By Anuradha Rao and Jon Marshall, Curtis Instruments Inc

PROVIDING POWER FOR ELECTRIC VEHICLES FOR WORLDWIDE USE REQUIRES KNOWLEDGE OF ENERGY-CONSERVING AND HIGH-EFFICIENCY TECHNOLOGIES. DESIGNING PRODUCTS WITH A HIGH POWER FACTOR AND EFFICIENCY IMPROVES POWER QUALITY AND CONFORMS TO EXISTING OUTLET POWER LIMITS.

Optimizing high-frequency battery-charger performance for worldwide applications

Manufacturers of power-conversion products are responding to the increasingly stiffer requirements in power quality and performance that the standards originating with EU (European Union) agencies prescribe. These standards address the susceptibility of ac electrical-distribution circuits to equipment damage and line interference due to harmonic distortion. Power factor, which is the ratio of the working (active) power to total kilovolt amperes, is a measure of the variation from the precise relationship of current and voltage waveforms. It is the focus of methods for controlling harmonic distortion. Failing to maintain a power factor of an established limit perpetuates compromised efficiency and productivity of both power-distribution systems and consumer equipment. Using power-factor correction with high efficiency, manufacturers are optimizing the output power for a given source current. A worldwide concern for limiting pollution and for energy consumption elevates the issue of harmonic distortion to a level worthy of the attention of all design, manufacturing, engineering, and management staff.

The makers of battery-charging systems for electric vehicles and for use in the telecommunications and information technology fields are also responding to the new standards by identifying the relevant design and manufacturing issues of products that meet the new standards. Designers of battery-charging systems need to address the issues of power factors, product-package sizing, and thermal management.

Power-quality problems result from the use of inductive loads or of solid-state devices that lack filtration. Spurious harmonics in the distribution system can put capacitor banks, motors, and transformers at risk. Protective relays and fuses can fail. Reactive line interference can disrupt communications circuits, consumer computers, and other powered systems.

TABLE 1–MAXIMUM HARMONIC CURRENT LIMITS PERMITTED BY EN 61000-3-2 FOR CLASS D EQUIPMENT

Harmonic order (n)	Maximum permissible harmonic current per watt (mA/W)	Maximum permissible harmonic current (A)
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
13	0.30	0.21
15<n<39 odd harmonic only	3.85/n	0.15×15/n

Harmonic distortion increases the kind of power losses in distribution circuits that result in significant increases in energy and operating costs. Power companies address the problem through the utility bills of larger industrial customers with penalties for low power factors. Utility bills may reflect an increase in cost—sometimes as part of the peak demand charge—for a low power factor of typically less than 85 or 90%. Maintaining a high power factor avoids the added charges and prevents the destructive impact of harmonic distortion. It's best to eliminate harmonic distortion at its source by modifying equipment or by installing filtering equipment that blocks the distortion's path to the distribution system.

