VOLTAGE QUALITY:
SAGS AND OTHER ISSUES

THE RELEVANCE OF POWER QUALITY

MAIN VOLTAGE QUALITY PROBLEMS

- Harmonic voltage
- Frequency variations
- Transient overvoltage (spike)
- Voltage interruptions
- Voltage Swell
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THE RELEVANCE OF POWER QUALITY

Modern industry is becoming more automated and the sensitivity of processes to power quality events is increasing.

It is generally recognized that quality is an important aspect of the electricity service. Not only low prices are important, also high-quality matters to customers.

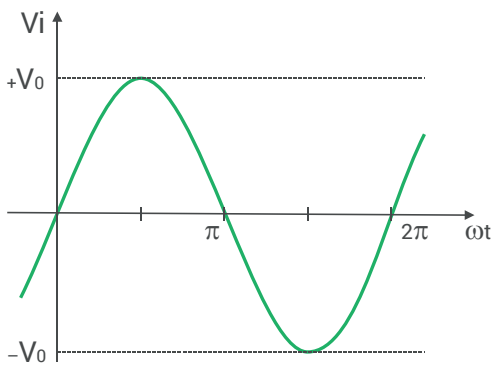
Price and quality are often complementary aspects; together they define the value that customers derive from consuming electricity.

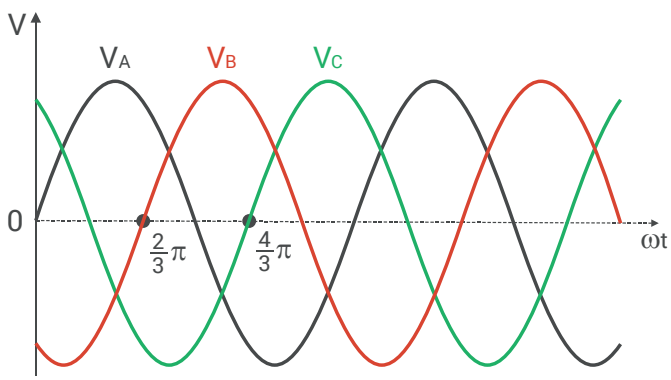
Companies are more and more sensitive to Power Quality issues because they can cause troubles and damages to equipment, up to interrupting the production cycle.

Examples costs of poor power quality are:

- Costs for unproductive personnel due to the discontinuity of the production cycle.
- Costs for raw materials scrap.
- Costs for incomplete or wasted work.
- Costs for damage and/or malfunction of machinery (reparation, temporary renting).
- Penalties caused by contractual shortcomings.
- Sanctions for damage to the environment.
- Increase in general insurance costs.

Three-phase voltage from the power supply network should ideally be balanced, symmetrical, sinusoidal, with constant frequency and RMS.



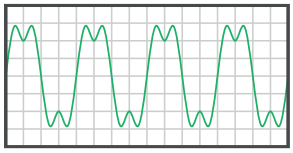


In practice the voltage is never perfect.

According to EN50160 standard the voltage problems can be different.

MAIN VOLTAGE QUALITY PROBLEMS

Harmonic voltage



Sinusoidal voltage with a frequency equal to an integer multiple of the fundamental frequency of the supply voltage. Harmonic voltages can be evaluated:

- individually by their relative amplitude (u_h) which is the harmonic voltage related to the fundamental voltage u_1, where h is the order of the harmonic;
- globally, for example by the total harmonic distortion factor THD, calculated using the following expression:

$$THD = \sqrt{\sum_{h=2}^{40} (u_h)^2}$$

Harmonics of the supply voltage are caused mainly by network users' non-linear loads connected to all voltage levels of the supply network. Harmonic currents flowing through the network impedance give rise to harmonic voltages. Harmonic currents and network impedances and thus the harmonic voltages at the supply terminals vary in time.

Under normal operating conditions, during each period of one week, 95 % of the 10 min mean r.m.s. values of each individual harmonic voltage shall be less than or equal to the values given in the following table. Resonances may cause higher voltages for an individual harmonic.

