CHARGE!

EVERYTHING YOU ALWAYS WANTED TO KNOW ABOUT STATIONARY CHARGERS

William K. Bennett

BATTERY CHARGERS

POWER CONVERSION: CHARGERS ARE POWER CONVERTERS?

WHY DC POWER? 2.1.1

Modern institutions rely increasingly on electrical and electronic controls. Where continuous service is critical, redundant power sources are needed to ensure reliability. Where locally-provided redundant power is required, the use of dc powered controls, operating on storage batteries, is one of the most reliable solutions. In stationary applications, ac power from the mains is converted directly to dc to provide power to controls and operating equipment, while maintaining a battery to provide emergency power. In motive power applications, the dc power is used only to restore the charge to the battery, which is used elsewhere.

Figure 2a: Typical charger used for stationary & emergency power applications

Most of the battery-powered installations in the US are based on lead-acid batteries. While the conversion of ac power to dc power is independent of the storage medium, the major focus of this section will be on chargers for lead-acid batteries, such as the one pictured in Figure 2a.

RECTIFICATION: HOW DO WE CHANGE AC TO DC? 2.1.2

In the beginning, there was the dynamo. Actually, there wasn't even a dynamo. Although Planté invented a practical storage battery in 1859, early experimenters had no way to charge it other than using primary batteries. Doing that today, we would quickly consume the world supply of zinc.

Anyway, back to the dynamo. Siemens and Wheatstone each developed practical dc generators, or dynamos, by 1867. This led to the first practical way to charge the infant lead-acid battery. When Camille Alphonse Faure invented the pasted-plate lead-acid battery in 1881, we finally had an easily manufactured source of stored dc power, and the battery could be easily recharged using a dynamo (usually steam powered). However, there was no ac power yet. No grid or mains. No substations. No transformers. These words weren't even in the English language yet. Also, no power failures.

But I digress. You want to know about changing ac power to dc power. Tom Edison was distributing dc power in limited areas in the late 1800s. You know how that turned out. By the mid-1890s, Westinghouse had won the "current wars," and was building widespread ac distribution systems. Now that customers had a source of ac power, they needed a means to convert it to dc to charge their storage batteries. That was the dynamo, mechanically coupled to an ac motor (the M-G set, which puts the ac motor part and the dc generator part in the same machine, came later).

Dynamos[1], of course, have some disadvantages, chief among them being weight, floor space, and maintenance requirements. By the 1920s, vacuum-tube or gas-filled rectifiers (ignitron, thyratron) were replacing dynamos in static converters (that is, no moving parts). Finally, by the 1960s, silicon diodes and SCRs (silicon controlled rectifiers), used in various circuit configurations, came to dominance in converter technology.

The rectifier circuit, of course, is at the heart of any battery charger. Although chargers are frequently called "rectifiers" in stationary applications, we'll use the term "rectifier" here to mean only the part of a battery charger that changes ac to dc.

1 There's more on dynamos and static converters in *Ripple* (CHAPTER 3) and *Output Current Limit* (CHAPTER 4).

POWER SUPPLIES: HOW RELATED TO BATTERY CHARGERS? 2.1.3

A battery charger, as you will see, is a special case of a dc power supply. Common technologies used in power supplies are discussed here.

Linear Power Supplies 2.1.3.1

Linear power supplies usually consist of a transformer, rectifier circuit, output filter, and control circuit. Since the rectifier operates at line frequency (60 Hz in the Americas), extensive filtering is required. They are capable of very accurate dc voltage control and are suitable for low power applications; they're frequently used for variable output voltages, such as laboratory power supplies. Their efficiency is limited unless designed for a specific constant load.

Ferroresonant & Magnetic Amplifier Designs 2.1.3.2

For high power applications (up to 100 kW or more), power supplies using magnetic controls have been developed. Ferroresonant supplies (aka "ferros") depend on the characteristics of a special transformer design, whose secondary voltage is fiercely independent of changes in the input voltage; that is, it's an excellent line regulator. The transformer has inherent current limiting, which by design could be as low as 200% of the power supply rated output. The rectifier circuit uses only silicon diodes, so the supply is extremely rugged. Efficiency is good at full load, and input power factor is high. A variant, the controlled ferroresonant transformer, improves the output voltage regulation at the expense of added complexity, and provides the capability to have separate float and equalize voltages. But, the transformer is larger than a standard linear transformer, generates more acoustic noise, and costs more. It operates only on single-phase ac sources; a three-phase power supply requires two or three transformers.

A magnetic amplifier (usually called "mag amp") power supply also uses a special transformer design, or a standard transformer coupled with another magnetic component, a saturable reactor. Like the ferroresonant supply, it uses silicon diodes in the rectifier, and is extremely rugged, although it lacks the high input power-factor of the ferro. The mag amp supply is available in single-phase or three-phase versions. One limitation of the mag amp rectifier is that the dc output current cannot be reduced to zero, so loading or bleed resistors are required for effective float-voltage control.

Phase Control Power Supplies 2.1.3.3

We've previously mentioned ignitrons, thyratrons, and SCRs. These are all examples of controlled rectifiers – that is, they are electronic devices that, like diodes, conduct current in only one direction. Unlike diodes, which have only two terminals (an input and an output), they have (at least) a third control terminal. They will conduct, or "turn on," only when given a signal to do so at the control terminal. This gives rise to phase-controlled rectifiers: the rectifier element (SCRs in modern supplies) conducts for only part of each cycle of the ac input power. By adjusting the conduction duration in each cycle, the power supply can control its output current from zero to its maximum rating.

The combination of a linear transformer and silicon controlled rectifiers makes for a very rugged supply. Phase control supplies can have very high efficiency, even at light loads, and have lower costs than mag amp or ferro supplies of the same rating. Because the output voltage waveform is discontinuous, however, the dc output requires more filtering, and there are more harmonics in the input current than for a ferro. But three-phase versions are simple and reliable, and don't suffer from potential instabilities that may occur in magnetically controlled supplies.

An exhaustive explanation of how phase control works appears in Chapter 3, *Ripple*.

