

Measuring Energy Efficiency Improvements in Industrial Battery Chargers

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ABSTRACT

Industrial battery chargers have provided the energy requirements for motive power in industrial facilities for decades. Their reliable and durable performance, combined with their low energy consumption relative to other industrial processes, has left the core charger technology unchanged since its introduction to the market. Recent improvements in charger technology have led to a new generation of high frequency chargers on the market that can provide energy efficiency improvements over existing Silicon Controlled Rectifier (SCR) and Ferroresonant charger technologies. We estimate there are approximately 32,000 three phase chargers in use within Pacific Gas & Electric Company's service area, using roughly 750 to 1,000 GWh per year. A 10 percent efficiency improvement on every charger would save about 75 to 100 GWh per year.

There are three areas of energy losses in the battery and charger system:

- Power Conversion Efficiency (energy out of charger vs. energy into charger)
- Charge Return (energy out of battery vs. energy into battery): some amount of overcharge is necessary for battery health, but chargers vary in the degree which they overcharge
- Standby losses when no battery is connected

Figure 1 shows a schematic of the energy flow through a battery and charger system.

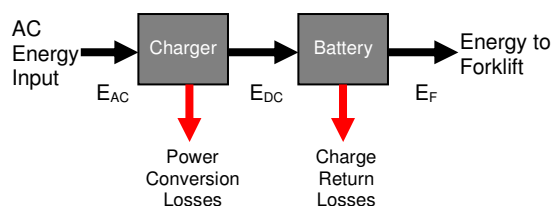


Figure 1 Battery and Charger Energy Losses

PG&E and Southern California Edison (SCE) are testing industrial battery chargers according to a California Energy Commission (CEC) approved test procedure. This test procedure, developed with charger manufacturer input as part of the CEC's Codes and Standards process, specifies test conditions during active charge, maintenance charge and standby modes. The results from this testing are expected to provide independent confirmation of

vendor claims of energy efficiency improvements during all modes of charger operation, and will form the foundation of data for utility energy efficiency programs.

Initial test results of one battery charger from each technology type show the Hybrid and High Frequency technology as the top performers when compared to the SCR and Ferroresonant chargers. Multiple chargers from each technology group will be tested in the first half of 2009 to determine an average performance for each technology type. The full set of results will be available in summer 2009.

Table 1 Charger Test Results

Technology	Power Conversion Efficiency	Charge Return*	No-battery Power (W)
SCR	83%	1.348	10
Ferroresonant	85%	1.149	8
Hybrid	87%	1.119	6
High Frequency	89%	1.107	15

*based on 80% depth of discharge

CHARGER TECHNOLOGY

Three primary battery charger technologies exist that are common to forklift chargers: Ferroresonant, Silicon Controlled Rectifier (SCR), and High Frequency (or IGBT). The difference in charger efficiency and other characteristics are primarily determined by the core technology used to rectify the AC input power to DC output to the battery and transform the voltage to one that is appropriate for the battery.

Ferroresonant

The Ferroresonant charger takes advantage of the unique properties of ferroresonance to supply a regulated output that is relatively independent of AC input voltage fluctuations. The ferroresonant transformer is able to accomplish this by using a three winding transformer, with the output winding in parallel with a capacitor. This resonant tank circuit drives the transformer core into magnetic saturation, enabling it to provide a constant output despite input fluctuations. This enables the charger to provide a consistent output to the battery without the presence

of any advanced electronics, resulting in a very durable, long-lasting charger.

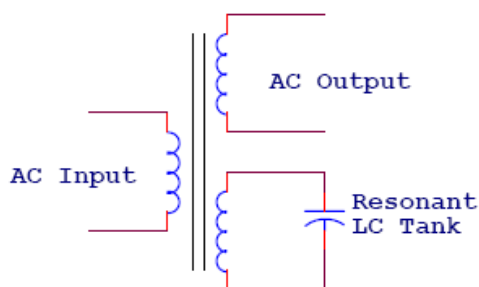


Figure 2 Ferroresonant Transformer

The properties of the ferroresonant transformer make for a simple, durable and cost-effective charging technology, but have disadvantages in their size, weight and energy efficiency, particularly at part load. Ferroresonant chargers are relatively efficient at full load, achieving efficiencies of 88 to 90 percent but at lower loads, the power conversion efficiency drops off dramatically due to the large fixed losses in the transformer. Also, the absence of advanced electronic charge control circuitry, though improving durability, can cause damage to more sensitive, modern sealed batteries such as NiMH and Li Ion technologies.

