Designing Battery Charger Systems for Improved Energy Efficiency

A Technical Primer

Authors:

Tom Geist
EPRI Solutions, Inc.
tgeist@epri.com

Haresh Kamath
EPRI Solutions, Inc.
hkamath@epri.com

Suzanne Foster Porter
Ecos Consulting
sporter@ecosconsulting.com

Peter May-Ostendorp
Ecos Consulting
postendorp@ecosconsulting.com

Prepared for the California Energy Commission
Contract # 500-04-030, Brad Meister, Contract Manager
September 28, 2006

Acknowledgements

A number of individuals reviewed this paper to help refine concepts and check for technical accuracy. We want to thank the following people for contributing to this review process:

Jordan Smith, Southern California Edison
Loic Gayllac, Southern California Edison
Richard Cromie, Southern California Edison
David Korn, Cadmus Group
Shawn Shaw, Cadmus Group
Chuck Mullet, ON Semiconductor
Chris McCoy, TIAX
Chris Calwell, Ecos Consulting

Introduction

While most modern electrical appliances receive their power directly from the utility grid, a growing number of everyday devices require electrical power from batteries in order to achieve greater mobility and convenience. Rechargeable batteries store electricity from the grid for later use and can be conveniently recharged when their energy has been drained. Appliances that use rechargeable batteries include everything from low-power cell phones to high-power industrial fork lifts. The sales volume of such products has increased dramatically in the past decade. Hundreds of millions of these products are sold annually to businesses and consumers, with close to a billion in use in the U.S. alone.

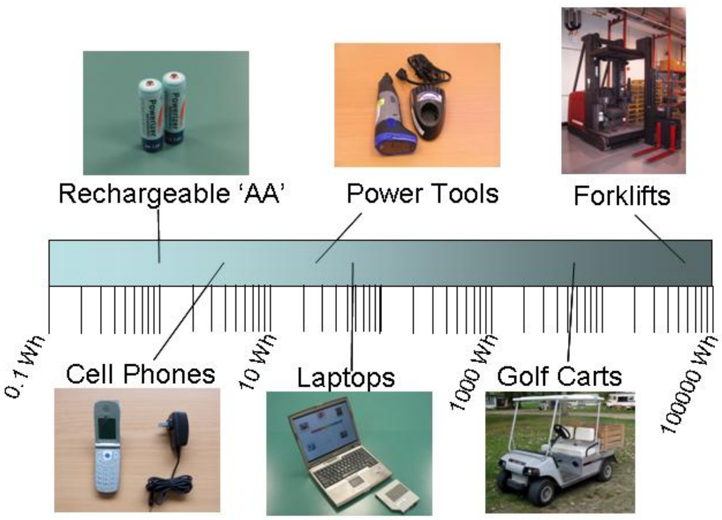


Figure 1. Various battery-powered devices and their relative battery capacities

The system used to draw energy from the grid, store it in a battery, and release it to power a device is called a *battery charger system.* While designers of battery charger systems often maximize the energy efficiency of their devices to ensure long operation times between charging, they often ignore how much energy is consumed in the process of converting ac electricity from the utility grid into dc electricity stored in the battery. Significant energy savings are possible by reducing the conversion losses associated with charging batteries in battery-powered products. We can achieve these savings using technology that is readily available today and employed in existing products.

In this primer, we will describe today's standard battery charger designs and then highlight several design strategies for improving their efficiency.

Battery Charger Systems: Functions and Efficiency

Construction and Basic Functions of a Battery Charger

Batteries cannot be charged simply by connecting them to a standard wall outlet. A series of power conversion steps must be performed to shape the high-voltage ac electricity from the utility into low-voltage dc electricity that can be accepted by the battery, and the charging process must be controlled so that the battery receives the appropriate amount of current. Battery chargers accomplish all this through three functions: 1) reducing voltage from the utility level to the lower voltage at which batteries operate, 2) rectifying ac electricity into dc electricity, and 3) controlling the low-voltage dc current into the battery. The first two stages are functions typically incorporated into *ac-dc power supplies*.[1] The addition of the third stage – controlling the rate of charge of the battery with *charge control circuitry* – is typically what distinguishes a battery charger from an ac-dc power supply. These power supply and charge control circuitry subsystems are illustrated in Figure 2.

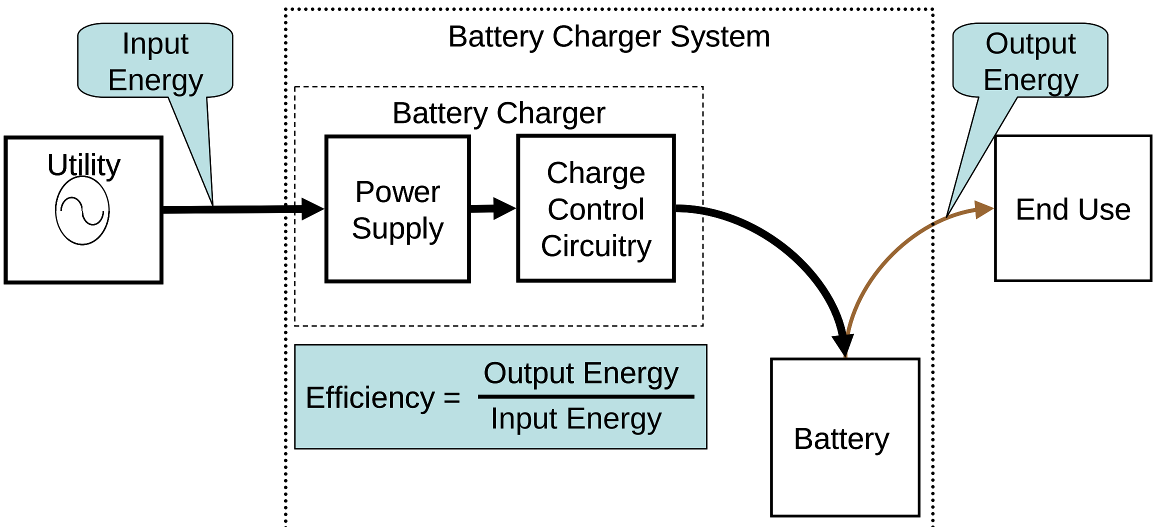


Figure 2. Block schematic showing the general configuration of a multi-piece battery charger system with a discrete power supply and charge control circuitry. The efficiency calculation is made over a 24 hour charge and maintenance period and a 0.2 C discharge for the battery[2].

