

Power Quality Requirements for Plug-In Electric Vehicle Chargers

RATIONALE

The proliferation of nonlinear loads such as switching power supplies, variable frequency drives and battery chargers have led to a higher level of concern over the impacts of power quality. More precisely there are three major reasons for these concerns:

1. Sensitive microprocessor based devices are more susceptible to power variances.
2. The increased number of non-linear devices has resulted in the rise of harmonics onto the power system leading to reduced system reliability.
3. The vast networkability of devices has led to larger consequences from failure.

Ultimately, the success of widespread plug-in electric vehicle (PEV) charging depends in major part to the reliability of both the electric grid and the charger. To meet the needs of PEV operators, PEV chargers must be sufficiently robust, reliable and cost effective. In order to achieve this goal, vehicle and equipment manufacturers along with electric utility companies must understand the characteristics of the AC service to which the charger will be connected, as well as the impact chargers can have on service quality. The charger is the "conduit" through which energy moves from the AC line to the vehicle's battery. For practical purposes, it is the charger that controls power quality.

FOREWORD

Designers and the vehicle manufactures that implement PEV battery chargers must understand the characteristics of the AC service to which the equipment will be connected if they are to develop products that are sufficiently robust, reliable and cost effective to satisfy the needs of the PEV owner. The charger designer and vehicle manufacturer must also understand that the battery charger can have a significant impact on the quality of the AC service to which it is connected. The information presented in this Recommended Practice may be used by charger power supply designers, managers of charger development programs, and an electric utility.

NOTE: This SAE Recommended Practice is intended as a standard practice and is subject to change to keep pace with experience and technical advances

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1. SCOPE

The intent of this document is to develop a recommended practice for PEV chargers, whether on-board or off-board the vehicle, that will enable equipment manufacturers, vehicle manufacturers, electric utilities and others to make reasonable design decisions regarding power quality. The three main purposes are as follows:

1. To identify those parameters of PEV battery charger that must be controlled in order to preserve the quality of the AC service.
2. To identify those characteristics of the AC service that may significantly impact the performance of the charger.
3. To identify values for power quality, susceptibility and power control parameters which are based on current U.S. and international standards. These values should be technically feasible and cost effective to implement into PEV battery chargers.

SAE J2894/2 Power Quality Requirements for Plug-In Electric Vehicle Chargers – Test Methods will describe the test methods for the parameters / requirements in this document.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

- | | |
|-------------|---|
| SAE J1772 | Standard for Electrical Connectors for Electric Vehicles |
| SAE J1773 | Electric Vehicle Inductively Coupled Charging |
| SAE J2293 | Energy Transfer System for Electric Vehicle |
| SAE J2847 | Communication between Plug-In Vehicles and the Utility Grid |
| SAE J2894/2 | Power Quality Requirements for Plug In Vehicle Chargers |

2.1.2 IEEE Publications

Available from IEEE Operations Center, 445 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org

- | | |
|-------------|--|
| IEEE 519 | Harmonic Specifications |
| IEEE 1159 | Recommended Practice for Monitoring Electric Power Quality |
| IEEE 1547 | Standard for Interconnecting Distributed Resources with Electric Power Systems |
| IEEE 2030.1 | Draft Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and End-Use Applications and Loads |

2.1.3 International Electrotechnical Commission Publications

Available from IEC, 3 rue de Varembe, PO Box 131, CH – 1211 Geneva 20 – Switzerland, Tel: 41-22-919-02-11, www.iec.ch

IEC 1000-3-2 Standards for Equipment for Low Voltage Appliances Absorbing Currents Under 16A

IEC 1000-3-4 Standards for Equipment for Low Voltage Appliances or Installations Absorbing Currents Exceeding 16A

2.1.4 ANSI Publications

Available from American National Standards Institute, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

ANSI C62.41 Recommended Practice for Surge Voltages in Lower-Voltage AC Power Circuits

ANSI C62.45 Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits

ANSI C84.1 Electric Power Systems and Equipment – Voltage Ratings (60 Hz)

2.1.5 Underwriters Laboratories Inc. Publications

Available from Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062-2096, Tel: 1-847-272-8800, www.ul.com

UL 1741 Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources

2.1.6 National Electrical Manufacturers Association Publications

Available from NEMA, 1300 North 17th Street Suite 1752 Rosslyn, VA 22209, Tel: 1-703-841-3200