Switching-Mode Power Supplies (SMPS) 2.1.3.4

All the power supply designs that we've discussed use transformers to isolate the dc output circuit from the ac power source, for safety reasons. The transformer also scales the output, by suitable selection of the secondary voltage, to the range needed for the dc voltage. So far, all the transformers have operated at line frequency, which means 60 Hz in the western hemisphere.

Line frequency transformers are large, heavy, and expensive. They're also unbelievably reliable. OK, so a pole (utility distribution) transformer in your neighborhood failed last summer, and you were in the dark for four hours. I assure you that's a rare event, compared to the number of transformers in service.

Switching-mode, or high frequency, power supplies have been in development since the 1960s. The switching-mode power supply (or SMPS) incorporates three power conversion stages: an ac to dc converter (rectifier) to provide a dc supply to an inverter, which drives a high frequency transformer to achieve isolation between the ac line and the dc output. Finally, another rectifier on the transformer secondary side produces the dc power for the load.

This seems a long way around the barn to get from ac to dc. The impetus, of course, is that the high frequency transformer is smaller, lighter, and less expensive than its line frequency counterpart, operating at frequencies from 20 kHz to several hundred kHz. The savings in the transformer can more than offset the extra cost of two more conversion stages.

Despite the multiple conversions, switching-mode chargers can reach efficiencies of at least 90%. Modern circuit design techniques can give them very high power factors. The switching components in the inverter stages, usually MOSFETs (metal-oxide-semiconductor field-effect transistors) or IGBTs (insulated-gate bipolar transistors), while not as rugged as SCRs, are achieving high reliability with careful circuit design, and can handle high power levels.

SMPSs are cost effective in power ranges up to many hundreds of watts for low voltage applications. They're the supply of choice for desktop computers because of their small footprint. Note, though, that the small footprint is obtained by including a cooling fan – not desirable in a remote application, such as a substation. The SMPS hasn't made significant inroads into higher voltage charger applications (125 to 480 Vdc), or stationary applications in general. Yet.

BATTERY CHARGERS: HOW DIFFERENT THAN POWER SUPPLIES? 2.1.4

There are just two qualities of a dc power supply that we need to control: dc output voltage and dc output current. Real-world dc loads have resistance, measured in ohms, and may be associated with a voltage source, such as a battery. So, to a power supply, a battery looks like an ohmic load and another power supply at the same time.

If we connect a resistor to the output of a dc power supply, we can calculate or measure the current; see the boxout *Ohm's Law* below. But if we connect a battery, the battery voltage opposes the power supply voltage. This is known as a *back EMF.* The current that flows is proportional to the difference between the power supply voltage and the battery voltage, following Ohm's law.

EXAMPLE

So, in the example in the following boxout, if the load is a battery with a voltage of 120 Vdc and an internal resistance of 1.25 ohms, and the charger is set to 125 Vdc, the current will now be 4 amperes (125 – 120, or 5 volts, divided by 1.25 ohms), instead of the expected 100 A.

By the way, 1.25 ohms would be an unacceptably high internal resistance for a secondary battery. I hope your battery never gets that bad.

KEY CONCEPT

It's the nature, then, of real world loads to respond to a voltage or current stimulus according to their ohmic value. That means that if you apply a voltage, the load decides how much current to draw. And if, instead, you apply a current, the load decides what the voltage will be.

> OHM'S LAW
>
> One way of stating Ohm's law for dc circuits allows us to calculate the current that will flow in a resistor, if we know the voltage:
>
> $I = V \div R$
>
> where V is the power supply output voltage, R is the value of the resistor in ohms, and I is the resulting current in amperes.
>
> Example: For a voltage of 125 Vdc, and a resistor of 1.25 ohms, the current is 100 A.
>
> If you know any two of the quantities in a dc circuit, you can calculate the third.

An Important Law 2.1.4.1

KEY CONCEPT

That leads us to the First Law of Battery Chargers: In a dc system with a battery, *the battery, not the charger*, determines the dc bus voltage. In the example above, the battery voltage is 120 Vdc, even though the charger is set to 125 Vdc, because 120 Vdc is the voltage the battery will maintain while receiving a current of 1.25 Adc. It appears that the battery voltage is 125 Vdc, but some of that voltage is lost in the internal resistance.

But, you say, when you set up your system, you're setting the float voltage. Right, but what you're really setting is the upper voltage limit for your power supply. A battery charger, you see, is a current source, not a voltage source. Your world is upside down.

KEY CONCEPT

If you have a regulated, constant-voltage power supply and a resistive load, you of course set the voltage where you need it. In most cases, you also set a maximum current that the supply can deliver, just in case your resistive load starts to demand too much current. But from zero current up to that current limit, your power supply provides the same voltage. This is how a current-limited, constant voltage power supply works. With only a resistive load, a battery charger looks just like a power supply, and works the same as any constant voltage power supply.

KEY CONCEPT

But as soon as you connect a battery to the charger, things change. A battery charger, when connected to a discharged battery, becomes a current source. The current value is the current limit setting of the charger. From zero voltage all the way up to the voltage limit (float voltage), your charger provides the same current. This is a voltage-limited, constant-current power supply. When the battery becomes fully charged, things look more normal.

If this seems confusing, don't worry. You can still operate your charger normally, with all the settings you're used to, and everything will be fine.

UNINTERRUPTIBLE POWER SYSTEMS: USE OF INVERTERS & CHARGERS 2.1.5

In Section 2.1.3.4, which discussed SMPS, we used the word *inverter* without much of an explanation, other than that it is some sort of power conversion thing.

By now, you have a pretty good idea about the available methods for converting ac power to dc power. An inverter covers the other direction: changing dc into ac. Normally, when we speak of an inverter, we mean a device that generates line frequency power from a dc source, to power conventional ac-powered loads such as a personal computer, or industrial controls and instrumentation. A UPS integrates an inverter and battery charger in a single system, providing backup ac power for critical loads. Many modern UPS also include the battery and charging controls in the enclosure.