Some battery chargers, which we call *multi-piece chargers*, are simply conventional power supplies with additional control circuitry added to the output. Multi-piece chargers are cheap to design and build, being specified from pre-designed, off-the-shelf

---

[1] Mansoor, A. and Calwell, C. "Designing AC-DC Power Supplies for Improved Energy Efficiency: A Technical Primer." Published by the California Energy Commission through the Public Interest Energy Research (PIER) Program, available at http://www.efficientpowersupplies.org.

[2] Porter, S.F., Kamath, H. and Geist, T., "Draft 2 Energy Efficiency Battery Charger System Test Procedure, February 28, 2006." Published by the California Energy Commission through the Public Interest Energy Research (PIER) Program, available at http://www.efficientpowersupplies.org

components, but tend to be relatively inefficient. They are commonly used in smaller, less expensive products. The power supply, often an *external power supply*, may be an ac-dc power supply with a regulated output voltage, or an ac-ac power supply with an ac output. The output from this kind of power supply is changed to regulated dc current through the charge control circuitry.

Single-piece battery chargers are integrated devices custom-designed for a specific application. In such devices, the power supply and charge control circuitry are integrated. Figure 3 shows common examples of multi-piece and single-piece battery charging products.

Figure 3. A multi-piece battery charger for AA batteries (left) and a single-piece battery charger for a power tool (right). Note that the multi-piece charger connects to ac with an external power supply.

Battery chargers operate in three *modes*:

1. *Active charge mode*, during which the battery is being charged from a discharged state. Most battery chargers draw the most power from the outlet during this mode.

2. *Maintenance charge mode*, during which the battery charge state is being maintained at a fully-charged state. A battery charger typically draws less power in this mode than in active charge mode.

3. *No battery mode,* during which no battery is connected to the charger at all. Many chargers continue to draw a current in this mode, even though they are doing no useful work.

Each of three modes has inefficiencies associated with it. Depending on how the product is used, wasted energy may be largely associated with a particular mode. For instance, a UPS system spends the majority of its time in maintenance mode, and experiences active charge relatively rarely. In this case, wasted energy depends largely on maintenance mode efficiency. Cellular phones, on the other hand, are usually drained and fully recharged every day, so that they spend a significant time in active charge mode. In many cases, the chargers for cellular phones are left plugged in even if the phone is not present, so that no-battery mode may also be important. The 24-hour charging and maintenance period used in testing is intended to capture inefficiencies in both active charge and maintenance modes; separate no-battery mode testing is required to measure inefficiencies when a battery is not attached.

The Battery

Batteries are electrochemical energy storage devices. The chemical energy contained within the battery can be converted to dc electrical energy. In rechargeable batteries, the process can be reversed, converting dc electrical energy into stored chemical energy.

Rechargeable batteries are classified by their *chemistries*, a term used to describe the reactant materials and underlying chemical reactions which form the mechanism for energy storage. Four chemistries are commonly used in consumer applications: lead-acid, nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and lithium ion (Li Ion). Battery chemistries are assessed according to a number of criteria, which include cost, self-discharge (rate at which batteries naturally lose their charge while not in use), energy density (the energy a battery can store, divided by its volume), specific energy (the energy a battery can store, divided by its weight), and cycle life (the number of times a battery can be discharged and recharged before it wears out).[3] Every battery chemistry has its own advantages and disadvantages with respect to these criteria. Table 1 provides a brief overview of the characteristics of various battery chemistries commonly used in consumer products.

Table 1: Characteristics of Various Battery Chemistries[4]

	Lead Acid	**NiCd**	**NiMH**	**Li-ion**
Self-Discharge Rate	Very low	High	High	Moderate
Overcharge tolerance	High[a]	Moderate	Low	Very Low
Specific Energy (Wh per kg)	25to 35	35 to 65	40 to 100	110 to 190
Cycle Life (up to 80% of initial capacity)	200 to 300	1000 -1500	750 to 1000	500 to 1000[b]
Cost per unit Energy ($/Wh)[c]	$0.22 to $1.00	$0.80 to $2.00	$0.40 to $2.00	$0.60 to $2.50
Voltage per cell (volts)	2	1.2	1.25	3.6

[a] Valve-regulated lead-acid batteries are less tolerant of overcharge than flooded lead-acid
[b] Li-ion polymer has a shorter cycle life (300-500).
[c] Based on average prices for commercially-available small batteries purchased in quantity, 12/2005

Battery Charger System Efficiency

As shown in Figure 2, the “battery charger system” comprises both the battery charger (providing energy conversion) and the battery (providing energy storage). The boundary of the system occurs where energy enters from the utility grid and where energy is released to an end use appliance such as a cordless phone. The efficiency of the system is

---

[3] Strictly speaking, “energy density” is the energy capacity divided by the battery’s displacement volume, while “specific energy” is the energy capacity divided by the battery’s weight. The term “energy density” is often used for both metrics.

[4] Data compiled from: Buchmann, Isidor. *Batteries in a Portable World*, Second Edition, Cadex Electronics. 2001; *Handbook of Batteries*, ed. David Linden, McGraw-Hill, 2001.

defined as the total energy released by the battery to the powered appliance divided by the total energy required to charge and maintain the battery over 24 hours[5]. Figure 4 shows the results of a system efficiency test of a battery charger system. Plotted in this graph are the energy used to charge the battery and the useful energy extracted from that battery for use by a golf cart.

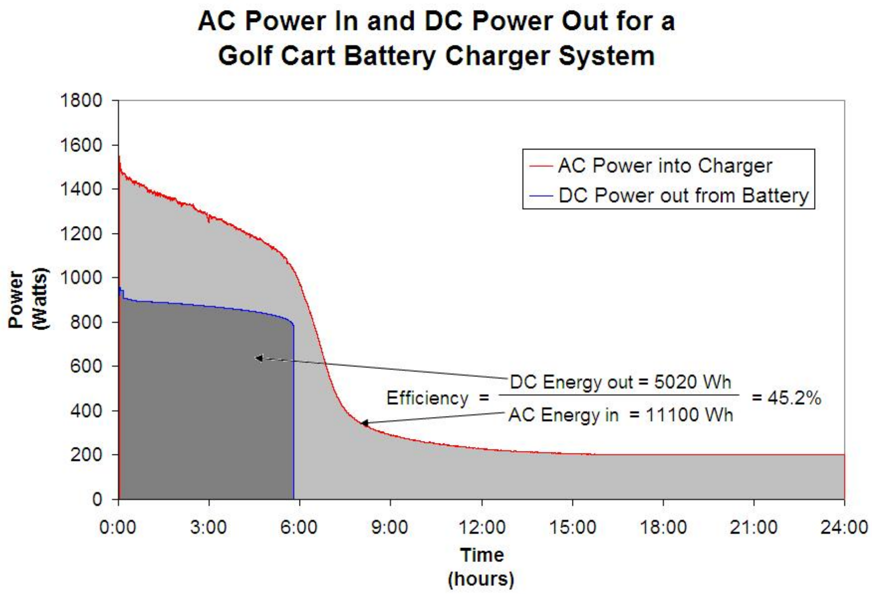


Figure 4. Plot of power versus time for both charge and discharge of a battery charger system. The lightly shaded area between the two lines represents the energy lost to inefficiencies during the charging process.