National Electrical Code, NFPA 70 Article 625

2.1.7 Japanese Electric Vehicle Standard Publications

JEVS G 101 Electric Car Vehicle Conductive Charging System

3. DEFINITIONS

3.1 AC LEVEL 1 CHARGING

A method that allows a plug-in electric vehicle (Battery Electric Vehicle (BEV) or Plug-In Hybrid Electric Vehicle (PHEV)) to be connected to the most common grounded electrical receptacles (NEMA 5-15R and NEMA 5-20R). The vehicle shall be fitted with an on-board charger capable of accepting energy from the existing single phase alternating current (AC) supply network. The maximum power supplied for AC Level 1 charging shall conform to the values in Table 1 of SAE J1772™. A cord and plug EVSE with a NEMA 5-15P plug may be used with a NEMA 5-20R receptacle. A cord and plug EVSE with a NEMA 5-20P plug is not compatible with a NEMA 5-15R receptacle.

3.2 AC LEVEL 2 CHARGING

A method that uses dedicated AC BEV or PHEV supply equipment in either private or public locations. The vehicle shall be fitted with an on-board charger capable of accepting energy from single phase alternating current (AC) electric vehicle supply equipment. The maximum power supplied for AC Level 2 charging shall conform to the values in Table 1 for SAE J1772™.

3.3 CHARGER

An electrical device that converts alternating current energy to regulated direct current for replenishing the energy of an energy storage device (i.e., battery) and may also provide energy for operating other vehicle electrical systems. A charger can be on-board or off-board the vehicle.

3.4 CHARGER – ISOLATED

A charger that incorporates galvanic isolation between the AC line and the charger DC output.

3.5 CHARGER – NON ISOLATED

A charger that provides no galvanic isolation between the AC line and the charger DC output.

3.6 CHARGER – INDUCTIVELY COUPLED

A charger where galvanic isolation is provided by the charge coupling which is composed of two components; the vehicle inlet and the coupler. The charge coupling is actually a take-apart transformer, the coupler comprising the transformer primary and the vehicle inlet housing the transformer secondary.

3.7 ON-BOARD CHARGER

A charger located on the vehicle for the purpose of delivering DC energy to the PEV's energy storage device. Typically requires an AC input from an external EVSE.

3.8 OFF-BOARD CHARGER

A charger located externally to vehicle for the purpose of delivering DC energy to the PEV's energy storage device. Typically requires an AC input from the site's electrical infrastructure.

3.9 DC CHARGING

A method that uses a dedicated off-board direct current (DC) BEV or PHEV supply equipment to provide energy from an appropriate off-board charger to the BEV or PHEV in either private or public locations.

3.10 ELECTRIC VEHICLE SUPPLY EQUIPMENT (EVSE)

The conductors, including the ungrounded, grounded, and equipment grounding conductors, the electric vehicle connectors, attachment plugs, and all other fittings, devices, power outlets, or apparatuses installed specifically for the purpose of delivering energy from the premises wiring to the electric vehicle. Charging cords with NEMA 5-15P and NEMA 5-20P attachment plugs are considered EVSEs.

3.11 FREQUENCY VARIATION

The normal range of variation of the AC line frequency.

3.12 MOMENTARY OUTAGE

A complete loss of AC line voltage for a 12 Cycles (200 ms) or more.

3.13 VOLTAGE RANGE

The normal range of variability of the AC line voltage. Voltage Range is generally expressed as a "percent of nominal" of the nominal value of line voltage varies regionally.

3.14 VOLTAGE SAG

A reduction in the AC line voltage below the normal range of variability, typically of relatively short duration, typically 30 to 120 cycles (500 ms to 2000 ms).

3.15 VOLTAGE SURGE (TRANSIENT)

A temporary increase in the AC line voltage far beyond the normal range of variability that is evidenced by a sharp brief discontinuity of the waveform, typically of very short duration (sub-cycle)

3.16 VOLTAGE SWELL

A temporary increase in the AC line voltage of more than 10% of the normal range of variability at the power frequency, typically of relatively short duration of half a cycle to a few s (8ms – 5000ms)

4. CHARGER POWER QUALITY PARAMETERS

4.1 Displacement Power Factor

Total power factor is defined as the ratio of real power in Watts to apparent power in Volt-Amps, and is expressed by the following formula:

Displacement Power Factor = Real Power (kW) / Apparent Power (kVA)

If voltage distortion is negligible, total power factor is equal to the product of displacement power factor and distortion power factor. Displacement power factor, which is the ratio of real power to apparent power at the fundamental frequency (50Hz / 60 Hz), is a measure of the phase shift that occurs between line voltage and line current when the AC line is loaded with a linear load having reactive characteristics, such as an AC motor. The line current is sinusoidal in shape, but either leads or lags the line voltage in phase (Figure 1).