An inverter is different from an alternator, or ac generator, in that it's static (no moving parts), being based entirely on semiconductor circuitry. In a traditional inverter, a transistor (or SCR) circuit switches the current (from a dc source) in the primary winding of a linear transformer to generate an ac voltage in the secondary. The transformer is designed to provide the required ac voltage; it also provides the necessary safety isolation from the battery or other dc source. Using this method, the transformer operates at line frequency, which means that it's large and heavy, albeit reliable.

Inverters using line frequency transformers may have square wave or sine wave outputs. Square wave inverters are lower in cost, but are suitable only for simple linear loads, such as incandescent lighting. The square waveform has high harmonic distortion and may cause an unacceptable increase in temperature in transformer-operated equipment, such as another power supply or fluorescent lighting. They are also not very good at handling low power factor loads.

Line frequency inverters with sine wave outputs usually use ferroresonant transformers or brute force filtering and are generally more expensive than square wave inverters. An inverter described as "quasi sine wave" (or similar weasel-wording) is a square wave inverter with a limited pulse width, usually 120 to 126 degrees (see *Enter phase control* in Section 3.2.1.3 for some insight on pulse width). This output is a little easier to filter, but a little harder on the inverter transistors.

Pulse width modulation (PWM) is a technique that can be used to drive the primary of a standard transformer with a "chopped" square wave that results in a pretty good synthesized sine wave. This is the preferred technology in most high-power inverters and UPS. The advantage is that the output can be easily filtered to produce a good low-distortion sine wave. The disadvantage is higher complexity in the inverter circuit. Despite the complexity, the cost is a little lower than a ferro inverter. PWM inverters have been used in economical line-interactive UPS and in "on-line" or double-conversion UPS.

Modern inverter circuits also can use multiple power conversion stages, similar in operation to the SMPS, to generate a low-distortion ac output. The difference is that the last power conversion stage switches the isolated dc power to generate a line frequency ac, usually as a synthesized low-distortion sine wave.

DC-DC CONVERTERS: A SUITABLE ALTERNATIVE TO BATTERY CHARGERS? 2.1.6

What if you had all the power you wanted or needed at 125 Vdc, but your site manager suddenly handed you a requirement for 24 Vdc to run some communication gear? You might tell him to buy a 24 V battery and a 24 V battery charger. But, these elements come with costs: initial, maintenance, and probable future battery replacement.

There is another way: for approximately the same cost as the battery charger, you can install a dc-dc converter. This product accepts a power input at 125 Vdc, and through internal magic, produces an output of 24 Vdc for your communications gear. You can eliminate the cost and maintenance requirements of another battery. Another advantage is that the output voltage won't vary: it's 24 Vdc regardless of whether the battery is on float or equalize, or the dc bus voltage is decreasing due to a power emergency.

Is there a downside? Well, of course. If the primary 125 Vdc battery fails, you lose communications. With a separate 24 V system, you at least would be able to call someone to inform him that the 125 V battery had failed. But, statistically, the converter approach is more reliable, since there is one less failure point.

A dc-dc converter is based on SMPS technology. Most designs are isolated, meaning that the output power is ohmically isolated from the input. A 125 Vdc system is usually floating; that is, the battery has no connection to earth ground, whereas many 24 Vdc systems are grounded (usually at the positive terminal of the battery). An isolated converter makes this possible; you ground the positive output of the dc-dc converter, and the floating operation of the 125V system won't be affected.

Isolation, in the sense we use here, is usually expressed in volts. The minimum isolation requirement for a 125 Vdc bus would be 1,250 volts, as specified in nearly every industry standard for power conversion equipment.

GENERATORS: WHAT ROLE DURING POWER EMERGENCIES? 2.1.7

Well, back to moving parts for a moment. There is another way to get emergency or standby power, at least of the ac variety, and that is with a gasoline- or diesel-powered generator. Most large generators are diesel powered; gasoline power is generally limited to small generators, such as for residences. Some large generators may use natural gas turbines. We'll discuss diesel generators, as used in emergency power applications.

Generators may be used stand-alone for emergency power, which implies that there will be an interruption in power availability between the instant of mains power failure and when the generator is started and up to speed. This isn't a viable situation for continuous process control, such as that needed in utility applications. In generating stations, backup generators may be used to provide emergency power to the charger/rectifiers and other ac loads during long-term power outages, where the battery backup time is insufficient. The generators may also be used to "cold start" remote stations, such as natural gas-powered turbines. In these cases, the generators are sized with spare capacity of at least 25%, in order to provide inrush currents for chargers, ac motors, and similar equipment.

In applications where a generator will be used for continuous duty, such as peak load shaving, it will be sized for the expected load with a small capacity margin, to avoid causing diesel motor damage from operating at a continuous light load.

CHARGER SIZING: WHAT CAPACITY DO I NEED?

HOW MUCH DOES EXTRA CHARGER CAPACITY COST? 2.2.1

It's no secret that you pay for power, and since power is voltage times current, you are going to pay more for higher voltage and for higher current. What isn't so clear is just what the differences are.

As the current output requirement of a battery charger increases, the cost of the components to handle that current increases proportionally to the current. That is, it costs about twice as much to provide a charger output of 100 A than an output of 50 A. This ratio isn't reflected in charger prices, though, because it doesn't take into consideration the fixed costs, such as control circuitry and cabinetry. When all that is included, the ratio is closer to the square root of the current.

Increasing the voltage has a similar impact. If you double the output voltage (but keep the same current), the cost of the power-handling components increases by about 1.4, but the fixed costs remain the same. So, it makes sense not to buy more charger than you need. There are intangible reasons, also. A larger charger might come in a larger enclosure, and you would need more floor space. You may need to beef up floor load-bearing capacity. You may also require additional ventilation. Plus, there's the challenge of getting it past your purchasing manager.

Well, you wouldn't buy more voltage than you need, at any rate, since the battery voltage determines the charger output voltage. But it's tempting to specify a higher current rating than you need initially, on the theory that the final system may somehow work better. It makes sense to overspecify if you're confident that the site's power needs will expand. But how do you know how much margin to order when the power requirements and the battery size are fixed and known?

Fear not. Help is right around the corner (or at least in the next paragraph). There is an easy method to calculate the charger size you need.