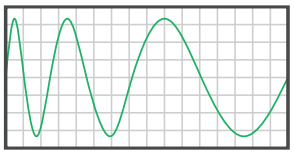
Moreover, the THD of the supply voltage (including all harmonics up to the order 40) shall be less than or equal to 8%.

Values of individual harmonic voltages at the supply terminals for orders up to 25 given in percent of the fundamental voltage u1.

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order [h]	Relative amplitude [uh]	Order [h]	Relative amplitude [uh]	Order [h]	Relative amplitude [uh]
5	6,0%	3	5,0%	2	2,0%
7	5,0%	9	1,5%	4	1,0%
11	3,5%	15	0,5%	6...24	0,5%
13	3,0%	21	0,5%		
17	2,0%				
19	1,5%				
23	1,5%				
25	1,5%				

No values are given for harmonics of order higher than 25, as they are usually small, but largely unpredictable due to resonance effects.

Frequency variations



The nominal frequency of the supply voltage shall be 50 Hz. Under normal operating conditions the mean value of the fundamental frequency measured over 10 s shall be within a range of:

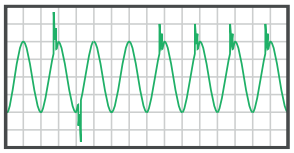
- for systems with synchronous connection to an interconnected system:

  50 Hz ± 1 % (i.e. 49,5 Hz... 50,5 Hz) during 99,5 % of a year;
  50 Hz + 4 % / - 6 % (i.e. 47 Hz... 52 Hz) during 100 % of the time;

- for systems with no synchronous connection to an interconnected system (e.g. supply systems on certain islands):

  50 Hz ± 2 % (i.e. 49 Hz... 51 Hz) during 95 % of a week;
  50 Hz ± 15 % (i.e. 42,5 Hz... 57,5 Hz) during 100 % of the time.

Transient overvoltage (spike)

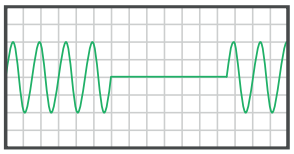


Transient overvoltage at the supply terminals are generally caused by lightning (induced overvoltage) or by switching in the system.

The rise time can cover a wide range from milliseconds down to much less than a microsecond. However, for physical reasons, transients of longer durations usually have much lower amplitudes. Therefore, the coincidence of a high amplitude and a long rise time is extremely unlikely.

The energy content of a transient overvoltage varies considerably according to the origin. An induced overvoltage due to lightning generally has a higher amplitude but lower energy content than an overvoltage caused by switching, because of the generally longer duration of such switching overvoltages.

Voltage interruptions



Condition in which the voltage at the supply terminals is lower than 5 % of the reference voltage.

Classification: a supply interruption can be classified as:

a) prearranged, when network users are informed in advance;

b) accidental, caused by permanent or transient faults, mostly related to external events, equipment failures or interference. An accidental interruption is classified as:

   1) a long interruption (longer than 3 min);
   2) a short interruption (up to and including 3 min).

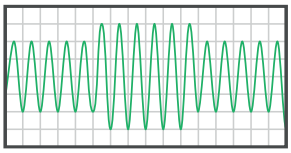
Normally, interruptions are caused by the operation of switches or protective devices. The effect of a prearranged interruption can be minimized by network users by taking appropriate measures.

Prearranged interruptions are typically due to the execution of scheduled works on the electricity network.

Accidental supply interruptions are unpredictable, largely random events.

For polyphase systems, an interruption occurs when the voltage falls below 5 % of the reference voltage on all phases (otherwise, it is considered to be a dip).

Voltage Swell



Temporary increase of the r.m.s. voltage at a point in the electrical supply system above a specified start threshold.

According to EN50160 standard, the swell start threshold is equal to the 110 % of the reference voltage, a voltage swell is a two dimensional electromagnetic disturbance, the level of which is determined by both voltage and time (duration).