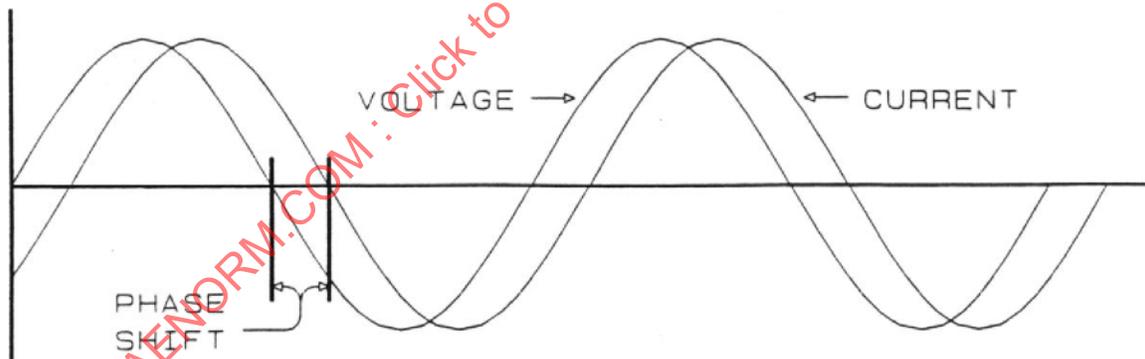


FIGURE 1 - AC LINE VOLTAGE/LINE CURRENT PHASE RELATIONSHIP

Distortion power factor is the ratio of fundamental current to total rms current. The line current distortion is normally the result of non-linear loading of the AC line. Most switching power supplies, except those that incorporate active power factor correction, use full wave bridge rectifiers with capacitive input filters to perform AC to DC conversion from the line (Figure 2). The rectified AC peak charges the input capacitor to produce a DC voltage nearly equal to the peak line voltage. Because the capacitor is peak charged, the diodes in the bridge rectifier are reverse biased for most of the AC sine wave, forward biasing only near the peak of the line voltage where

$V(\text{line})$ exceeds $V(\text{cap}) + 2 \times V(\text{diode})$. The resulting currents are highly distorted from the ideal sine wave, and contain harmonics of the fundamental line frequency.

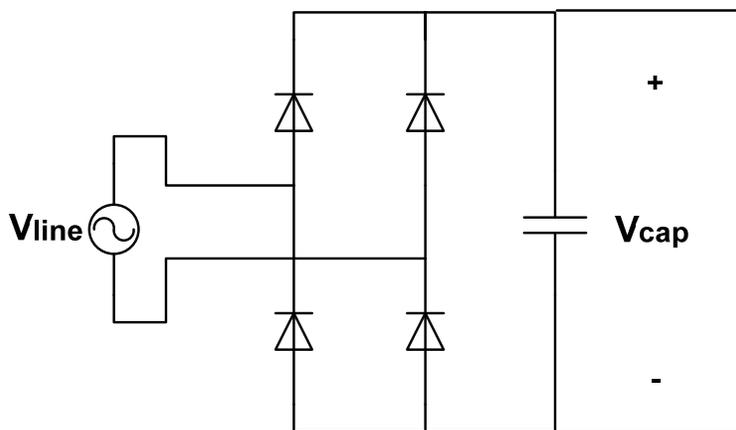


FIGURE 2 – TYPICAL INPUT CIRCUIT

Maintaining a high input power factor is important for two reasons.

- A. Maintaining a high power factor minimizes reactive line current and harmonic currents of the fundamental line frequency. Because available power is limited by available line current which is in turn limited by the circuit breaker protecting the line, minimizing reactive and harmonic currents maximizes the line current which is actually available for true power delivery.
- B. Minimizing reactive and harmonic currents minimizes heating of the AC service conductors for a specified delivered power. This permits optimal utilization of infrastructure and may eliminate the need to perform a service upgrade when EV battery chargers are installed.

The recommended minimum values for total power factor are defined in Table 1 below. These values are specified for operation at the full rated output power of the charger.

Recommended Displacement Power Factor Values		
AC Level 1	AC Level 2	DC
95%	95%	95%

TABLE 1 - MINIMUM RECOMMENDED GUIDELINES FOR TOTAL POWER FACTOR

4.2 4.2 Power Conversion Efficiency

Power conversion efficiency is a measure of how efficiently the charging equipment processes power from its input terminals to its output terminals.