Battery Charger Systems: Current Practice

Most battery chargers can be divided into four basic design types, or *topologies*:

- Linear chargers
- Switch mode chargers
- Ferroresonant chargers
- SCR (silicon controlled rectifier) chargers

Linear and switch mode chargers are analogous to linear and switch mode power supplies with the exception that the charger topologies also incorporate charge control circuitry on their outputs. Most multi- or single-piece chargers are either linear or switch mode chargers. These two categories are the ones most commonly found in consumer

[5] For more detail on definitions of battery charger efficiency and test methods, visit www.EfficientProducts.org.

applications, particularly in the residential sector. Ferroresonant and SCR battery chargers form a large percentage of the chargers used in industrial applications. The following sections describe the four types of chargers, where they are used, and their major advantages and disadvantages.

Linear Chargers

Linear chargers consist of a power supply, which converts ac power to lower voltage dc power, and a linear regulating element, which limits the current that flows into the battery. The power supply typically consists of a transformer that steps down ac power from 115 Vac to a lower ac voltage closer to that of the battery and a rectifier that smoothes out the existing sinusoidal ac signal into a constant-voltage dc signal. The linear regulating element may be a passive component such as a resistor or an active component such as a transistor that is controlled by a reference signal.

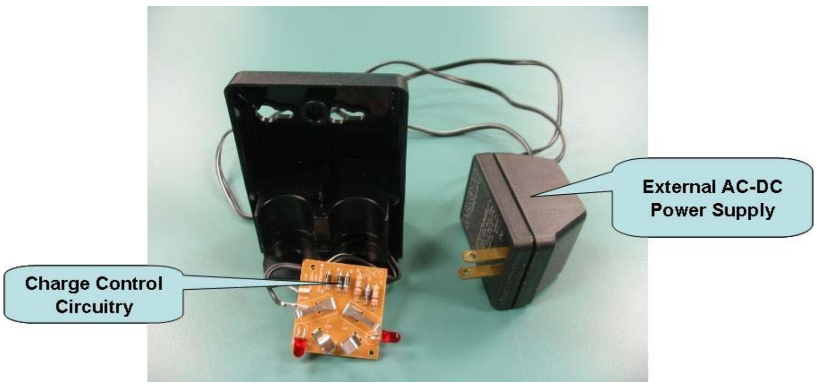


Figure 5. A linear charger using a resistor to regulate output current, designed to charge NiCd power tool batteries.

The principal difference between a linear power supply and a linear battery charger is that the battery charger incorporates a battery charge control element to regulate current output. Figure 6 shows a simplified schematic of a linear charger with a linear power supply and a resistor as the current regulating element.

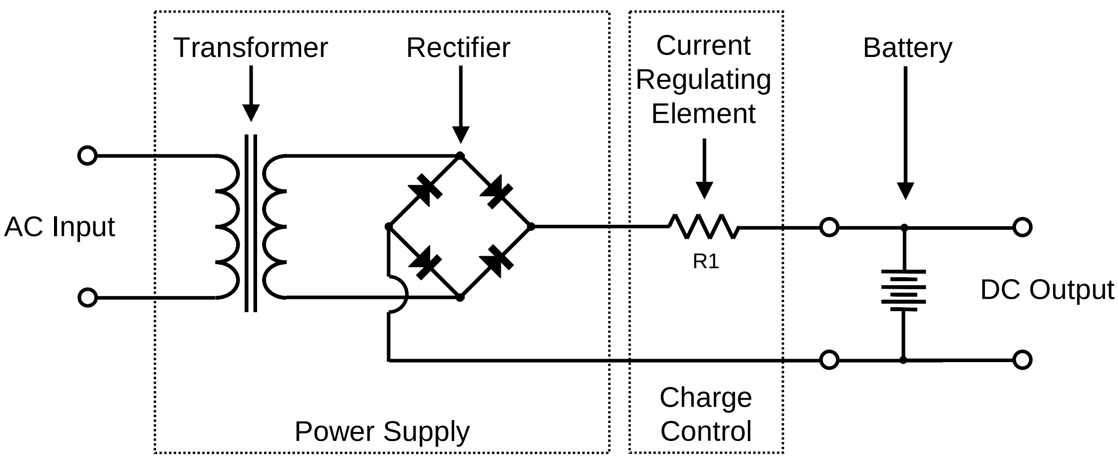


Figure 6. Simplified schematic of a single-piece linear charger using a resistor to regulate output current.

The functional components of the battery charger are not always as discrete as shown above. Consider, for example, the charger in Figure 7. The designer of this charger has further economized by reducing the rectifier to a single diode, and by using a high-resistance wire in the transformer itself as the current regulating resistor. This type of charger is common in the most inexpensive NiCd battery-powered products, since these batteries do not require sophisticated output regulation and sensing to prevent overcharge.

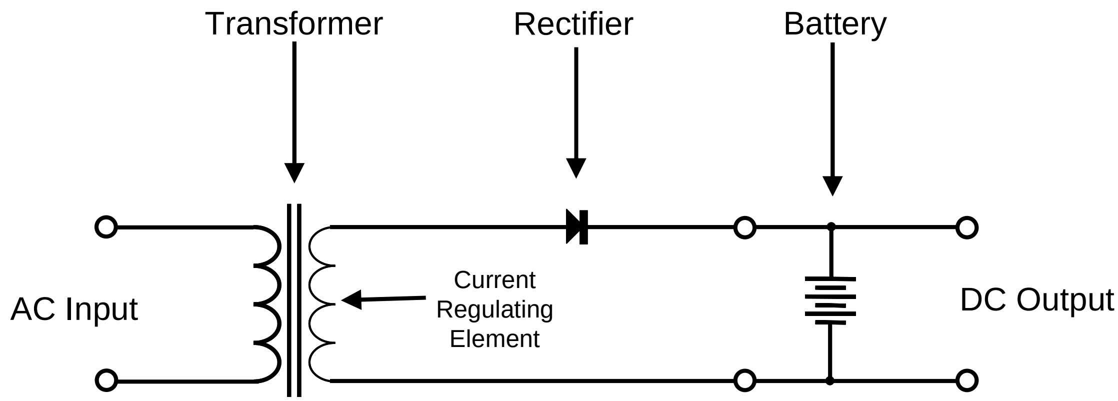


Figure 7. Simplified schematic of a severely economized single-piece linear charger

Some linear battery chargers are composed of two pieces, with an external power supply and battery charge control circuitry in separate housings. The power supply may contain only the transformer (for ac-ac power supplies), or both the transformer and the rectifier (for ac-dc power supplies). Other components may be located in a separate base station or with the battery.