Voltage swells may appear between live conductors or between live conductors and earth. Depending on the neutral arrangement, faults to ground may also give rise to overvoltages between healthy phases and neutral.

Voltage swell duration: time between the instant at which the r.m.s. voltage at a particular point of an electricity supply system exceeds the start threshold and the instant at which it falls below the end threshold. According to EN50160 standard the duration of a voltage swell is from 10 ms up to and including 1 min.

Voltage swell end threshold: r.m.s. value of the voltage on an electricity supply system specified for the purpose of defining the end of a voltage swell.

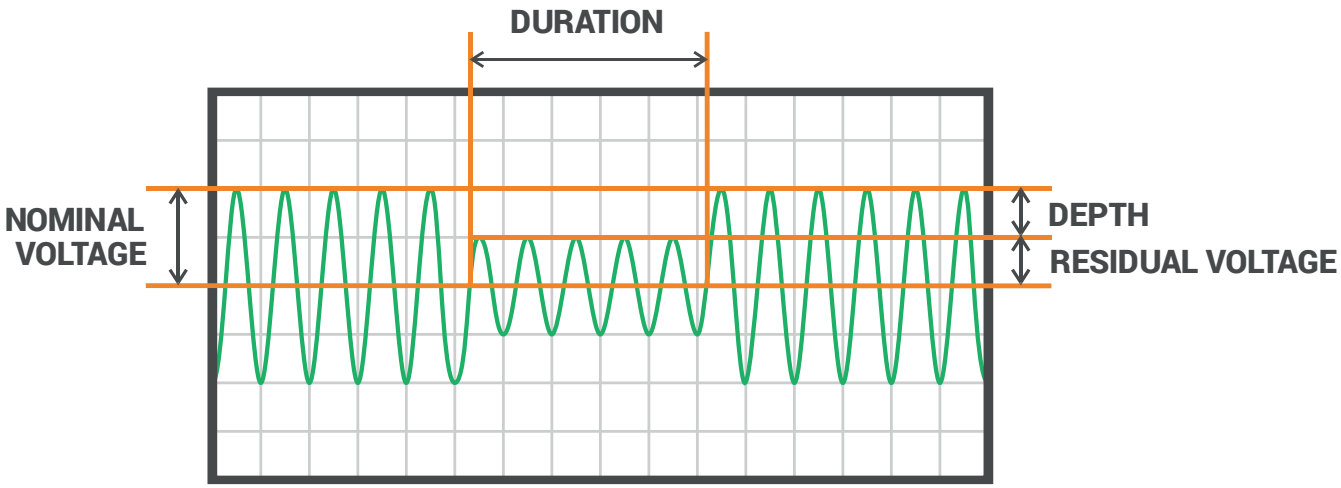
Voltage swell start threshold: r.m.s. value of the voltage on an electricity supply system specified for the purpose of defining the start of a voltage swell.

If statistics are collected, voltage swells shall be classified according to the following table.

Classification of swells according to maximum voltage and duration.

Swell voltage u [%]	Duration t [ms]		
	10 ≤ t ≤500	500 ≤ t ≤5000	5000 ≤ t ≤60000
u ≥ 120	CELL S1	CELL S2	CELL S3
120 > u > 110	CELL T1	CELL T2	CELL T3

Voltage sags or dips



Temporary reduction of the r.m.s. voltage at a point in the electrical supply system below a specified start threshold.

According to EN50160 the dip start threshold is equal to 90 % of the reference voltage. A dip occurs when the voltage falls until 5 % of the reference voltage on all phases.

Also the IEEE Standard 1159-20031 defines categories and typical characteristics for electromagnetic phenomena. By the IEEE 1159 definition, all voltage sags are short-duration variations. A short-duration variation is a variation of the rms value of the voltage from nominal voltage for a time lasting greater than 0.5 cycles of the power frequency but less than or equal to 1 minute.