Power conversion efficiency can be measured over the total charging cycle or at any point in the charging cycle. Due to the typical battery charging profile, the charger efficiency will be greatly reduced at the "finishing off" part of the charging cycle, when minimal power is delivered. Efficiency is most important when the charger is delivering maximum power to the load because low power conversion efficiency at full output may constitute a significant power loss.

Power conversion efficiency is defined as a ratio of the charger input power to the charger output power per the following equation:

Power Conversion Efficiency (%) = DC Power (kW) at Charger Output / AC Power (kW) at the Charger Input x 100

Full power efficiency is this ratio measured at the rated full power output of the charger. Because all power processing systems have loss, power efficiency is always less than 100%.

Full power efficiency is important for two reasons.

- A. An efficient charger reduces battery recharge time by optimally accessing energy from the AC line and delivering it to the battery. Since all electric services are current limited (therefore power limited) less wasted power equals greater power delivery to the battery which reduces charge time.
- B. High power conversion efficiency is consistent with the underlying philosophy of emissions reduction. A highly efficient charger reduces the required energy production for a given energy transfer to the vehicle, thereby, reducing the pollutants produced by the energy production process.

Recommended minimum values for power conversion efficiency are specified in Table 2. These values are specified at the full rated power of the charger into a resistive load.

Note: System energy efficiency defines how the system uses the energy that the charger delivers. The charger cannot control how the system uses energy. Therefore, it is not possible to specify system energy efficiency as a controlled parameter for a charger. Conversely, power conversion efficiency does not dictate how the system uses energy. It is a function of the design of the charger and therefore can be specified as a controlled parameter for the charger.

Recommended Full Power Conversion Efficiency		
AC Level 1	AC Level 2	DC
90%	90%	90%

TABLE 2 - MINIMUM RECOMMENDED GUIDELINES FOR FULL POWER CONVERSION EFFICIENCY

4.3 4.3 Total Harmonic Current Distortion

Periodic waveforms can be broken down into component sine waves which are referred to as 'harmonics' of the fundamental wave form. These harmonic frequencies are integer multiples of the fundamental frequency of the periodic wave form. Each harmonic has a specific amplitude and phase with respect to the fundamental. The vector sum of all harmonics produces the original periodic wave form.

If the periodic waveform is a "pure" sinusoid, then only the fundamental frequency is present. There are no harmonics. Any undesired departure from the purely sinusoidal wave shape is referred to as harmonic distortion. Total harmonic distortion (THD) is the root mean square of each individual harmonic distortion.

It is desirable for any current drawn from the AC line to have a fundamental frequency equal to the line frequency (50/60 Hz) with no harmonic distortion. This is because only fundamental current contributes significantly to true power delivery. Harmonic currents do not contribute to true power because the product of the undistorted line voltage and the harmonic currents, averaged over one full cycle of the AC line, is always equal to zero. In short, harmonic currents that flow on the AC line contribute nothing to true power delivery. They simply heat the wire and, in so doing, waste energy.

Harmonic currents can also cause distortion of the AC line voltage. This is dependent on the line impedance ($I \times R$ drops) and the presence of resonances due to the capacitances and inductances in the system. This distortion, if severe enough, may cause other equipment connected to the line to malfunction or even sustain damage.

Institute of Electrical and Electronics Engineers (IEEE) 519 is a guide for utilities on limiting the amount of harmonic voltage and current distortion allowed on their system. The guide specifies that the total harmonic distortion of the voltage waveform for voltages below 69 kV should not exceed 5 percent. In addition, no individual voltage harmonic should exceed 3 percent. This guide also provides for harmonic current limitations for customers at the point of common coupling (where the customer interfaces with other customers on the utility system) based on the ratio of total load current to the available short circuit current. There are specific limits for individual as well as total harmonic currents as a percentage of the total load current. For practical purposes, this guideline is applied only on large nonlinear loads. Since the guideline is based on available short circuit current which varies at each location, it cannot be used as an equipment guideline. It does contain useful information explaining how harmonics are produced and how they effect other equipment. It also contains recommendations for limiting harmonic currents, and thus voltage distortion to safe levels for proper equipment operation.

To minimize the adverse and potentially harmful effects of excessive harmonic current flow on the AC line, it is recommended that the total harmonic current distortion produced by the charger at full rated power as measured into a resistive load be limited per Table 3 below.