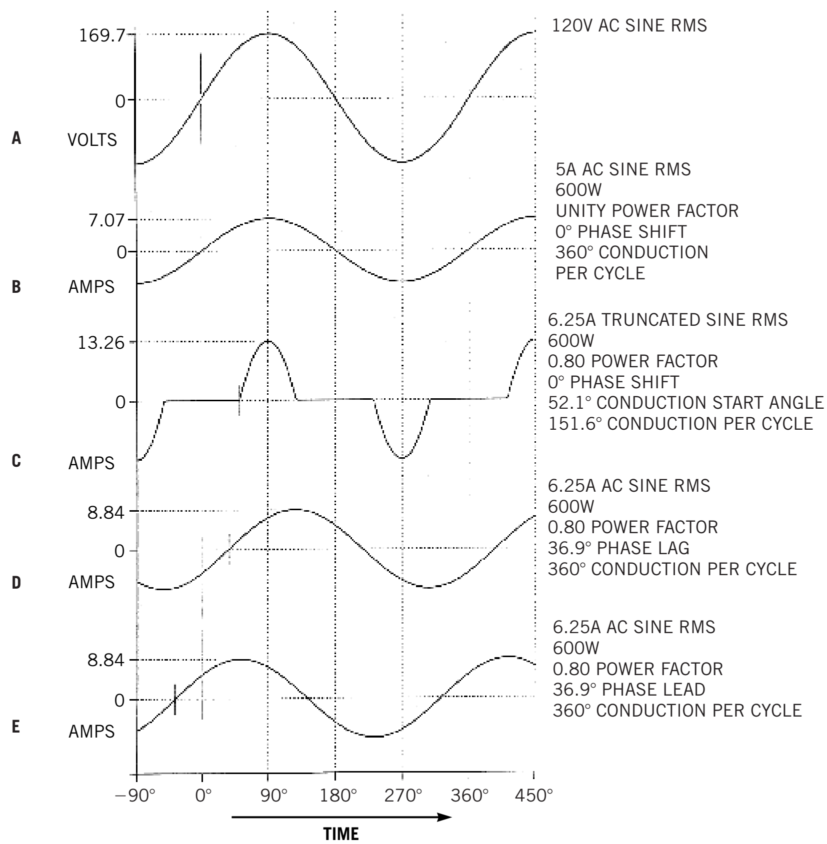
CONSIDER THE PRIMARY ISSUES

For a state-of-the-art battery-charger design, you need to address the issues that pertain to battery-charger performance, physical construction, and thermal management. These issues are load-related power-factor characteristics and problems; power-outlet ratings and available worldwide input current; power-factor-correction effects, especially on outlet current and power limits; outlet rating-based output-power limits for determining onboard and offboard charging; charger efficiency and power-density effects in defining the package, especially integrated battery/charger packs; and onboard-charger thermal management.

For those untutored in the problems of power-system pollution, a concise history and explanation of power factor and harmonic distortion is useful. In an ideal ac power system, a current waveform lags behind a voltage waveform precisely with respect to shape, proportion, and time. This ideal situation can occur only when the load is purely resistive or you synthesize it to appear so and when the load remains connected throughout the waveform cycle.

In the early years of electric power, industrial systems were relatively simple circuits for lights, basic motors, and other resistive equipment. With the development of more complex electrically powered equipment incorporating electrically active components reliant on capacitive and inductive characteristics

Figure 1



Traces A and B show the ideal relationship between voltage and current. Unfortunately, different loads cause the current waveform to stray from the ideal, as traces C, D, and E show.

TABLE 2–OUTLET VOLTAGE AND CURRENT RATINGS FOR MAJOR COUNTRIES

Country	Voltage (V)	Current (A)	Number of phases	Frequency (Hz)
United States/Canada	120	15	one	60
	230	20	one	60
	208	30	three	60
Europe	230	10	one	50
	230	13	one	50
	440	25	three	50
India	220	6	one	50
	220	12	one	50
	440	20	three	50
China	220	6	one	50
	220	13	one	50
Africa	240	6	one	50
	240	13	one	50
Australia	240	6	one	50
	240	13	one	50
Japan	100	15	one	50
	200	20	three	50

came the recognition and study of power factor and harmonic distortion. Unlike purely resistive loads, inductive and capacitive loads cause the current to shift phase relative to the voltage. In the case of an inductive load, the current waveform lags behind the voltage waveform; capacitive loads cause the current to lead the voltage.

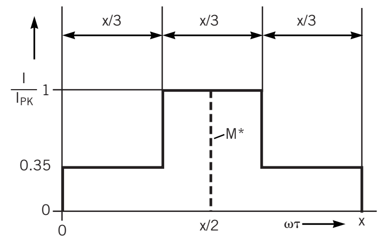
The waveforms in **Figure 1** illustrate good and bad power-factor conditions. **Trace A**, at the top of the **figure**, is the voltage common to the current waveforms below. **Trace B** is an ideal current, in phase, with a 1.0 power factor and delivering peak current of 7.07A. The waveforms in **traces C**, **D**, and **E** result in poor power factors of 0.80. **Trace C** shows how switch-mode equipment can create very high-peak currents—13.26A in this case—even though the waveform is in phase with the voltage. **Trace D** show a lagging current, and **Trace E** shows a leading current, each resulting in high peak current of 8.84A.