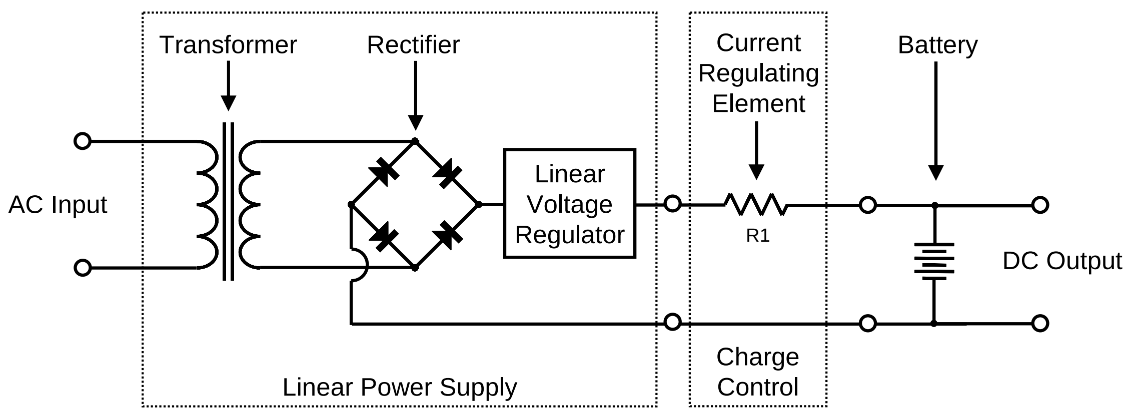


Figure 8. Simplified schematic of a multi-piece linear charger using an external power supply with a resistor as the regulating element

Note that the *power supply* might be either a linear or a switch mode power supply, but the presence of a linear current regulating element (the resistor) makes the *charger* a linear charger. When a linear power supply is used, there is a substantial reduction in efficiency, since there are *two* linear dissipative elements in series: one in the power supply to regulate voltage and one in the charge control circuitry to regulate current. This approach is common for less expensive equipment, because linear external power supplies are inexpensive and readily available off-the-shelf.

How efficient are linear chargers? Linear chargers control output current by dissipating excess energy from the regulator as heat, allowing only the desired current to reach the battery. As a result, a linear charger will always be somewhat inefficient due to the losses in the current regulating element. In active charge mode, energy losses occur mainly in the current regulating element, because of the voltage drop across the current regulating element. The battery voltage rises as it is charged, reducing this voltage drop and the corresponding loss. In maintenance mode and no-battery mode, energy losses occur primarily in the power supply section. These losses are independent of the losses in the battery during charge and discharge. Overall, linear battery charger systems may have total cycle efficiencies (as defined in Figure 2) ranging from 2 to 35%, including losses in the battery.

Switch Mode Chargers

The switch mode charger is similar to a switch mode power supply, in which ac power from a wall outlet is converted to high-voltage dc power by a rectifier, and then converted to low-voltage dc power through a dc-dc converter. Figure 10 illustrates the parts of a switch mode power supply for a cell phone. In this case the current control is performed by a dc-dc converter within the cell phone, making this product a two-stage multi-piece charger.

Figure 9. A switch mode charger designed to charge a cell phone battery.

In principle, the only difference between switch mode chargers and switch mode power supplies is that switch mode chargers contain additional charge control circuitry to regulate current flow into the battery. The charge control regulates the way in which the power switch turns on and off, and may be accomplished through a circuit, a specialized integrated chip, or some type of software control. A simplified schematic for a single-piece switch mode charger is shown in Figure 9.

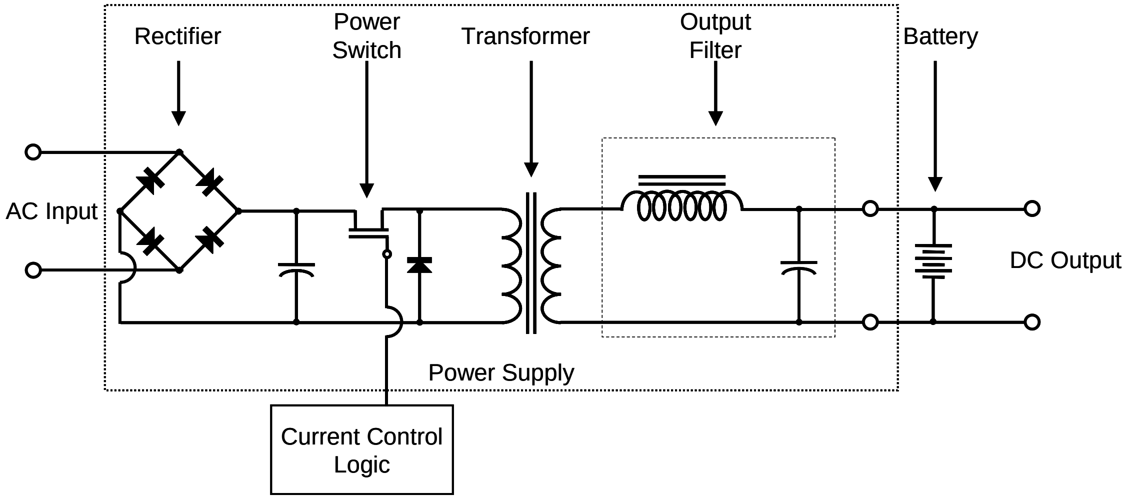


Figure 10. Simplified schematic of a single-piece switch mode charger[6].

In practice, most switch mode chargers (particularly those used for portable electronic products) are often constructed with two switch mode converters in series. The first converter, a conventional switch mode external power supply, converts ac power into a constant-voltage dc output. The second is a dc-dc converter, often housed with the battery. This two-stage charging system is more complicated and somewhat less efficient than the single stage charger described above. But it is often more cost-effective to design and build a two-stage charger for small equipment, as the power supply and the dc-dc converter can be purchased separately off-the-shelf. Two-stage chargers are commonly used in laptop computers and in some cellular phones. A simplified schematic for a two-stage multi-piece switch mode charger is shown in Figure 11.

[6] The schematic shown here describes only one of many different topologies that are used in switch mode power supplies and chargers. The topology used for a charger may vary with the application, the power output, and the manufacturer. Switch mode chargers of any topology are generally more efficient than the other types of charger.