HOW DO I CALCULATE THE CHARGER CAPACITY I NEED? 2.2.2

In a true standby application, such as some substations, emergency lighting and alarms, and even engine starting, you can safely ignore the standing load when sizing the charger. The purpose of the charger is to charge the battery within a certain time limit. But, you still need to know how much the battery is discharged, which varies widely depending on the application. A safe approach is to assume that the battery is fully discharged at the point where ac power is restored to the charger. Then, the charger rating is Ah ÷ T, where Ah is the ampere hour rating of the battery, and T is the allowed recharge time.

Wait, there's more. Since the charge acceptance decreases near the end of charge, you need to add a little fudge factor to the Ah rating. Use 10% for lead-acid, and 40% for nickel-cadmium. So the complete formula becomes

$$A_{DC} = \left(\frac{AH}{T} \times K \right)$$

where A_{DC} is the charger ampere rating, and K is 1.1 or 1.4 for lead-acid or NiCd, respectively.

If you're in a generating station, or have another application with a constant load on the dc bus, you must add that load to the charger rating. If the load is variable, and you don't know the average dc current, then a safe approach is to use the maximum load current in your calculation (you can cheat on this if you know that the maximum is a very short-term load, occurring infrequently). Then the sizing formula becomes

$$A_{DC} = \left(\frac{AH}{T} \times K \right) + I_L$$

where I_L is the continuous load in amperes.

EXAMPLE

Here's an example: At a site with a 100 Ah lead-acid battery, a standing switchgear load of 21 amperes, and an eight-hour recharge requirement, you would rate the charger this way:

$A_{DC} = (100 \div 8) \times 1.1 + 21$

$A_{DC} = 34.75$ amperes. So you would order a 35 A battery charger. Of course, if you expect your site to grow, you might have to obtain a larger charger initially to allow for increased loads later.

» ***Q: Isn't that cutting it close? There's essentially no margin there.***

A: Unlike batteries, chargers don't decrease in capacity as they age. You don't need to add margin to compensate for age or the normal operating temperature range, as you do for a battery. The necessary margin is built into the calculation.

OUTPUT VOLTAGE RANGE: THE LONG & SHORT OF BATTERY STRINGS

IN SECTION 1.4.5, *How Do I Size a Stationary Battery*, the first step is selecting the number of cells you need, based on several factors: the acceptable voltage range for your dc-powered equipment, the float and equalize voltages for the battery type, and the end-of-discharge voltage, which is dependent on the discharge rate.

The number of cells normally falls into a small range. For example, for 125 Vdc buses, using lead-acid batteries, most applications are satisfied with between 58 and 62 cells, with the most common being 60 cells (**Figure 2b**). For nickel-cadmium, the nominal number is 100 cells, but is usually lower, around 92 cells, because of the high charge voltage requirement of the NiCd cell.

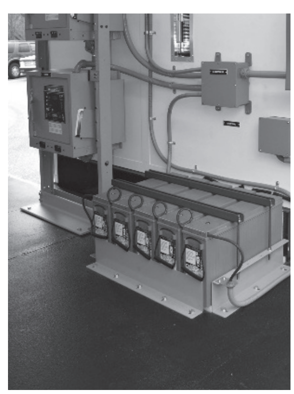

Figure 2b: Five VRLA battery containers on one wall of a trailer. Each has six cells, for a total of 30 cells. The other side of the trailer has 30 more. Combined it is a 60 cell, 120 V string, the most common combination

Battery chargers are designed with output voltage ranges that accommodate the usual range of cell combinations. For a 125 Vdc bus, for example, a typical equalize voltage range extends to an upper limit of 147 Vdc, adequate for 62 lead-acid cells or 100 NiCd cells. Some NiCd batteries may require higher voltages. Check with the manufacturer. There are similar ranges at the other standard bus voltages to accommodate varying cell combinations.

The NEMA (National Electrical Manufacturers Association) standard PE 5 for stationary chargers specifies the float and equalize voltage ranges for lead-acid and NiCd batteries. Most available chargers meet or exceed the required ranges.

» ***Q: I was just told that we need a new charger for an old, I mean old, emergency lighting system. It runs on 36 Vdc, using 18 old lead-acid cells. You don't have anything like that in your catalog. Where do I go?***

A: Not to worry. Application engineers at the manufacturer's factory can whip you up a custom charger in no time at all. All you need to tell them is the number of cells and the maximum equalize voltage. Oh, and of course, the output current.

AC POWER INPUT: WHAT FACTORS SHOULD I CONSIDER?

NOW THAT YOU know the charger rating you need, consider how to provide it with ac power. You can order a charger to operate on virtually any of the worldwide standardized ac mains voltages (up to a maximum of 600 Vac), as noted in **Table 2a**.

Table 2a: Worldwide ac mains voltages used to power chargers of various ratings for both single- & three-phase systems

Standard 60 Hz Voltages		Standard 50 Hz Voltages
Single Phase	Three Phase	Single & Three Phase
120 V	208/240 V	220 V
208/240 V	480 V	380/416 V
480 V	550 V (Covers 525-600 V)	
550 V (Covers 525-600 V)		

HOW MIGHT THE INPUT VOLTAGE SELECTED AFFECT COST? 2.4.1

The standard LVAC (low voltage ac) distribution voltages for the western hemisphere and for Europe are shown in **Table 2a** in the last section. Usually, utilities maintain a voltage within ±5%, but as you know, brownouts happen. NEMA PE 5 requires a charger to operate with an input voltage 12% below the nominal. This means that a charger wired for 120 Vac input can operate with an input as low as 105 Vac. At the high end, the NEMA standard allows the input voltage to be 10% over nominal.

TECH TIP

As you know, the ac input current depends on your choice of input voltage: the higher the voltage, the lower the current. This could have an impact on your wiring costs. Always choose the highest branch ac voltage available at your site that is convenient for wiring.