The mathematical definition of power factor is the ratio of real power to apparent power. If real and apparent power are equal, the power factor is 1. Battery chargers that use switching techniques draw discontinuous current and, thus, have low power factor and high harmonic distortion. The mathematical equation for the precise relationship of current and voltage waveforms is as follows:

$$\frac{\text{"REAL" POWER}}{\text{"APPARENT" POWER}} = \frac{\frac{1}{2\pi}\int_0^{2\pi} ei(\omega t)d\omega t}{\sqrt{\frac{1}{2\pi}\int_0^{2\pi} e^2(\omega t)d\omega t} \bullet \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i^2(\omega t)d\omega t}}.$$

The practical problems that arise when the power factor is significantly below 1.00 are:

- The rms current or effective current rises for any given delivered real power.
- The peak current during the cycle rises disproportionately higher for any delivered real power resulting in overdesigned and expensive systems.
- Excessive harmonic distortion on power lines from equipment with poor power factor results in damage to other equipment connected to the same line.



*COINCIDES WITH PEAK VALUE OF INPUT CURRENT

Figure 2

For Class D products with an active input power of 75W or more, the EN 61000-3-2 standard requires that the ac-line input-current waveform fall within this waveform's template's window more than 95% of the time.

Industrial consumers who are monitored by utilities pay higher electrical surcharges for low power factor.

Agencies of the EU issue directives regarding power-factor correction and the control of harmonic distortion. The EU adopts standards formulated by the IEC (International Electrotechnical Commission) as EN-61000-3-2. This standard specifies harmonic-distortion limits for equipment in four categories:

- Class A: three-phase equipment;
- Class B: portable tools;
- Class C: lighting equipment; and
- Class D: all other equipment.

Industrial battery chargers fall into the Class D category. EN-61000-3-2 includes a waveform template (**Figure 2**). For Class D products with an active input power of 75W or more, the standard requires that the ac-line input current waveform fall within the template's window more than 95% of the time. **Table 1** gives the maximum permissible harmonic current for odd harmonics to comply with EN-61000-3-2 Class D equipment.

Methods for correcting low power factor and affecting protection at the distribution-system level (and that add to the cost of the power system) include adding a capacitor bank to obtain a leading power factor, using an isolation transformer with high-pulse rectification, and using separate supplies for high distortion-causing equipment. These methods, however, correct only the effect of poor power factor and don't solve the root of the problem.

CORRECT FOR HARMONICS AT THE SOURCE

The best way to reduce harmonics is to correct for them at the source or in the equipment. You can use passive or active correction. The passive power-factor-correction method incorporates added capacitors and inductors in the front end of chargers for current smoothing. However, the required line-frequency inductors and capacitors are cumbersome, creating an extra-weight issue for onboard chargers. The active method incorporates a power-factor-correction stage that creates a voltage reference from the line and forces the switching device's current to follow the reference. The result is a sine-wave emulation with a power factor greater than 0.99 and a harmonic distortion lower than 3%.

In the United States, the power grid is larger than in other countries, so requirements are a bit less stringent. However, a limit exists on the amount of harmonic distortion a consumer can inject

TABLE 3—ONBOARD/OFFBOARD CHARGING DETERMINATION BASED ON OUTLET-POWER OUTPUT LIMITS

Vehicle type	Output power (W)	Outlet rating (A)	Onboard/offboard charger (A at V)
Bicycles	100 to 125	1	Onboard
Durable-medical-equipment scooters	125 to 250	2	Onboard
Sweeper/scrubbers	250 to 350	3 to 4	Onboard
Material-handling systems	500 to 750	5 maximum at 230 10 maximum at 120	Onboard Onboard
Golf/baggage handlers	750 to 1100	15 maximum at 120	Onboard/offboard
Fork-lift trucks	1000 to 2200	20 maximum	Offboard

back into the system in relationship to peak demand. The lower the harmonic distortion, the higher the peak demand that a consumer can make. Harmonics clearly affect facilities planning and operation. Pole-transformer heating due to harmonic distortion also limits the consumer. Circulating currents increase the temperature of the equipment that connects consumers to the utility. The harmonic current cannot exceed 5% of the transformer's rated current.