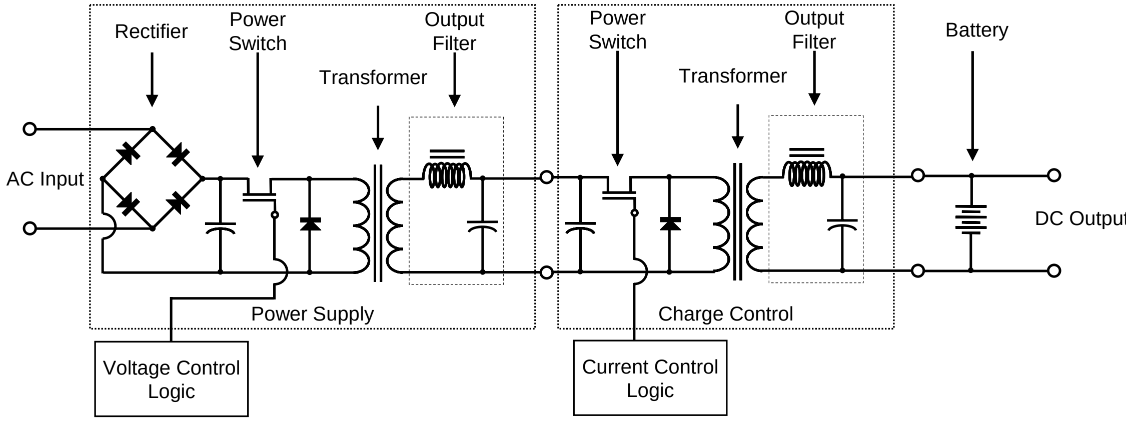


Figure 11. Simplified schematic of a two-stage switch mode charger. Note the split between the voltage-controlled power supply stage and the current-controlled charge control stage.

Switch mode chargers are widely used in small portable applications, especially in high-tech equipment such as laptop computers, cellular phones, and personal digital assistants (PDAs). While the cost of switch mode chargers makes them relatively rare in larger applications, they are gaining ground in specialized applications such as fast chargers for lead-acid forklift batteries and other materials handling equipment. The topology of the charger may change somewhat in larger applications, but the principle is the same.

Switch mode chargers are generally more efficient than linear chargers in all modes. During active charge, most losses occur in the switch and the output rectifier diode, since a great deal of power is passing through these components. During maintenance mode and no-battery mode, on the other hand, most losses result from the power drawn by the control circuitry. Overall, full-cycle efficiencies for switch mode battery charger systems range from 40 to 60%, including losses within the battery. We will address improvements to switch-mode chargers in the later section, "Improving the Efficiency of Switch-mode Chargers."

Ferroresonant Chargers

Ferroresonant chargers (sometimes called ferro chargers), operate by way of a special component called a ferroresonant transformer. The ferroresonant transformer reduces the voltage from the wall outlet to a lower regulated voltage level while simultaneously controlling the charge current. A rectifier then converts the ac power to dc power suitable for the battery. Figure 12 shows a block diagram of a ferroresonant charger.

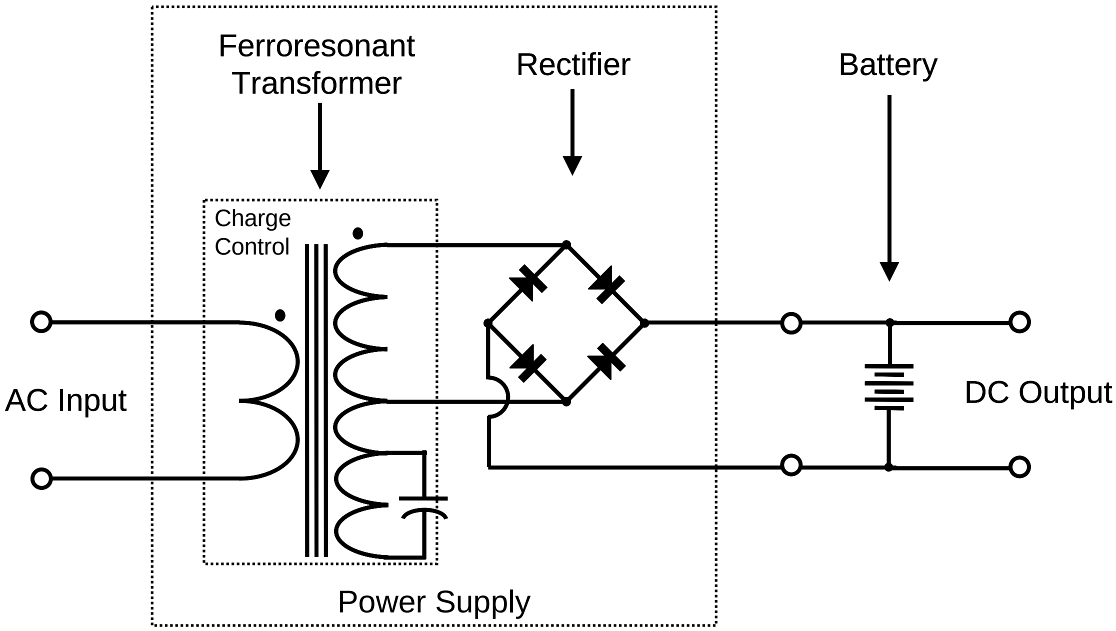


Figure 12. Simplified schematic of a ferroresonant charger.

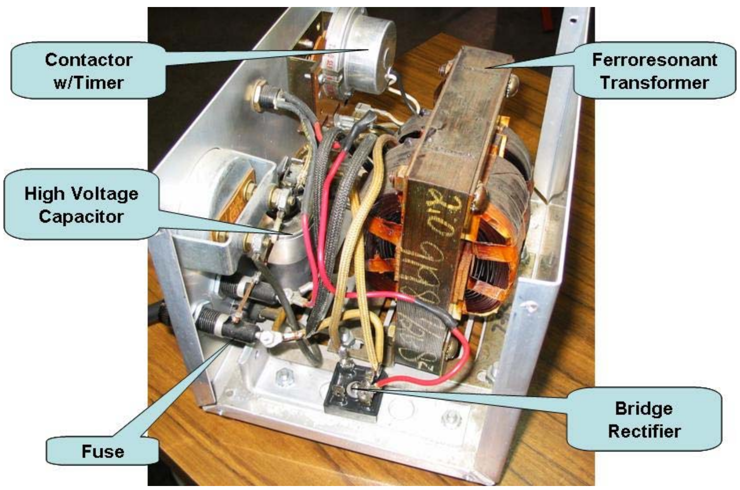


Figure 13. The view inside a 350 W ferroresonant golf cart battery charger.