Recommended Maximum Total Harmonic Current Distortion		
AC Level 1	AC Level 2	DC
10%	10%	10%

TABLE 3 - RECOMMENDED LIMITS FOR TOTAL HARMONIC CURRENT DISTORTION

4.4 4.4 Current Distortion at Each Harmonic Frequency

The International Electro-technical Commission (IEC) has established absolute limits for harmonic current distortion produced by equipment connected to the AC mains. IEC 555-2 and IEC 61000-3-2 specify maximum permissible harmonic currents at specific harmonic orders for equipment drawing less than 16 amps from the AC line. For equipment drawing more than 16 amps from the line, IEC 61000-3-4 (Technical Report) specifies harmonic current limits as a percentage of the fundamental current.

4.5 Inrush Current

Inrush current is the input current surge that occurs when the charger is connected to the AC line. This current surge is normally the result of input capacitor charging.

The amplitude of the inrush current is determined by the magnitude of the AC line voltage and the resistance in series with the input capacitors. This resistance is the total series resistance of the wiring, contactors, rectifiers, and other components that may be in series with the input capacitors. In general, this resistance is quite low (just a few tens of milliohms). The maximum peak inrush current occurs when the input capacitors are fully discharged and the charger is connected to the AC line at the peak of the line voltage.

The duration of the inrush current surge (with no inrush current limiting) is typically 1/2 cycle of the AC line voltage. After the first half cycle, the input capacitors have been charged to the peak of the AC line voltage. If the battery charger is not yet delivering power to the load, the input capacitors remain peak charged, and draw no current from the line on subsequent half cycles.

It is important to control and limit inrush current for three reasons.

- A. Uncontrolled inrush currents can cause nuisance tripping of branch circuit protection devices such as fuses and/or circuit breakers.
- B. Excessive inrush currents can cause premature failure of any or all components subjected to the inrush, such as contactors, rectifiers and capacitors.
- C. Excessive inrush currents may induce a sufficiently large sag in the AC line voltage to cause a perceptible momentary dimming of lights or a complete extinguishing of lights which are powered from dimmers.

Recommended limits for inrush current are specified in Table 4. These limits are based on limiting the momentary sag in line voltage to 95% of nominal, which will limit a perceptible dimming of lights, based on AC line impedances specified in IEC 555-3. These limits are also sufficiently low to prevent nuisance tripping of branch circuit protection devices, and to prevent premature failure of components subjected to the inrush current.

Recommended Maximum Inrush Current (At Maximum Nominal Current)		
AC Level 1	AC Level 2	DC
120% (in excess of 50ms)	120% (in excess of 100 μ s)	120% (in excess of 100 μ s)

TABLE 4 - RECOMMENDED INRUSH CURRENT LIMITS

5. CHARACTERISTICS OF THE AC SERVICE

Chargers should be designed to tolerate without hazard to equipment or personnel and without nuisance to the customer, the various perturbations of the AC service to which it is connected. These perturbations, which are summarized in Table 6.. Note that the expected ranges of some parameters differ from the formally defined ranges for these same parameters as defined in IEEE 1159.

The values shown in Table 6, are based on actual electric utility service field conditions (Distribution Power Quality - DPQ - EPRI Report #TR-106294 & DPQ-II EPRI Report #TR-1010927). These values cover 90-95% of the voltage and current variations found in the U.S. Electric service (parameters can vary more broadly throughout the rest of the world).

AC Service Limits		
Parameter	AC Level 1	AC Level 2
Voltage Range	90% - 110% of nominal	90% - 110% of nominal
Voltage Swell	175% of nominal for Min. ½ cycle (8 ms)	175% of nominal for Min. ½ cycle (8 ms)
Voltage Surge	6 kV minimum ANSI C62.41 & C62.45	6 kV minimum ANSI C62.41 & C62.45
Voltage Sag	Down to 80% of nominal for 2 s	Down to 80% of nominal for 2 s
Voltage Distortion	5%	5%
Momentary Outage	0 volts for 12 cycles	0 volts for 12 cycles
Frequency Variations	2% of nominal	2% of nominal

TABLE 5 – AC SERVICE LIMITS

NOTES:

5.1 Voltage Range

Voltage range is generally expressed as a "percent of nominal" because the nominal value of line voltage varies regionally. In selecting the recommended values shown in Table 6, the relevant standards included: IEC 718, IEC 146-1-1, ANSI C84.1, and JEVS G 101. The values chosen represent a reasonable average of these four standards.