Typically, a dip is associated with the occurrence and termination of a short circuit or other extreme current increase on the system or installations connected to it.

Voltage dip duration: time between the instant at which the r.m.s. voltage at a particular point of an electricity supply system falls below the start threshold and the instant at which it rises to the end threshold. Voltage sag duration is considered within 10ms up to 1min. The great deal of Voltage sags have a duration lower than 1 second and a residual voltage higher than 40% of the rated value.

For polyphase events, a dip begins when one voltage falls below the dip start threshold and ends when all voltages are equal to or above the dip end threshold.

Voltage dip end threshold: r.m.s. value of the voltage on an electricity supply system specified for the purpose of defining the end of a voltage dip.

Voltage dip residual voltage: minimum value of r.m.s. voltage recorded during a voltage dip. For the purpose of EN50160, the residual voltage is expressed as a percentage of the reference voltage.

Voltage dip start threshold: r.m.s. value of the voltage on an electricity supply system specified for the purpose of defining the start of a voltage dip.

Voltage dips are typically originated by faults occurring in the public network or in network users' installations. Voltage swells are typically caused by switching operations and load disconnections.

Both phenomena are unpredictable and largely random. The annual frequency varies greatly depending on the type of supply system and on the point of observation. Moreover, the distribution over the year can be very irregular.

The most significant of all PQ phenomena is the voltage sag: experience has shown that the single most potent cause of end user PQ problems is voltage sags. Given the number of these sorts of events documented by EPRI and other organizations, this should come as no surprise.

More than 60% of poor Power Quality costs are consequence of Voltage SAGs. Voltage SAG cost is normally lower than a Voltage Supply Interruption one, but the first is by far more frequent. Troubles increase with sophisticated and electronic appliances.

VOLTAGE SAG MEASUREMENT AND DETECTION

If statistics are collected, voltage dips/swells shall be measured and detected according to EN 61000-4-30, using as reference the nominal supply voltage. The voltage dips/swells characteristics of interest for this standard are residual voltage (maximum r.m.s. voltage for swells) and duration.

On LV networks, for four-wire three phase systems, the line to neutral voltages shall be considered; for three-wire three phase systems the line to line voltages shall be considered; in the case of a single phase connection, the supply voltage (line to line or line to neutral, according to the network user connection) shall be considered.

Typically, on LV networks:

- if a three-phase system is considered, polyphase aggregation shall be applied; polyphase aggregation consists of defining an equivalent event characterized by a single duration and a single residual voltage;
- time aggregation applies; time aggregation consists of defining an equivalent event in the case of multiple successive events; the method used for the aggregation of multiple events can be set according to the final use of data; some reference rules are given in IEC/TR 61000-2-8.

If statistics are collected, voltage dips shall be classified according to the table below:

Classification of sags according to residual voltage and duration.

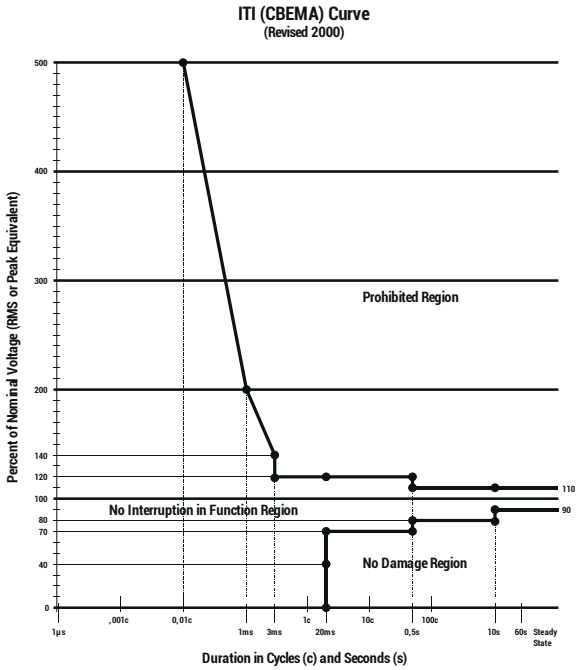
Residual voltage u [%]	Duration t [ms]				
	10 ≤ t ≤200	200 ≤ t ≤ 500	500 ≤ t ≤ 1000	1000 ≤ t ≤ 5000	5000 ≤ t ≤ 60000
90 > u ≥ 80	CELL A1	CELL A2	CELL A3	CELL A4	CELL A5
80 > u ≥ 70	CELL B1	CELL B2	CELL B3	CELL B4	CELL B5
70 > u ≥ 40	CELL C1	CELL C2	CELL C3	CELL C4	CELL C5
40 > u ≥ 5	CELL D1	CELL D2	CELL D3	CELL D4	CELL D5
5 > u	CELL X1	CELL X2	CELL X3	CELL X4	CELL X5