Ferroresonant chargers have been used for decades to charge flooded lead-acid batteries, including those used in electric vehicles such as golf carts and material handling applications such as forklifts and electric pallet jacks. These chargers are highly cost-effective for larger applications (particularly those for which average ac power input exceeds 500 watts), especially if the charger targets one application with a single battery voltage. They are extremely durable because of the absence of sensitive electronic components. Unfortunately, they are also heavy and bulky and are not capable of highly sophisticated current control. These disadvantages make ferroresonant chargers unattractive for smaller batteries in portable applications and unsuitable for more sensitive batteries, including those based on NiMH and Li Ion technologies.

Ferroresonant chargers tend to be less efficient than switch mode chargers, with a full-cycle efficiency range of 25 to 50% (including the battery). In all modes of operation, the largest source of energy loss is the ferroresonant transformer, which draws and consumes a fixed amount of magnetizing current regardless of the charging current. The magnetizing current is dissipated as heat within the transformer. During active charge, the losses compose a small percentage of the overall power consumption, and ferroresonant chargers are nearly as efficient as switch mode chargers. During maintenance mode, however, the losses due to magnetizing current can constitute a large percentage of the input.

Some ferroresonant chargers use an active circuit to reduce this current, resulting in higher efficiencies during maintenance charge. Active circuits are commonly used in applications in which the charger spends a large portion of its operating time in maintenance mode, such as in standby batteries used in uninterruptible power supplies (UPS), telecom reserve batteries, and utility substation batteries. Figure 14 shows charge profiles for two ferroresonant chargers, similar except for the presence of an active cutoff circuit.

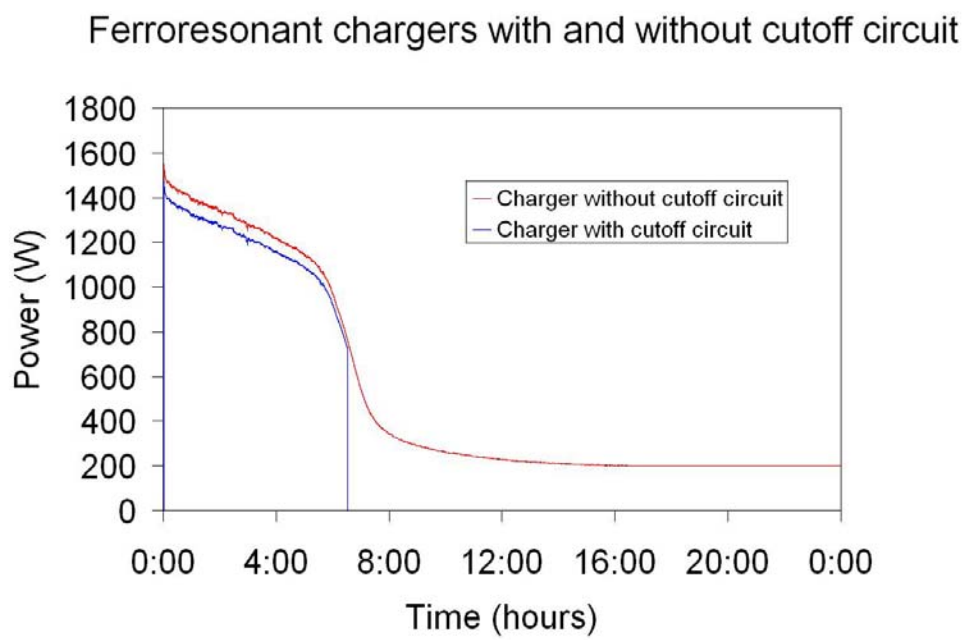


Figure 14. Charge Profiles for ferroresonant chargers, one with and one without a cutoff circuit.

If connected to the grid, the ferroresonant transformer will draw magnetizing current even if no battery is connected to the output of the charger. For this reason, most ferroresonant designs already incorporate an automatic switch to disconnect the ferroresonant transformer from the grid if there is no battery attached to the output.

SCR Chargers

SCR chargers use a special component known as a silicon controlled rectifier (SCR) to control the current to the battery. The SCR is a controllable switch that can be turned on and off many times a second. After a transformer reduces utility voltage to a value near that of the battery, the diodes rectify the current while the SCR enables the flow of charge current according to a control signal. A block diagram of an SCR charger is shown in Figure 15.

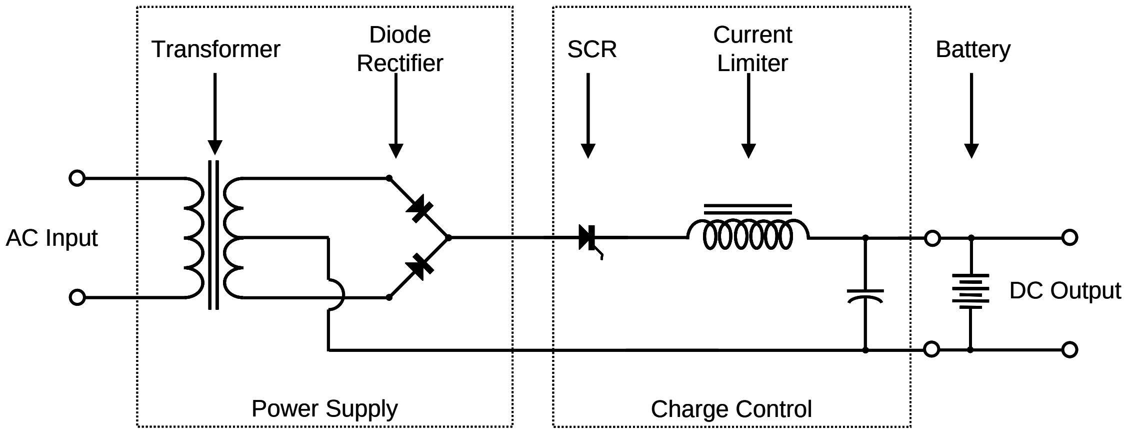


Figure 15. Simplified schematic of an SCR charger.

SCR chargers provide more charge current control than ferroresonant chargers, but are not as precise as switch mode chargers. Also, these chargers are too large for use in portable applications. Their greatest advantage is the ability to produce a number of different output voltages, allowing SCR chargers to work with a variety of different batteries. For this reason, SCR chargers are often found in multipurpose battery charging applications, such as charging engine-starting batteries. Though common in industrial applications, SCR chargers are rarely found in residential or commercial applications except where large banks of lead-acid batteries are used, such as in mid-range UPS systems.