Silicon Controlled Rectifier (SCR)

SCR battery chargers use a standard transformer to reduce the AC voltage input, and a diode rectifier to convert AC to DC for charging the battery. Unlike a Ferroresonant charger, where the transformer also controls the charge output, the SCR charger uses a Silicon Controlled Rectifier to control the charge output current. The SCRs are controlled and can be interfaced with a microprocessor to allow the charger to perform various charging profiles.

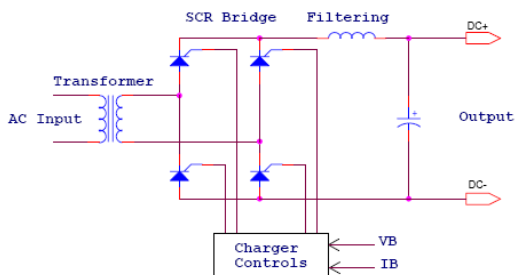


Figure 3 Silicon Controlled Rectifier

The presence of an SCR allows the charger to provide more precise charge control, enabling the charger to charge more advanced sealed batteries, as opposed to only flooded lead acid batteries. It also

allows the chargers to charge a range of battery voltages, adding flexibility for users.

High Frequency

High Frequency chargers, often called Switch Mode, MOSFET, or IGBT chargers, are commonly found in many portable charging applications, where their small size and weight coupled with good charge control are valuable. They are increasingly making their way into forklift charging applications where their improved energy efficiency, charge control and power factor can provide energy savings, a smaller and lighter charger and better charge control and flexibility.

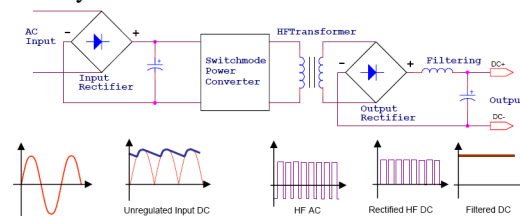


Figure 4 High Frequency Charger

High Frequency chargers contain a rectifier to convert the AC input power to an uncontrolled DC output. This DC output is then chopped into a High Frequency AC output at a frequency ranging from tens to hundreds of kHz. This is four to five orders of magnitude larger than the input AC frequency of 50 or 60 Hz. The High Frequency AC output voltage is transformed to the charger output voltage and then rectified and filtered to provide a smooth DC output at the required voltage and current. The advantage of this architecture is that the High Frequency transformer is drastically decreased in size compared to a transformer operating at 50 or 60 Hz, which decreases energy losses. This is because the size of an isolation is inversely proportional to the operating frequency.

Hybrid

The hybrid charger combines the constant voltage output possible with the ferroresonant transformer with the charge control circuitry of the SCR charger. This charger takes advantage of the Ferroresonant chargers durability and simplicity while improving the energy losses and charge control for the charging finishing rate possible by using the SCR controls.

TEST PROCEDURE

A test procedure was developed for the California Energy Commission's (CEC) Codes and Standards process. This test procedure was developed with industry stakeholder input for battery and charger systems. This procedure, developed by Ecos

Consulting, for PG&E, and SCE, specifies test conditions for both chargers and batteries in three modes of operation:

- Active charger
- Maintenance Charge
- Standby or No-battery mode

The procedure is divided into two parts, part one for battery and charger systems less than 2 kW that operate on single phase AC power and part two which provides a method for testing battery charger systems designed to power motive equipment. Forklift battery chargers, which are primarily powered by three-phase AC power and charge lead acid batteries, fall under part two of the test procedure.