KNOW OUTLET RATINGS AND INPUT CURRENTS

A global economy and trade necessitate designing a product suitable for different national standards and requirements, which particularly influences the power levels and construction details of the product. **Table 2** provides the voltage and current ratings of outlets in different parts of the world. Also, knowing a country's outlet ratings helps to determine the power limits and to decide whether a vehicle will have an onboard or offboard battery charger (**Table 3**).

The effect of power-factor correction with respect to outlet rating translates to an economic and performance constraint. Typical 120V circuits provide a 15 or 20A rms current capacity with a resistive load or a power factor-corrected load. The resultant power level is V×I×PF=1800W, or 2400W maximum at nominal 120V. Safety agencies limit the design of any single load to 80% of the intended circuit maximum. **Table 4** shows the power output with a unity power factor. **Table 5** shows the effect of a low power factor of 0.66 on the power output and the effect of varying levels of efficiency on the power output. **Figures 3a**, **3b**, and **3c** graphically illustrate the data from **Tables 4** and **5.** You can see that without power-factor correction, available power is limited.

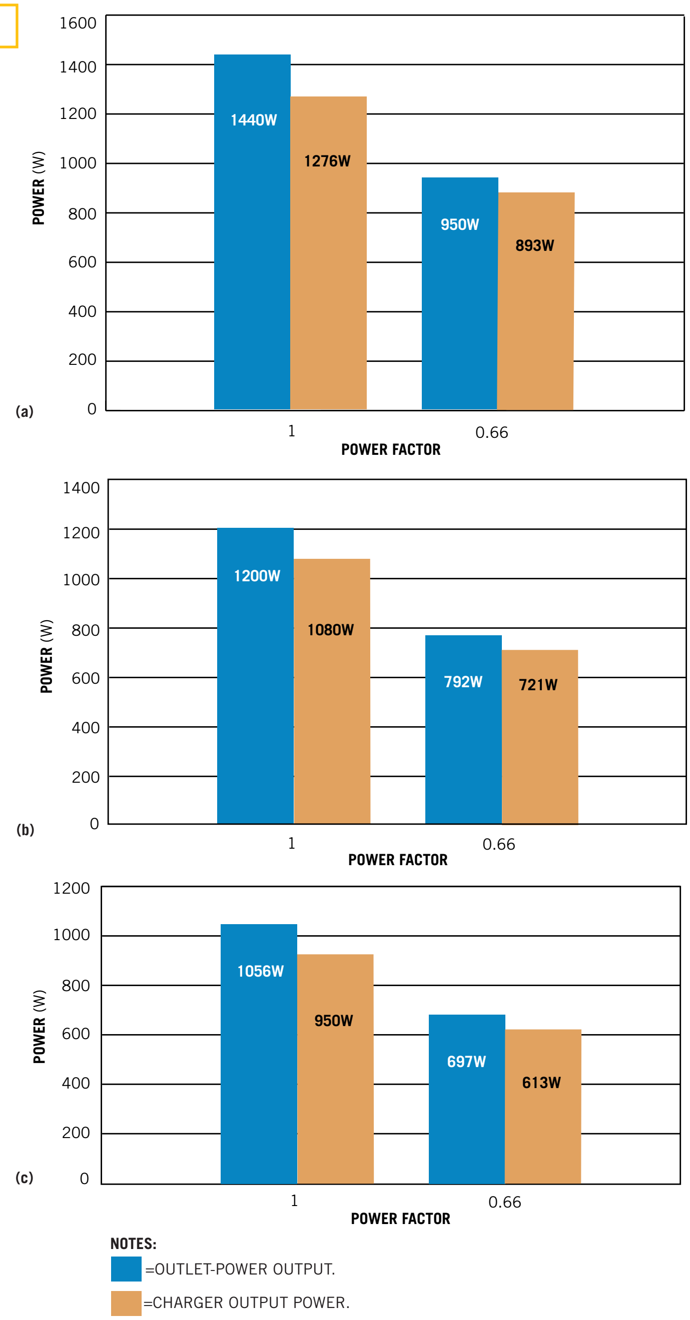
Figures 4a, **4b**, **4c**, and **4d** show the relationship between input voltage, input current, and output current of a 48V charger. You can use these figures as a guide to determine the design constraints of maximum power loss and maximum input current to obtain a desirable charging time.