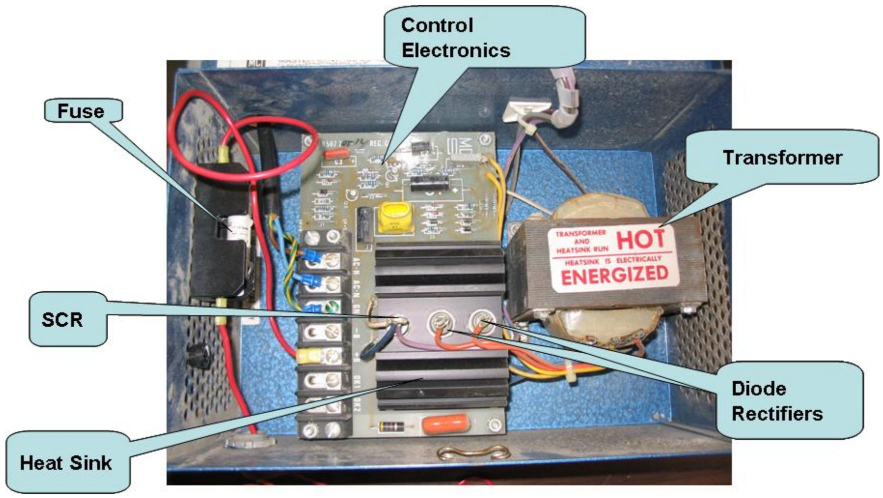


Figure 16. The view inside a SCR battery charger.

From an efficiency standpoint, SCR chargers fall between ferroresonant chargers and switch mode chargers with a full-cycle efficiency range of 30% to 55% percent (including the battery). During active mode, the largest sources of inefficiency in SCR chargers are the voltage drops across the SCR and the rectifying diodes. In maintenance mode and no-battery mode, the magnetizing current drawn by the transformer is the largest power draw.

An SCR charger configured for use with a range of battery voltages is often less efficient than an SCR charger specially designed for a specific battery voltage. In fact, an SCR charger designed for use with a number of different batteries will charge a battery less efficiently than a ferroresonant charger designed specifically for that battery.

The various charger topologies and their typical characteristics are summarized in Table 2.

Table 2: Summary of Battery Charger Topologies

Topology	***Typical Efficiency Range***	***Example Products***	***Market Segment***	***Relative Cost per Watt***
Linear	2 % - 35%	Cordless phones, power tools	Residential, Commercial	Low
Switch Mode	40% - 60%	Laptop computers, cell phones	Residential, Commercial	High
Ferroresonant	25% - 50%	Golf carts, forklifts	Commercial, Industrial	Low
SCR	30% – 55%	Recreational vehicle battery chargers, forklifts	Commercial, Industrial	Medium

Opportunities for Energy Savings

Though energy efficiency is not a high priority given to designers of battery charging products, many battery charger designers have migrated towards more efficient designs. This movement is typically motivated by other customer requirements. For example, computer manufacturers have responded to market pressure for small, light laptop computers that can operate on a wide range of international utility grid systems with systems built around integrated switch mode chargers. These chargers happen to be highly efficient, a fringe benefit that arose from the need to reduce the size and weight of the charger. Similarly, the adoption of lithium ion batteries in compact mobile applications such as cell phones came about because of their superior energy density, but brought with it the advantage of higher energy efficiency, since lithium ion batteries do not have the relatively high maintenance charge requirements of NiCd and NiMH batteries.

Even if all manufacturers adopted highly efficient battery charger systems using switch mode chargers and lithium ion batteries, there would still be opportunities for efficiency improvements, many of which can be addressed with the application of specific technologies readily available to designers today.

As is the case with power supplies, methods that lead to improved efficiency in high power operation may lead to no improvement or even reduced efficiency in low power operation. This trade-off is particularly important for battery chargers, because a battery charger must be efficient in *both* active charge (high-power operation) *and* maintenance and no-battery modes (low power operation). Designers should choose methods that are effective in improving overall system efficiency in all operational modes.

We will address improvements in all battery charger system technology types in turn, starting with linear battery chargers and switching chargers. After that, we will discuss general strategies to improve efficiency of all chargers. Lastly, we will give a conceptual design example of the most efficient charger that could be built today.

Improving Efficiency in Linear Battery Chargers

Replacing Linear Power Supplies with Switch Mode Power Supplies

As shown above, two-piece linear chargers that are composed of external power supplies with regulating elements tend to be among the most inefficient designs, since losses occur in both the power supply and the regulating element. A simple way to save energy is to ensure that both parts of this design are as efficient as they can be. Replacing linear power supplies with switch mode power supplies can improve efficiency substantially. Switch mode power supplies are now readily available from a variety of vendors, and their prices have fallen significantly, making them a competitive alternative to linear power supplies. Despite the use of a switch mode *power supply*, the *charger* is still considered a linear charger because of the presence of a linear charge current regulating element.

The gains that can be achieved through these approaches are illustrated in Figure 17 and Figure 18. Figure 17 shows a linear power supply with a resistor used as a linear regulator. We measured the energy passing through each point in the system (in mWh) over a 24-hour period to understand where losses were occurring. We then discharged the battery under standard conditions to measure the energy that was extracted (in this case 10 mWh) The resulting full-cycle charging efficiency (with the battery) is only about 10%, meaning that 90% of the energy supplied from the grid is dissipated as heat without performing useful work.

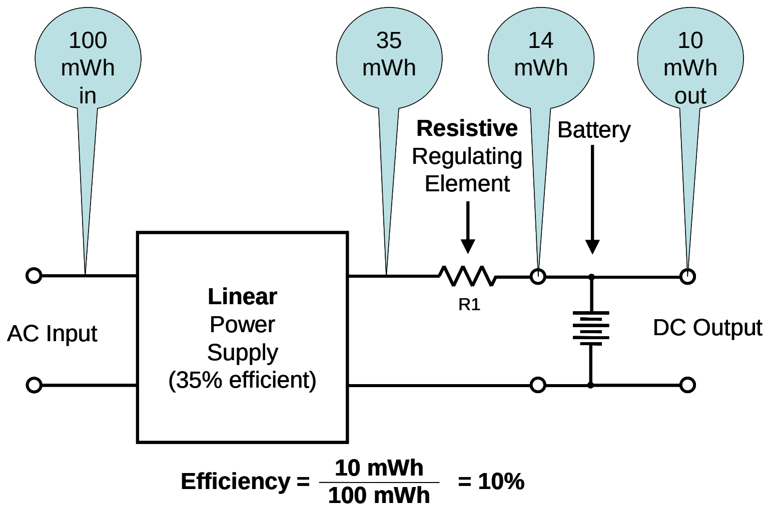


Figure 17. Two-piece charger composed of a linear power supply and a resistive linear regulator

Figure 18 shows a more efficient approach. Here, a switch mode power supply replaces the linear power supply, causing the overall battery charger system efficiency to increase more than two-fold to 24%.