5.2 Voltage Swell

IEEE 1159 defines the duration of a swell as .5 cycles to 1 min. Based on both the EPRI DPQ & DPQII study and findings of the Computer and Business Equipment Manufacturer's Association (CBEMA), the duration of modest swells can be as long as 1 min. This Recommended Practice is aligned with CBEMA in that the voltage swells of the greatest magnitude typically occur within the first ms of the occurrence.

5.3 Voltage Surge

As indicated in Table 6, the values are as defined in ANSI C62.41 and ANSI C62.45.

5.4 Voltage Sag

Studies have shown that sags are responsible for more than 80% of the power quality events experienced on a utility distribution system. Sags have a number of potential sources. Typically they are the result of remote line faults such as lightning, weather, animal interference, etc. Based on both IEC 718 and IEC 146-1-1, these values address sags of one s and 30 cycles respectively. Based on actual field data (EPRI DPQ & DPQII study), these values must cover a sag of up to two (2) s.

5.5 Voltage Distortion

Voltage Distortion is any deviation from the nominal sine waveform of the input AC line voltage. IEEE 519-1992 limits the voltage distortion at the point of common coupling (PCC) to 5% and hence why we used this value in table 6 above.

5.6 Momentary Outage

IEEE 1159 defines the duration of a momentary outage as 3 s to 1 min. Because of the unique characteristics of PEV battery chargers, this document defines a restart procedure for chargers which "go down" after an outage greater than 12 cycles in duration (see Cold Load Pickup Restart Procedure in the next section). For this reason, a momentary outage in this document is defined as zero (0) volts for 12 cycles or less. If a charger designer chooses not to keep control functions active during the momentary outage (ride through), it is recommended that the Cold Load Pick-Up Restart procedure be used whenever AC power is restored.

5.7 Frequency Variation

Frequency variation is generally expressed as a "percent of nominal". Three relevant international standards were reviewed, (IEC 718, IEC 146-1-1, and JEVS G101) and found values of $\pm 1\%$ to $\pm 5\%$. Although somewhat more restrictive than the JEVS standard, this document recommends $\pm 2\%$ to align with the IEC 718, IEC 146-1-1, and JEVS G101.

5.8 Portable (Self) Generation / Distributed Energy Resources

It is likely that over the life of a PEV battery charger an attempt will be made to power it from portable generating equipment (including but not limited to gasoline generator, photovoltaic systems or wind generation units). An extended loss of AC service at an EV owner's residence is a much greater problem than that at a PEV owner's residence. Therefore, some owners may choose to install portable generating equipment at their residences to facilitate vehicle charging during power outages or as an extension of the home energy management system. It is important, then, that designers of PEV battery chargers understand the characteristics and limitations of portable generating equipment to ensure that the charger will operate properly if it is intended to be connected to portable generation equipment.

Generally, the AC voltage produced by generators is not as well regulated as the utility provided AC line voltage, which is typically of relatively low impedance. In portable generators, voltage regulation is typically accomplished by an electro-mechanical control system. The response of this voltage regulation system is normally not fast enough to regulate the AC output voltage when sudden load changes occur. Transient load regulation is primarily a function of the rotational inertia of the rotating components. If the load change is small compared to the kinetic energy of the rotating mass, then the generator output voltage may stay within acceptable limits of regulation while the control loop is catching up with the load change. However, if the load change is large compared to the kinetic energy of the rotating mass, then one can expect that the generator output voltage will either sag or swell considerably before the control loop can regain control of the output voltage.

This Recommended Practice addresses sag and swell of the AC line voltage, and they are clearly not unique to portable generators. A key difference, though, is that a PEV battery charger represents a relatively small load to the power distribution grid, and the normal sags and swells of the utility supplied AC voltage are not the result of a single battery charger load. Sudden loading of the AC line with a PEV battery charger will not cause the line voltage to sag excessively. Conversely, the sudden removal of a charger load will not cause a line voltage surge.

The characteristics of the power distribution grid are not applicable to portable generating equipment. As an example a 6 kW charger constitutes a significant load to a 10 kVA generator. Sudden loading of the generator output with a 6 kW load will cause excessive voltage sag which, if severe enough, may cause the charger to shut down as soon as it attempts to start up (particularly if the charger has AC line under-voltage lockout protection). This effect is exacerbated by the fact that many PEV battery chargers are constant power devices. As the line voltage sags, line current increases to maintain a constant power level, leading to a more severe line voltage sag. It is left to the vehicle manufacturer to determine the requirements for portable generating equipment not attached to the electric power grid.