Figure 4a shows a charger limited to a

TABLE 4—THE EFFECT OF UNITY POWER FACTOR ON MAXIMUM OUTLET-POWER OUTPUT

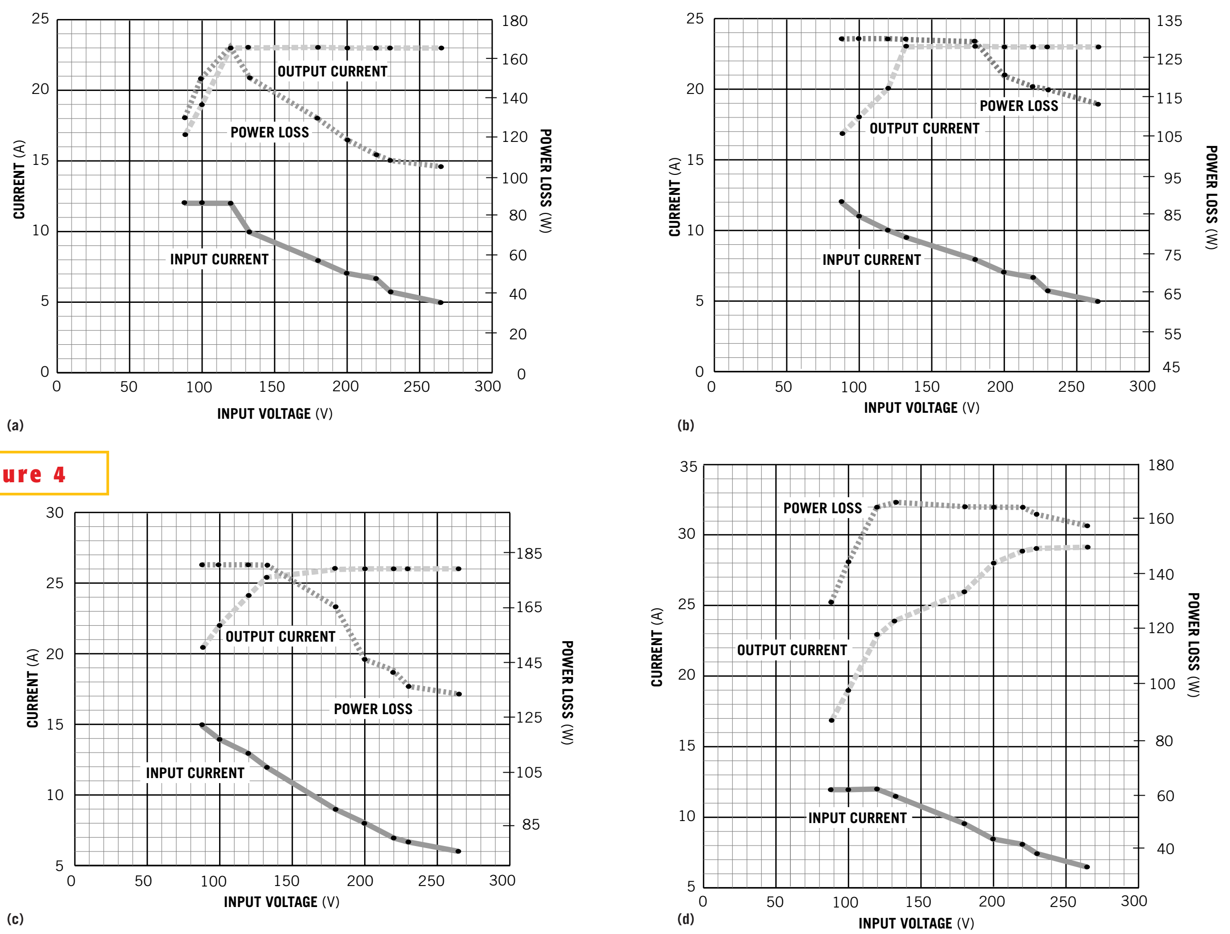
Input voltage (V)	Input current (A)	Power factor	Outlet-power output (W)
88	12	1.00	1056
88	16	1.00	1408
100	12	1.00	1200
100	16	1.00	1600
120	12	1.00	1440
120	16	1.00	1920