Cells A1, B1, A2, B2 for class 2;
Cells A1, B1, C1, A2, B2, A3, A4 for class 3.
Classes 2 and 3 defined by EN 61000-4-11 and EN 61000-4-34.

EQUIPMENT IMMUNITY TO SAGS

A number of simplified methods have been developed to index voltage sags.

Curve developed by **ITIC** (Information Technology Industry Council) and **CBEMA** (Computer and Business Equipment Manufacturers' Association) allows to understand the capabilities and limitations of computers and business equipment and their voltage stability requirements.



Troubles come above 110% of nominal voltage and starting from 0,5 sec (CBEMA).

The IEEE 1564 recommends that the **SEMI F47** curve be used. SEMI, the industry association for the semiconductor industry, has developed the SEMI F47 voltage sag immunity standard. SEMI F47 is important because semiconductor plants require high levels of power quality due to the sensitivity of equipment and process controls, especially semiconductor processing equipment, which is susceptible to voltage sags.

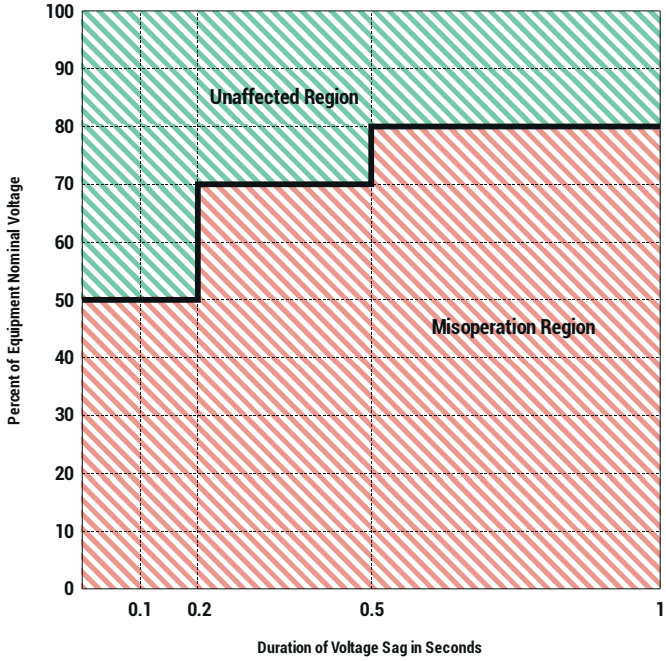
SEMI F47 requires that semiconductor processing equipment tolerate voltage sags connected onto their AC power line. They must tolerate sags to 50% of equipment nominal voltage for duration of up to 200 ms, sags to 70% for up to 0.5 seconds, and sags to 80% for up to 1.0 second. These requirements are defined by values shown in table below:

SEMI F47 Voltage Sag Duration and Percent Deviation from Equipment Nominal Voltage.