Single-phase chargers can accept any voltage from 120 V to 480 V or higher. However, 120 Vac isn't available on some large charger ratings, such as 130 V at 50 Adc; for these ratings, you would select 208 Vac or higher. And of course, 120 V isn't available on three-phase chargers at all.[2]

You also may have a choice between single-phase and three-phase ac inputs. In general, a single-phase charger costs less than a three-phase charger, and the site wiring costs may be affected. Here's a little table **(Table 2b)** to help you decide, based on the popular 130 Vdc, 50 A charger rating:

Charger Model	AC Current @ 208 Vac	AC Current @ 480 Vac	Relative Cost
130 V, 50 A, Single Phase	72 A	31 A	1.00
130 V, 50 A, Three Phase	37 A	16 A	1.26

Table 2b: Relative cost when comparing single-phase & three-phase ac inputs for the popular 130 Vdc, 50 A configuration

Although you would need larger wire and a larger branch circuit breaker (see boxout *About that breaker…*) for the single-phase charger, you're running only two wires instead of three, and you have the offset of the lower charger cost. Of course, there may be other considerations, such as maintaining balance on a distribution transformer, that will dictate your use of a three-phase charger. Decisions, decisions...

2 Manufacturers sometimes see a request for "120 V Three phase." The user is probably distributing 208 Vac 4-wire power in the building, and is measuring the voltage from line to neutral. The charger doesn't care whether the supply is 3-wire or 4-wire, so you should order the 208 V input.

ABOUT THAT BREAKER...

Circuit breaker ratings can be complex. AC circuit breakers with trip ratings up to 100A use a hydraulic/magnetic trip mechanism. This breaker type is sensitive to the average value of the input current.

AC breakers with trip ratings over 100A use a thermal/magnetic trip mechanism, which is sensitive to the rms value of the input current.

What is the difference? The rms value is a mathematical representation of the effective, or heating, value of an ac current. Normally, the rms value of an ac input current will be a little larger than the average value.

Both circuit breaker types provide safe and adequate protection for the charger and the ac power source it's connected to.

An important specification for circuit breakers is the ampere interrupting rating. For more on this, see Standards & Codes in Chapter 9.

DETERMINING THE AC INPUT CURRENT 2.4.2

The ac input current is generally published in the charger manufacturer's literature. The published value is usually the maximum current under all worst-case conditions: extremes of ac input voltage, maximum output current limit, and maximum battery equalize voltage.

Chances are good that you'll never see an input current that high. First, you probably aren't equalizing the battery at the maximum available voltage, and the ac input current is usually close to the nominal value. But since the charger's ac input circuit breaker must be sized for the maximum possible current, your wiring and your branch breaker must do the same.

TECH TIP

This brings up a very important point. To meet agency certification requirements, the charger's input breaker must be rated to carry 25% more than the actual maximum input current (and could be as much as 100% higher). Since circuit breakers are available only in certain increments, you should rate your wiring and branch breaker according to the charger's input breaker rating, not the published input current rating.

TECH TIP

Another important rule: You must size your branch circuit wiring according to the trip rating of *your* branch circuit breaker, not the input breaker in the battery charger. Your branch circuit breaker will be rated the same as, or larger, than the charger's input breaker.

There are some infrequent applications where you might order a charger with multiple input voltage capability, such as 120/240 Vac. The charger's input breaker trip rating has to carry the input current for 120 Vac, but you might actually wire the charger for a 240 Vac input. In cases like this, the ac input breaker might be rated for even more than 200% of the actual input current.

AC INRUSH CURRENT 2.4.3

Most available stationary chargers are based on circuits using line frequency transformers. Like ac motors, transformers have an inrush current when ac voltage is first applied, due to the initial magnetizing current requirement. The inrush current is large but lasts only for one or two cycles of the line frequency.

Maximum inrush is specified as a peak current, expressed as a multiple of the normal full-load ac current. If the full-load input current is 16 Aac (from **Table 2b**, **Section 2.4.1**), and the inrush is 15 times, then the peak inrush current is $15 \times 16 \times \sqrt{2}$, or about 340 amperes. The branch circuit breaker must be rated to withstand this inrush for at least two cycles; we recommend a medium or long time-delay circuit breaker. If your branch circuit breaker has an adjustable magnetic trip, set it to its maximum value. See the boxout on the previous page for additional technical details on circuit breaker ratings.

TECH TIP

SOFT START 2.4.4

Soft start (also known as "walk-in") is unrelated to the ac inrush current. You're going to have an inrush current whether the charger is equipped with soft start or not.

The soft start feature slowly ramps up the dc output current from zero to its maximum required value, over a period of a few seconds to 10 seconds or more. It was initially added to battery chargers to prevent oscillation or overshoot in the output voltage when an underdamped charger[3] was connected to a relatively small battery. The requirement now appears in most charger specifications. Soft start also reduces transients fed back to the ac source, in case the charger is operating from a generator, since a generator may have a higher source impedance than a normal ac supply.

INPUT VOLTAGE & CURRENT HARMONICS 2.4.5

The ac voltage delivered by the utility to your battery charger, or any other device or equipment, is a pure sine wave, or at least it's supposed to be. If you would like more information on ac voltage and sine waves, see *Under the Hood: Sources of Ripple* in Section 3.2.

The current that is drawn by ac-operated equipment, though, might not be a pure sine wave. If the ac load is a pure resistance, such as incandescent lighting, the current will be sinusoidal. This is also true of loads like small ac motors. These are examples of *linear* loads; in this sense, linear means that the current follows the voltage, and isn't interrupted during any part of the ac line cycle. A linear load won't cause any harmonic currents or voltages to be generated; that is, its harmonic distortion is zero.

If there are linear loads, then there must be non-linear loads, right? A non-linear load is characterized by a load current waveform that doesn't look like the voltage waveform; that is, it's non-sinusoidal. It causes harmonic distortion. A phase-controlled battery charger is an example of a non-linear load.

You may be asking, "What's a harmonic?" A harmonic is an electrical signal that can be impressed on the ac line voltage or current that is some multiple of the base line frequency. We call the base frequency (60 Hz, for example) the *fundamental*, or *first harmonic*. Without harmonic distortion, this is the only signal present. Harmonic distortion introduces *higher order* harmonics: the second harmonic is 120 Hz, the third 180 Hz, and so forth. An example of ac line voltage containing multiple harmonics is shown in **Figure 2c**.