Figure 3



Power factor and efficiency—in this case, 90%—affect outlet power versus charger output power for input voltages of 120V (a), 100V (b), and 88V (c).

Figure 4



A 48V, 23A charger with an input-current limit of 12A (a) can charge in 8.33 hours at 120V. A 48V, 23A charger with a power-loss limit of 130W (b) can charge in less than 10 hours at 120V. A 48V, 26A charger with an input-current limit of 15A at 88V (c) can charge in seven hours at 120V. A 48V, 23 to 29A charger with an input-current limit of 12A (d) can charge in 10 hours at 120V and seven hours at 230V.

maximum level of 12A at the 88, 100, and 120V input levels. The charge time at 120V drops to 8.33 hours, which is a design goal. In this example, a maximum level of 160W dissipation at the 120V level constrains the thermal design. The other input voltages maintain the same output current and charge time.

Figure 4b shows a charger limited to a maximum level of 12A at the 88V level. The thermal-design limit is constant at 130W for all input levels of 88, 100, 120, and 132V. The output current rises, and charge time decreases. The 120V charge time is less than 10 hours. The other input voltages maintain the same output current of 23A and charge time of 8.3 hours as in **Figure 4a**.

Figure 4c shows a charge limited by a maximum level of 15A at the 88V level. The thermal-design limit is constant at 182W for 88, 100, 120, and 132V input levels. The output current rises, and charge time decreases. The 120V charge time is less than eight hours. Note that the input-current service and power cord must have a 20A rating to allow for safety derating. If you incorrectly size the wiring to 15A, there may be nuisance tripping of the primary service, even though no safety hazard exists.

Figure 4d shows a charge limited by a maximum level of 12A at the 88, 100, and 120V input levels. The charge time at 120V drops to 8.33 hours, again a design goal. In this example, a maximum level of 160W dissipation at the 120V level limits the thermal design. The increasing input voltage allows the output current

TABLE 5–THE EFFECT OF A LOW POWER FACTOR OF 0.66 AND EFFICIENCY ON MAXIMUM OUTLET-POWER OUTPUT

Input voltage (V)	Input current (A)	Power factor	Outlet-power output (W)	Efficiency	Outlet-power output (W)
88	12	0.66	697	0.88	613
88	16	0.66	929	0.88	818
100	12	0.66	792	0.91	721
100	16	0.66	1056	0.91	961
120	12	0.66	950	0.94	893
120	16	0.66	1267	0.94	1191

to rise and charge time to decrease. The output current is limited to less than 30A.

EFFICIENCY AND POWER-DENSITY EFFECTS

Building and space constraints play a big role in the design of electric vehicles for the European market, and these vehicles are thus typically smaller. The result is a size constraint on all vehicle components, including the charger. As the power density increases in a charger, efficiency plays an increasing role in defining the package size, shape, and orientation. The general definition of efficiency is as follows:

$$\text{EFFICIENCY} = \frac{\text{OUTPUT WATTS}}{\text{INPUT WATTS}}.$$

Or,

$$\text{EFFICIENCY} = \frac{\text{(INPUTS WATTS}-\text{LOSSES)}}{\text{INPUT WATTS}}.$$

The losses in the equation result in heat that the equipment must be able to dissipate. Theoretically, you can make a charger as small as the physical-component layout permits. However, heat dissipation and, hence, efficiency determine the practical limitations, such as size, reliability, and cost. For the same output-power rating, the higher the efficiency, the smaller the package. Higher efficiency results in compact size without resorting to special thermal-management designs and cost.