Voltage Sag Duration				Voltage Sag
Seconds (s)	Milliseconds (ms)	Cycles at 60Hz	Cycles at 50Hz	Percent (%) of Equipment Nominal Voltage
<0,05 s	<50 ms	<3 cycles	<2,5 cycles	Not specified
0,05 to 0,2 s	50 to 200 ms	3 to 12 cycles	2,5 to 10 cycles	50%
0,2 to 0,5 s	200 to 500 ms	12 to 30 cycles	10 to 25 cycles	70%
0,5 to 1 s	500 to 1000 ms	30 to 60 cycles	25 to 50 cycles	80%
>1,0 s	>1000 ms	>60 cycles	>50 cycles	Not specified

The equipment must be able to continuously operate without interruption during conditions identified in the area above the defined solid black line.

Required Semiconductor Equipment Voltage Sag Ride-Through Capability Curve.

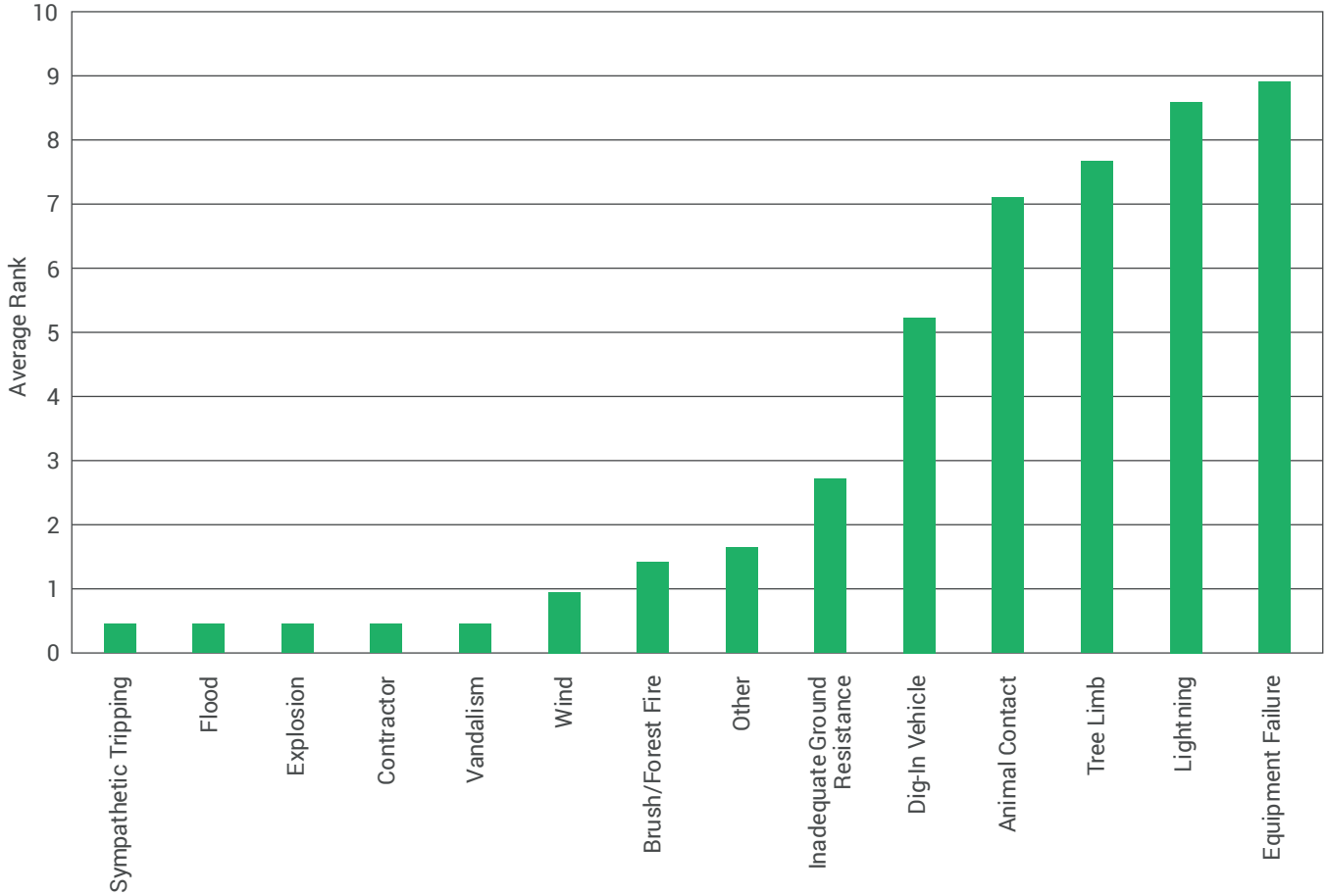


VOLTAGE SAG CAUSES

Voltage SAGs are generally caused by faults in the public network or in the installations of network users, in few cases by transient overloads due to the gearing up of large motors or the switching on of large loads. Faults that result in voltage sags can also occur on the customer-side of the meter.

Faults may occur within transfer switches, transformers, bus ducts, feeder cables, and circuit breakers internal to facilities.

Voltage SAG causes, source EPRI, Electric Power Research Institute.



The voltage SAG propagates from the higher voltage levels to the lower ones, the critical load is often connected to a lower voltage level than the point of failure.

Faults in the network cause deep voltage SAGs if they occur nearby the loads.

According to an Italian CESI study, the probability of voltage SAGs is much greater in the case of an aerial MV network than with underground cables.

IMPACTS ON PROCESSES

The costs of equipment downtime to manufacturing facilities can be high, possibly higher than that associated with financial institutions, data centers, and healthcare facilities. In addition, manufacturing facilities can be sensitive to a wider range of electrical disturbances than just outages that are counted in traditional utility reliability statistics.

Voltage sags that last less than 100 milliseconds (instantaneous sags) can have the same effect on an industrial process as an outage that lasts several minutes.

All of today's processes contain some level of automation, and many are nearly completely automated. Automated processes are linked together via data network systems to ensure that the process timing is controlled. Each part of the process is carried out via a dedicated machine, unique to the process step, and powered by its own dedicated power supply.