This procedure was specially tailored toward accounting for the unique variability of lead acid batteries. Care is taken to ensure that consistent battery conditions provide for comparable test results on charger performance. Initial battery capacity must be certified to Battery Council International Standard 14 (BCIS-14) and battery specific gravities, temperatures and voltages must be recorded after each test.

The test procedure calls for three charge and discharge cycles for each battery and charger, one to 80 percent depth of discharge (DOD), one to 100 percent DOD, and one to 40 percent DOD. Following these charge/discharge cycles, the charger is tested in maintenance mode for 72 hours with the battery connected and is then tested for one hour in no-battery mode with the AC power still connected to the charger.

The full test procedure (Energy Efficiency Battery Charger System Test Procedure Version 2.2, November 12, 2008) can be seen here:

<http://www.efficientproducts.org/>

FAST AND CONVENTIONAL CHARGING

There are two general methods of managing forklift battery charging and battery swapping operations. These are generally referred to as fast charging and conventional charging. The primary difference between the charging schemes is the presence of a battery swapping station in conventional charging.

Conventional: To fully recharge a battery at 80 percent DOD requires approximately 8 hours. Each lift truck will have two or more batteries dedicated to it. When the battery on the lift truck has reach 80

percent DOD, the truck returns to the battery swapping station to exchange the empty battery for a fully charged battery. In this configuration, one battery is always on the truck while another battery is charging.

Fast: These chargers can charge the battery in as little as one hour. In this scheme, each truck has only one battery and it is charged during breaks in the operation. Capital requirements are significantly reduced from the lower number of batteries needed and the lack of a battery swapping infrastructure. However, the charge rate is significantly increased and coupled with the fact that all batteries are charged at the same time (during staff breaks), fast charging will certainly impact facility energy demand. This can often occur during peak billing periods as the charging time that is common to most facilities is during the lunch break.

There is no attempt to differentiate between the energy impacts of different charging methods through this efficiency testing. The choice to use fast charging, opportunity charging or conventional charging is based upon the needs of the facility and the priorities of the organization and will not be driven by energy efficiency alone. The focus of this test work is solely on the energy efficiency of conventional battery charger technology.

MARKET OPPORTUNITY

PG&E is sponsoring this test work as a direct result of the energy saving opportunity that is available in the installed base of forklift battery chargers in our service territory. It is estimated that 32,000 three phase chargers and 12,500 single phase chargers are in use in PG&E's service territory of northern California. It is estimated that the 32,000 three phase chargers consume 750 to 1,000 GWh/yr in energy. A 10 percent power conversion efficiency improvement on all the three phase chargers would result in energy savings of 75 to 100 GWh/yr. Those savings do not even account for the opportunity from lower the Charge Return losses. The savings across the US could be twenty times that figure, or 1,500 to 2,000 GWh/yr.

TEST RESULTS

As of late February 2009, the charger testing is still ongoing, but initial results of one representative charger from each technology family are available. The final report of all results will be posted to the Emerging Technologies Coordinating Council (ETCC) website in summer 2009:

www.etcc-ca.com

There are a number of elements that make up battery charger energy efficiency including: power conversion efficiency, charge return and standby losses.

Power conversion efficiency is a measure of the energy lost as the charger converts the AC input power to DC output power. It is defined as:

$$\text{Eff}_{\text{PC}} = E_{\text{DC}}/E_{\text{AC}} \quad \text{Equation (1)}$$

where E_{DC} and E_{AC} are shown in Figure 1.

Charge return, or overcharge losses occur when the charger supplies excess energy to the battery which is dissipated as heat. Some amount of overcharge is required for battery health, as it keeps the electrolyte from stratifying within the cells and ensures all cells maintain a consistent voltage. Charge return is defined as:

$$\text{Charge Return} = E_{\text{DC}}/E_{\text{F}} \quad \text{Equation (2)}$$

where E_{DC} and E_{F} are shown in Figure 1.

Losses also occur when the charger draws a small amount of AC power to energize the charger controls when no battery is attached to the system.