Non-linear, single-phase loads usually generate harmonics starting with the third, but only if the current has the same waveform for both the positive and negative voltages. Three-phase loads, such as a three-phase charger, generate harmonics starting with the fifth.

3 An underdamped control circuit achieves fast response but allows some voltage overshoot or undershoot. Conversely, an overdamped control circuit minimizes overshoot or undershoot, but at the expense of slower response.

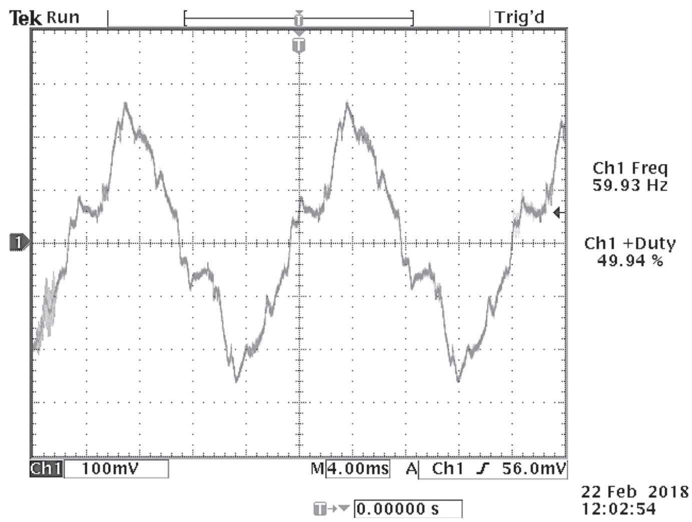

Figure 2c: Measured ac voltage that exhibits multiple harmonics of the main 60 Hz sine wave

What's wrong with harmonics? They don't do any work in the battery charger or any other useful equipment (except for incandescent lighting or resistive heating). Instead they cause extra heating in the load, in the wiring to the load, in the distribution transformers, and all the way back to the generating station. Harmonic currents even force the utility to oversize the overhead distribution cables.

For any non-linear equipment, such as a battery charger, the input current may have harmonic distortion. The current distortion causes some fluctuation in the sinusoidal voltage that powers the charger; thus current harmonic distortion is translated to voltage harmonic distortion, which is then spread to other equipment in the facility. If the ac supply has a low impedance, such as that supplied by a standard distribution transformer, the voltage harmonic distortion that results is usually very low. Low harmonic voltage distortion is important to prevent excess heating in other loads connected to the facility's ac supply.

Power Factor in Linear Loads 2.4.5.1

We mentioned *power factor* in the description of various ac to dc conversion methods back in Section 2.1.3. You may be familiar with power factor correction, where a facility will install a capacitor bank to raise the power factor presented to the utility source. This is a good way to compensate for inductive loads, such as large ac motors or ballasted (e.g. fluorescent) lighting.

If the current in a load is linear, and exactly follows the voltage, the power factor is 1.0. This is the most desirable situation. A lot of loads, however, such as ac motors, are inductive. This means that the current has the same shape as the voltage but lags the voltage by some phase angle. Mathematically, we define power factor for this type of load as the cosine of the phase angle between the voltage and the current.

Examine the waveforms in **Figure 2d**. This is the relationship you might expect to see in a fractional horsepower motor. The applied voltage (trace A-A) is 120 Vac (rms), and the motor current (trace B-B) is about 14 Aac (rms). Note, though, that the peak value

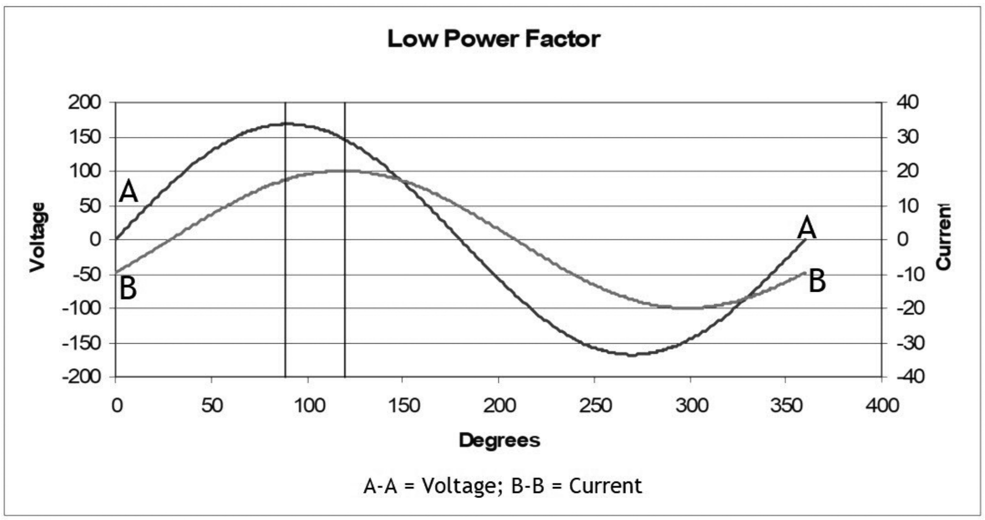

Figure 2d: Example of current lag in inductive circuit; the peak voltage at the first vertical occurs about 30 degrees ahead of the peak current. This phase difference results in a lowering of real power by a factor

of the current occurs later than the peak value of the voltage. We say that the current lags the voltage, which is what happens if the load is inductive. AC motors are inductive, especially if lightly loaded.

If you multiply the voltage by the current, you get $120 \times 14 = 1680$ VA (VA stands for volt-amperes). This isn't all real power, though. The real power is lower, reduced by the power factor. The motor produces real power only when the instantaneous voltage and current are positive, or when they're both negative. When one is positive and the other negative, it actually subtracts from the work done by the motor. By the way, power factor defined this way is also known as *displacement power factor.*

Vertical lines are drawn through the peaks of the voltage and current waveforms above. We can measure the time or phase difference between the peaks, in degrees. In the example above, it's about 30 degrees. The power factor, then, for the motor in this picture is the cosine of 30°, or 0.866. So the real power, with rounded off values, is:

120 Vac × 14 Aac × 0.87 = 1,462 watts

I hedged a little bit when I called this example a "fractional horsepower" motor. At 1,462 watts, it's a little over one horsepower (746 watts). To factor in average motor efficiency, you can use an approximate value of 1,000 watts per horsepower.