Varying immunity to sags and interruptions exists with each power supply. Machine manufacturers specify the power supply of their choice, with each having a differing load level and likely to have a different input voltage range. Moreover, each contains a unique power supply design characteristic of a unique response to sags.

Many of today's manufacturing processes use systems that contain power supplies sensitive to even common shallow voltage sags. Because immunity levels to sags depend upon a number of characteristic power supply factors, a wide range of immunity to sags among the power supplies in a single process is not uncommon. Some processes use power supplies that would fail to meet voltage-tolerance curves such as the ITIC and SEMI F47 curves.

There are several mechanisms by which a voltage sag can interfere with industrial and commercial processes:

- **Control Error**. Loss of control power results in the inability to control the process. This may well be the most pervasive problem, especially among commercial users.
- **Contactor Dropout**. Many industrial controls employ magnetically latched contactors as motor-control devices. A voltage sag can cause a momentary collapse of the magnetic field that holds the contacts closed. When the contacts open, the motor stops.
- **Voltage Flicker**. Flicker is the repetitive variation in intensity of lighting and is more of a human irritation factor than a direct cause of process disruption.
- **Machine Dynamics**. Because voltage magnitude is essential to transmitting power, voltage sags limit the ability of a power system to distribute power from sources to loads. This limitation in power transfer can lead to generators not being able to maintain stability.
- **Stall and Reacceleration**. Motors will stall if the supply voltage is depressed for a prolonged period. This may be a problem if the motor is not properly protected. Furthermore, motors must reaccelerate when normal voltage is restored. Reacceleration involves higher-than normal motor currents, which may result in further voltage-sag problems.

Bibliography

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SEMI F47-0200, Specification for Semiconductor Processing Equipment Voltage Sag Immunity
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CEI EN 50160:2011-05, European Standard