Initial results show a 6 percent power conversion efficiency improvement from the worst to the best performing charger. This figure represents the percentage of energy delivered as DC power from the charger compared to the AC energy input to the charger. Even more dramatically, the charge return multiple can vary from 1.107 to 1.348. This means that the chargers are returning from 11 percent to 35 percent energy in excess of that dissipated from the battery in as it discharges to 80 percent depth of discharge. While some overcharge of the battery is necessary, there is ample opportunity to reduce wasted charging energy by as much as 24 percent per charge.

The losses from no battery mode from all chargers were minimal, ranging from 6 to 15 watts.

Table 2 Charger Test Results

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When compared to the poorest performing charger (the SCR) customers could save approximately 10,740 kWh/yr if they were to upgrade to a High Frequency charger. That figure assumes 20 charges per week, 52 weeks per year, with each charge cycle lasting 8.4 hours. At \$0.10 per kWh, that is annual energy cost savings of over \$1,000 per charger.

It should be noted that charge return results can vary from charger to charger within technology families, so care should be taken when drawing broad results from the small sample of test results. But even when comparing the Ferroresonant results to the High Frequency results, where the charge return results are within 5 percent, there is an annual energy use difference of 2,580 kWh/yr, which indicates an energy cost savings opportunity of \$260 per year.

Power Factor

One of the often touted benefits of certain charger technologies is an improvement in power factor, the ratio of useful power to apparent power on the facilities electric circuits. The test results confirm that there is an improved power factor, particularly when compared to an SCR charger.

Table 3 Charger Power Factor

Technology	Power Factor
SCR	0.853
Ferroresonant	0.966
Hybrid	0.966
High Frequency	0.937

One important point to understand is that improved power factor does not directly correlate to kWh saved from the utility bill. Utility revenue meters will track and record power factor for the facility. The additional amperes generated by the apparent power are not billed as kWh in the same way that the useful power is billed as kWh. Often, utilities charge power factor penalties as a separate item on the bill if they fall beneath a certain threshold. If your facility has a

poor power factor and you have a large proportion of your facility load as battery chargers, then improving the battery charger power factor can have a direct impact on the power factor portion of your utility bill. The impact is highly site specific, difficult to calculate up front and strongly dependent on how your electric utility handles power factor charges.

FUTURE EFFICIENCY OPPORTUNITY

Both the High Frequency and Hybrid chargers offer energy savings over the traditional SCR and Ferroresonant battery chargers. The most efficient chargers have a nearly 90% power conversion efficiency, making additional improvements costly and limited in opportunity. However, a great variability exists in charge return optimization. The results of these four charger tests indicate charge return varies from as high as 1.35 to as low as 1.11.

One of the challenges in reducing charge return is in the variability of battery conditions. Batteries are returned to the charger in widely varying states of charge, and it is dependent on the charger intelligence to determine when the battery is fully charged. Often the batteries and chargers are made by different manufacturers and do not have any capability to communicate to each other. Technologies to measure and communicate the battery state of charge as a feedback loop to the charger controls can offer the opportunity to optimize the charge return levels to the lowest required to maintain battery health.

In addition to improving energy efficiency, the nature of battery charge allows for shifting the load out of the utility peak hours. Timers and improved controls on the chargers can enable this function. This can reduce the cost for energy to charge the batteries, provided the facility shift schedule allows it.

REFERENCES

Foster-Porter, Suzanne et al., Energy Efficient Battery Charger System Test Procedure, Version 2.2, 12 November 2008, <www.efficientproducts.org/reports/bchargers/BatteryChargerSystemTestProcedure_V2_2.pdf>

Geist, Tom, et al. Designing Battery Charger Systems for Improved Energy Efficiency, 28 September, 2006, <www.efficientproducts.org/reports/bchargers/1270_BatteryChargerTechnicalPrimer_FINAL_29Sep2006.pdf>

Kutkut, Nasser, Battery Charger – Technology Overview, <www.catalina-capri-25s.org/tech/BatteryChg.pdf>

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