You see that with an inductive load, we can calculate power factor by measuring the phase angle between the voltage and current. But utilities don't do it that way. They say:

$$PF = \frac{watts}{VA}$$

where PF is power factor, watts are the real power in the load, and VA is the product of the voltage and the current in the load[4]. The VA product, or *volt-amperes*, is never less than the power in watts, so that you cannot have a power factor greater than 1.0. A power factor of 1.0 is ideal, since the entire current contributes to powering the load.

Power Factor in Non-Linear Loads 2.4.5.2

When you calculate power factor as the ratio of watts to VA, you find that non-linear loads also have a low power factor, even if there is no phase angle between the voltage and current, during the periods when current is flowing. Consider a simple power supply, with a simple diode rectifier, and a large filter capacitor connected to the output of the rectifier. The diodes conduct current only when the applied ac voltage is higher than the dc output voltage of the power supply, but there isn't a lag between the voltage and the current. Yet the power supply has a low power factor. Why? The answer is tied up in that definition for power factor, **W ÷ VA**.

The result is those pesky harmonics. When the current flows through the diodes for only part of a cycle, lots of harmonics are generated in the input current. But remember that harmonics don't do any work; they just add to the VA measurement at the input to the power supply. So, the power factor looks low – actually *is* low – because of the non-linearity of the load. This is the way a phase-controlled battery charger behaves, and why the power factor for a charger is less than 1.0, especially at light load.

At very light loads, you might not care about the power factor. For a substation application, where the float current is near zero, the power consumed by the charger is

4 Also known as *apparent* power.

low – just enough to cover the charger's fixed losses, such as power for the control circuits and the exciting current for the main transformer. The power factor in this condition will be low. The power factor increases as the dc output current increases, until the charger reaches its maximum power factor at full load. This usually ranges from about 0.8 to 0.9.

Incidentally, while the capacitor bank mentioned a few paragraphs back can compensate for an inductive power factor from linear loads, it does nothing for the low power factor caused by a non-linear load.

WHAT ALTERNATE AC POWER SOURCES CAN A BATTERY CHARGER USE? 2.4.6

Generators 2.4.6.1

Sites are sometimes equipped with auxiliary diesel generators, either to extend the backup time in power emergencies, or to provide power for a "cold start" for a remote or isolated power generator. Most battery chargers will operate fine with a generator power source, but the generator must be able to provide the necessary inrush current (see Section 2.4.3) when the charger is energized.

Generators are generally sized with some excess capacity in applications where ac motors or transformer-operated equipment are involved. For a full discussion of generator sizing, see *Can I run a charger from an auxiliary generator?* in Chapter 7, *Applications.*

Multiple Grid Sources 2.4.6.2

Site planners sometimes seek a level of redundancy by having a second ac power source available for critical equipment. Of course, the battery charger is critical, right?

The ac power input for a charger can be switched between two (or more, but it gets complicated) ac sources, using suitably rated contactors. There will be a short interruption of power to the charger, since the switching contactors need to be in a break-before-make configuration. Because of the interruption, the charger will also trigger the soft start feature, so the interruption of dc output current may be several seconds. Keeping the battery connected to the dc bus is tactically important in this kind of installation.

» ***Q: Can a charger be powered by a UPS?***

A: Well. The main question here isn't "Will it work?," but "Why?"

A UPS is normally used to power critical ac loads during a power failure. A charger is normally used to maintain the charge on a battery so that the battery can power critical dc loads during a power failure.

Using a UPS to power a charger is robbing Peter to pay Paul. Backup time for ac-powered loads will be reduced in order to maintain the battery, which is presumably sized to power dc loads throughout a utility power failure. And it would be ludicrous to use a battery to power a UPS to power a charger to charge the same battery.

If you insist, there isn't any reason that a properly coordinated system won't work. If the UPS is a ferroresonant type, there could be some instability caused by ac harmonic currents in the charger input current. Also, the charger would take longer to "cold start," since the UPS might not be able to provide the ac inrush current for the transformer.

PACKAGING: WHY DOES IT MATTER?

WHAT ENVIRONMENTAL EFFECTS CAN MY CHARGER ENDURE? 2.5.1

NEMA Enclosures 2.5.1.1

The standard cabinet style for a battery charger is a NEMA 1 enclosure. NEMA 1 enclosures, such as the one pictured in **Figure 2e**, are made entirely of sheet metal, with provision for wall mounting or floor mounting, depending on the charger rating. Optional brackets are available for wall-mounted chargers, and some small floor-mounted chargers, to facilitate rack mounting.

Access to virtually all internal components is through the front door. The standard door requires a tool (usually a screwdriver) to open but isn't lockable. Again, there is an option to provide a padlock hasp for the door.

The NEMA 1 design is vented, usually through vent hole patterns on the top, bottom, and one or more sides, which makes it non-waterproof. Falling or dripping water can enter

Figure 2e: Example of battery charger in NEMA 1 enclosure during production before wiring has been completed

the enclosure, so it isn't suitable for wet locations or exterior installations (although drip shields are available that are effective against vertically dripping water).

For those locations, there are NEMA 12 and NEMA 4 designs. NEMA 12 is designed to resist dripping and splashing water, and the ingress of dust and foreign objects, and may be provided with knockouts for external electrical connections. It isn't intended for outdoor installation.

NEMA 4 is designed for indoor or outdoor installation. It is drip- and dust-proof, and will withstand hose-directed water. If a charger requires forced convection cooling, the NEMA 4 is fitted with watertight ventilation ports and dust filters on the ports. NEMA 4X is a corrosion-resistant construction, such as stainless steel.

IP Enclosure System 2.5.1.2

The IEC IP enclosure designation system defines construction features similar to the NEMA styles, but there is no exact correlation. An approximate equivalence can be determined from Table 2c.

