for industrial-plant electrical distribution design. Recognizing the site-specific nature of plant design, it states, "Facility power systems should be examined on a case-by-case approach…" [9]. However, F49 does offer general guidance, especially relating to distribution redundancy and its effect on service reliability. The specification also offers an enumeration of equipment and techniques used in industrial facilities.

The relevant regulation addressing semiconductor tools is SEMI F47 "Specification for Semiconductor Processing Equipment Voltage Sag Immunity." Figure 2 shows the SEMI F47 voltage dropout curve for single-phase or phase-to-phase voltage sags on three-phase systems. Since the F47 sag characteristic does not include three-phase blackouts as part of its specification, it can be inferred that it describes power system faults that are not directly in line with the power feed to the equipment in question. These remote faults occur either on a different branch of the radial distribution system or on a distant part of the feeding transmission system. This leads to two presumptions: first, the system fault is cleared effectively without interrupting service to the factory with a complete blackout; and second, that all phases are at low source impedance at all times.

Semiconductor process equipment compliant with this standard is expected to ride through voltage sags either without any observable process change, or at the very least, without process interruption. The latter option necessarily admits the potential for loss of product in process at the time of disturbance. Process power supplies are of special interest in this regard because of all process equipment they have the highest power throughput/unit of stored energy. The next section discusses F47-compliant power-supply design.

Solutions for process power supplies

There are a variety of semiconductor process tools that can ride through F47-type events with no interruption at all. However, many power-supply architectures will likely drop output during the event.

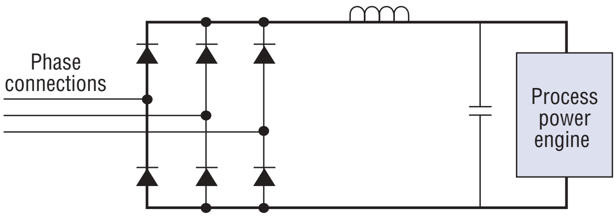

Figure 3. Conventional supply frontend.

A process power supply that could ride through all F47 events would offer significant improvement in reducing loss of product or deterioration in product quality. There are two ways to meet this objective: provide uninterrupted power by drawing energy from the power system suffering from an F47-type event, or draw the necessary energy from a stored reserve. This can be better understood by considering various power-supply frontend design architectures.

The circuit diagram shown in Fig. 3 illustrates the frontend of a conservatively designed power supply. The design allows for high input-power factor (~0.95) and relatively low harmonic injection.

The capacitor, typically sized at several milliFarads, provides a modest amount of stored energy, allowing reasonable ride-through of short-duration sags. Unfortunately, due to the large inductor, typically sized at several milliHenries, supplies like this tend to be large and costly.

Alternatively, many modern architectures eliminate this inductor altogether and reduce the size of the bus capacitor to around several microFarads. Compared to the previous design, this frontend is both smaller and less expensive, and has a slightly lower power factor and higher harmonic content. It does not have enough stored energy to offer any process-power engine ride-through capability for the lower voltage regions of the F47 specification. A tempting solution is to increase the energy storage capability with a larger bus capacitor of several milliFarads. This is relatively inexpensive and only somewhat bulky. It has marginally better ride-through from the process perspective, but has disturbingly poor frontend performance. Depending on the size of the capacitor, the power factor can be thrown below 0.7 with high harmonic content. The lower power factor requires the factory to size the AC distribution system to handle the higher currents.

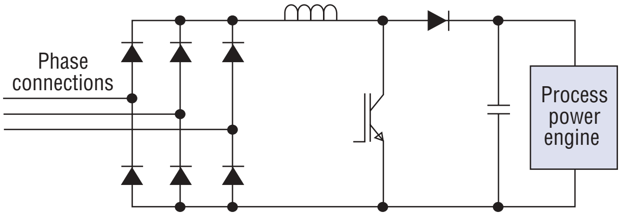

Figure 4. Frontend with boost.