Thus, it is important to use high-efficiency techniques, such as zero-voltage and zero-current switching on the power stage of the charger. Also, try to use power switches with low on-resistance. Use of low-loss cores and special winding techniques can yield cooler magnetic components. By using these methods, onboard chargers with 90% efficiency are possible.

Figure 5

Tests using this high-frequency, power-factor-corrected sealed charger illustrate the importance of thermal management.

TABLE 6–COOLING METHODS AND ASSOCIATED PACKAGING PARAMETERS

Cooling method	Package size	Shape	Orientation
Convection	Largest	External fins	Fins vertical
Conduction	Large	Large conduction surface area	Independent
Forced air	Smaller	Fan height may dictate unit height	Fan in the bottom

KEEP ONBOARD CHARGERS COOL

With output powers as high as 1000W, even the highly efficient chargers have to dissipate a fair amount of power. It is important to limit the temperature rise inside a charger for long-term reliability. Adequate cooling of chargers is imperative. Various ways exist to cool chargers in an onboard application (**Table 6**).

For example, you can use the vehicle's body as an extended heat sink for a charger to provide optimal cooling. Two tests of the sealed charger in **Figure 5** examine the effects of using a vehicle's body as a heat sink. The charger under test is a typical 550W, sealed charger with no air-moving device. The typical efficiency is 90%, and the total dissipation is 60W.

In Test Case 1, the charger casting rests on wooden stakes, which represent a nonconducting vehicle body. Natural convection removes 60W of heat. The temperature rise is high and ultimately unacceptable. Thus, the product is not viable.

In Test Case 2, the charger mounts on an infinite, $1m^2$ heat sink, which is the heat sink that uses the vehicle body. The surface area of the casting is $0.991m^2$. Conduction removes 40W of heat, and convection removes 20W. The temperature rise is 47°C, which may compromise long-term reliability.

A final test case explores the ideal charger design with low-profile components and flat magnetic components. In an ideal package, the heat load is evenly distributed along the surface of a 27.5×17-in. charger packed against the frame of the vehicle. Conduction dissipates 60W of heat, and the temperature rise is 23°C.

These test cases clearly demonstrate the need for a system approach to thermal management of battery chargers. You must design batteries and chargers in tandem to achieve this optimal thermal system. Using a fan greatly relieves the thermal burden and results in a smaller package. However, you have to also consider the reliability, sealing rating, and cost of the fan. An important consideration with a fan-cooled unit is the pressure loss versus airflow of the fan, which defines the system impedance of the package and dictates the heat-sink design.□

AUTHORS' BIOGRAPHIES

Anuradha (Anu) Rao has an MS in electrical engineering from the Indian Institute of Technology (Madras, India). Rao did additional graduate work at the University of Tennessee while working as a research assistant at the Oak Ridge National Labs. For 11 years with IBM, she served as a power-system/power-supply engineer on mainframe computers. With Curtis Instruments for the past seven years, Rao is senior project engineer in the power-conversion-products/battery-charger group.

Jon Marshall is a senior electrical engineer and group leader for power products with Curtis Instruments. He is responsible for product design of battery chargers for electric vehicles. A designer of power supplies for more than 18 years, Marshall has an MS in manufacturing engineering from Polytechnic University (Brooklyn, NY) with a National Science Foundation fellowship. He earned a BSEE from Worcester Polytechnic Institute (Worcester, MA) in 1980.

ACKNOWLEDGMENTS

The authors wish to thank Eugene Finger, vice president of engineering at Curtis Instruments Inc, for his guidance and Vincent Ioanna, mechanical-engineering group leader at Curtis Instruments Inc, for his helpful discussions.