IEC EQUIVALENCES	
IEC 529	NEMA 250
IP00	1
IP20	1
IP21	1 (with drip shield)
IP22	12
IP30	1 (with bug screening)
IP31, IP32	12
IP33	4
IP41, IP42	12
IP43, IP44	4
IP5x	4

Table 2c: Approximate equivalence between IEC 529 & NEMA 250 enclosure requirements. See Table 2d for explanation of 2 digits following "IP"

The degree of protection afforded by an enclosure is designated by "IP" followed by two digits (IPxy), that identify the level of solid object and water protection respectively, as listed in Table 2d. For example, IP22 protects against the ingress of moderately sized solid objects (approx. ½") and dripping water at an angle.

The meanings of IPx5 and IPx6 raise an interesting question, by grading the force of water jets. NEMA 4 enclosures are designed to withstand hose-directed water, without distinguishing between water jets and powerful water jets. The test specified

Numeral	First Digit (Dust & Solid Object Protection)	Second Digit (Water Protection)
0	Not protected	Not protected
1	Protects against solid objects of 50 mm diameter or larger	Protects against vertically falling water drops
2	As above, but 12.5 mm diameter or greater	As above, but with enclosure at 15° angle
3	As above but 2.5 mm diameter or greater	Protected against spraying water
4	As above, but 1.0 mm diameter or greater	Protected against splashing water
5	Protected against dust: ingress not prevented, but shall not penetrate in a quantity to interfere with satisfactory operation or safety	Protected against water jets
6	Dust-tight: no ingress of dust	Protected against powerful water jets
7	Not defined	Protected against temporary immersion in water
8	Not defined	Protected against continuous immersion in water

Table 2d: IP system for 2-digit (IPxy) rating for protection offered by an enclosure. The first digit (x) rates dust & solid object protection; the second digit (y) rates water protection

by NEMA to qualify a NEMA 4 enclosure uses a water jet delivering 65 gallons per minute. Is that powerful enough?

Note that all the enclosures defined above are designed for non-hazardous locations. There are additional NEMA styles intended for hazardous locations. Likewise, immersion in water requires special NEMA enclosure styles.

While we're on that subject, if your charger is ever in a flood, consider replacing it. Even if the charger appears to operate following a flood, persistent damage from immersion will cause problems at some point.

Rock-n-Roll: When the Earth Moves 2.5.1.3

Many chargers are mechanically designed to withstand some level of seismic activity. In the US, the expected severity of an earthquake is classified by seismic zones; zone 4 is the most severe. If you live in California, you already know this.

For example, HindlePower's AT series single-phase chargers are fully qualified for seismic zone 4, for installation at any point in the building (the tests are more severe for the upper floors of a building). AT30, the three-phase version, is qualified to zone 4 for the two smaller enclosures. The SCR/SCRF product line has no seismic qualification.

What altitude & temperature limitations do chargers have? 2.5.1.4

The method for sizing the battery charger presented earlier (Section 2.2.2) works for normal elevations, sea level to 3,000 feet, and for the charger's normal specified temperature range, 0° to 50 °C (32° to 122 °F). Outside those ranges, some derating is required. In other words, you have to purchase a slightly larger charger than the sizing calculation would indicate.

You can rate a charger for ambient temperatures up to 70 °C (158 °F), and for elevations up to 10,000 ft (~3,000 m). See *Temperature & Altitude Derating* in Appendix B.

» ***Q: What happens if we store a charger in a very hot warehouse – say 175 °F?***

A: Not a good idea. This is the same as 80 °C. While most electronic components tolerate high temperatures without permanent effects, some components, such as LCD displays, might be damaged.

WHAT'S AVAILABLE TO HELP IN PLANNING FOR CHARGER INSTALLATION? 2.5.2

Site planning requires accurate information on equipment installation requirements, such as overall dimensions, mounting or installation considerations, weight or floor loading, and locations of conduit entrances or other wiring provisions. Standard installation drawings are usually available on manufacturers' web sites, and the price is right. You may also be able to obtain documents for overall schematic diagrams, wiring diagrams, internal component layouts, and so forth. If you are ordering equipment with custom features, you can order an optional custom drawing package that will tell you everything you need for a successful installation.

WILL A CHARGER BE TOO LOUD FOR MY ENVIRONMENT? 2.5.3

In most cases, the sound level produced by a battery charger isn't above 55dB(A), and is described as a low hum, similar to what is produced by a distribution transformer. This level is roughly equivalent to normal conversation in a quiet room. So, acoustic noise often is not a factor in deciding where to locate a charger.

If the charger shares a work location such as an office, keep in mind that the charger may produce up to 65 dB(A) sound level when charging at full tilt. That's more like a loud conversation. But also consider that the battery will probably be nearby, with the inevitable release of fumes and gases, however slight. And, some people are more sensitive to noise, and may find even the low hum of a charger to be objectionable. You might want to build a separate closet for the system.

In case you're wondering where db(A) comes from, here's a quick run-down.

SOUND LEVEL

Sound, or noise, is measured by a logarithmic scale called *Sound Pressure Level (SPL)*. In the 1930s, Fletcher and Munson, working for Bell Labs, developed "equal loudness" curves for human hearing. Human ears aren't as good at hearing very low frequency sounds, especially below 100 Hz, as they are at the mid-range of normal voice frequencies, about 500 Hz to 3,000 Hz. Fletcher and Munson established 1.0 kHz as the reference point. They found that, for relatively quiet sounds, the SPL at 100 Hz had to be 20 dB louder for humans to perceive the same loudness as at 1.0 kHZ. For louder sounds, the difference wasn't as great.

The resulting curves, calibrated in *phons,* gave rise to three filter characteristics for measuring *Sound Level*, which is the term for Sound Pressure Level adjusted for the hearing contours. The filters are named – you guessed it – A, B and C. Filter A is used for virtually all acoustic Sound Level measurements in industry. A level of 65 db(A) is Sound Level, in phons. The A curve matches the ear's response at 40 phons; the B and C curves are used for higher Sound Levels.

The curves have been revised over the years, but the A filter remains the same.