Even this increase in capacitance adds only several hundred Joules at most, and only provides ride-through performance in relatively low-power equipment. To provide ride-through performance for higher-power equipment or entire tools, OEMs and facility designers have resorted to equipment capable of storing much more energy while maintaining constant voltage output, such as uninterruptible power supply (UPS) systems. There are numerous concerns with energy storage devices, however, including cost, safety, and size. While this article will not go into the specifics of batteries, superconducting energy storage, or flywheels, it is assumed that commercially viable options can be made safe. It is also assumed that the costs will be weighed by plant owners against whatever ride-through requirement they feel is justified. The task force that created SEMI F47 stated that "while it is recognized that in certain extreme cases or for specific functions battery storage devices may be appropriate, it is not the intent of this standard to increase the size or use of battery storage devices provided with equipment" [8]. Its original intent was to "focus on improvements in equipment component and system design" [8].

The frontend design examples given point out performance limitations using standard six-pulse diode rectifier designs mated to passive components. None of the previously mentioned examples provide relevant ride-through performance for supplies larger than a few kilowatts without additional energy storage. However, significant performance improvements are possible with the use of pre-regulators. The simplest pre-regulator circuit uses the standard boost topology, illustrated in Fig. 4.

This design pulls up any dips in the unregulated diode rectifier voltage caused by a sagging phase. The power factor and AC harmonic injections are reasonably good by the standards of power supplies. The inductor is much smaller than the series inductor in conventional power supplies (Fig. 3). When combined with the additional components, however, the result is a cost and volume burden that is presently not tolerated in high-quality cleanroom space. Several variations of this approach have been proposed to overcome these limitations [10].

There are some factories that have further extended the requirements for semiconductor equipment response to voltage sags beyond the SEMI F47 curve, requiring the equipment to tolerate a complete dropout of three-phase power for up to a full second. Precluding the use of external stored energy devices, one practical solution for process power supplies is to ensure that the control logic behaves gracefully during the event. That is, the logic should not lose power, latch to a fault state, or fail to resume power-supply operation after the event. This often can be implemented with appropriate digital logic design and without the addition of any stored energy or cost. If this is not the case and something more is required, logic power feeds can be connected to separate, secure sources of input power instead of the three-phase connections providing main power to the supply.

Observations/recommendations

Newer three-phase power-supply design efforts can incorporate the ability to ride through most SEMI F47 events. For voltage sag events outside of those specified by SEMI F47, the power-supply logic should be "awake" during such an event. This will enable the supply to either accurately report such events or even resume operation if the sag event lasted a reasonable amount of time so as to not compromise the safety of the system (i.e., usually <1 sec). Enabling semiconductor equipment to resume operation without human intervention will be a key requirement in highly automated lights-out factories in the future.

It is also useful to investigate potential advances offered by emerging technology. Such an exercise begins with identifying key goals based on technical and economic preferences. Following this, future process power architectures can be designed to meet these goals, which may include providing robust process power with an absolute minimum amount of equipment in high-quality cleanroom space; providing true ride-through for all process power supplies at a reduced cost; placing minimum burden on the power system (minimal harmonics, unity power factor, etc.); providing potential connection of immediate-response, high-energy storage devices; and limiting the use of external sag-correction equipment. Several new emerging technologies that satisfy these criteria are under investigation at Advanced Energy.

Conclusion

The fundamental goal of SEMI F47, F49, and F50 is to create unified design objectives for the construction of a semiconductor factory and its respective tools. The SEMI regulations seek the effective sharing of this responsibility among the parties most likely to solve this problem.

Some industrial facilities have been hardened against outages of any kind such as generating stations (the controls run on batteries) or hospitals. This is necessary to ensure personnel safety or avoid catastrophic equipment damage. Semiconductor factories have not been hardened in a similar manner because there is not a similar, absolute need to do so (hazardous materials are a clear exception to this observation).

As a result, justification of added cost for ride-through equipment becomes one of economic risk assessment — an assessment loaded with a number of highly uncertain variables such as the average outage duration and downtime cost estimates. Given that such justification often occurs after plant construction, operators will likely continue to shoulder most of the burden of interruption problems.

If this situation is to be improved substantially, industry participants will have to decide collectively to debut new technologies and distribution architectures. Even the SEMI task force responsible for these recent standards admitted, "Only the combined efforts will make a difference" [9]. ■

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