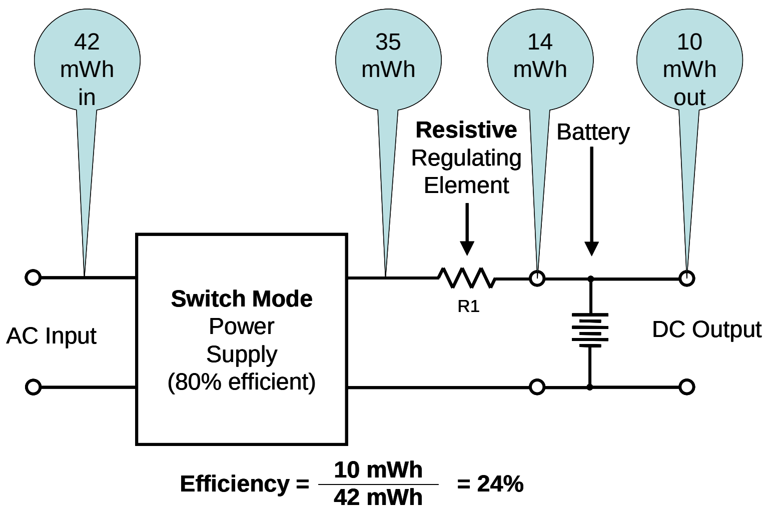


Figure 18. A more efficient two-piece charger with the linear power supply replaced by a switch mode power supply

While the efficiency is substantially improved, it is still relatively low; after all, the charge linear regulating element (in this case a resistor) still dissipates power. More substantial improvements in efficiency require improvements to the regulating element itself.

“Smart” Linear Regulators

It is more difficult to address efficiency in the regulating element, as the energy dissipated in this component will always be proportional to the voltage difference between the output of the power supply and the battery. One effective way to improve overall charge efficiency is through the use of “smart” linear regulators that reduce power consumption during maintenance charge.

Simple chargers using uncontrolled linear regulators do not detect when the battery is fully charged, and so do not differentiate between the active charge and maintenance modes. As a result, they continue to pass charging power to the battery at a relatively high rate, as shown in Figure 19. While a small amount of this power goes towards offsetting self-discharge, the rest is dissipated as heat. In addition to this loss, there are substantial losses due to the inefficiencies in the linear power supply (35% for the linear power supply compared to 80% average efficiency for the switching power supply) and resistive regulator, which occur in both the charge and maintenance parts of the profile.)

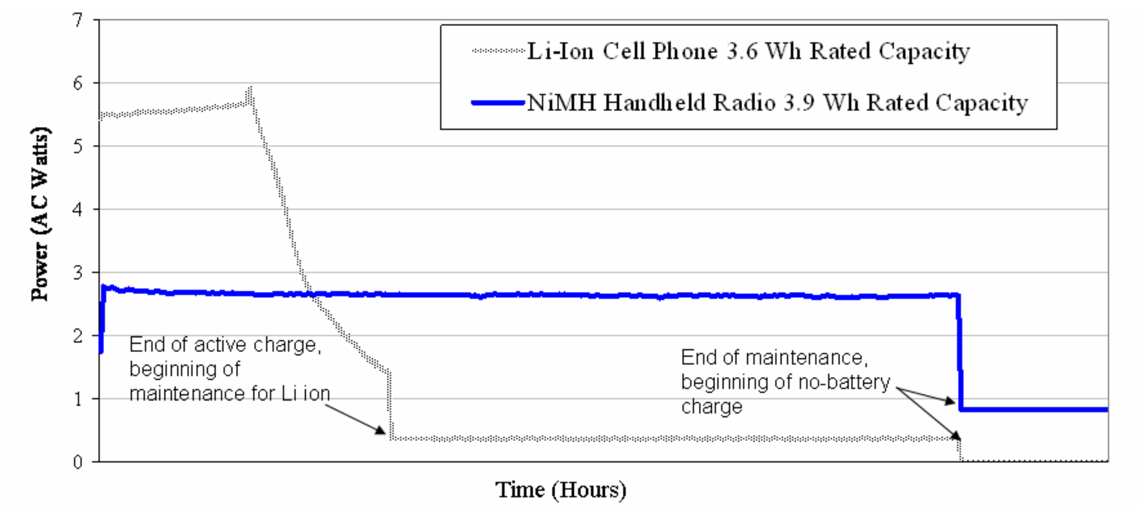


Figure 19. Charge profile for two linear chargers. The Li-ion cellular phone charger reduces the power draw when the battery is fully charged. The NiMH handheld radio charger does not reduce power draw when the battery is fully charged, but instead continues to draw the same amount of power.

“Smart” regulators can replace resistive linear regulators, reducing power consumption during maintenance mode. Such regulators typically contain control circuitry to sense the voltage, current, and temperature of the battery. The transistor acts as both the regulating element during charge and the switch to reduce charging current when the battery is fully charged.

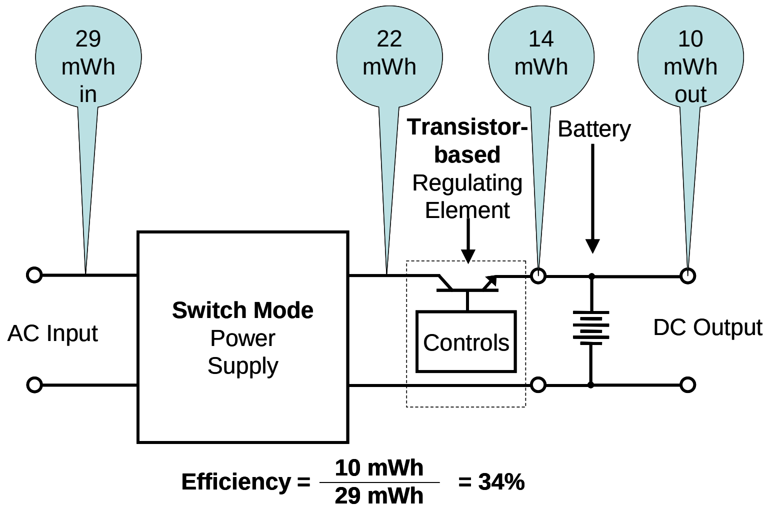


Figure 20. The effect of replacing the resistive element with a transistor-based regulator with controls to allow shutoff after full charge.

A smart regulator, inserted in the place of the resistive regulator, can sense the point at which the battery was fully charged and switch to a much lower float or trickle charge current. This approach reduces the energy dissipated in the battery as well as the total power demand in the remainder of the battery charger system.

Smart regulators are available as packaged modules and can be found in surprisingly small packages. They can be integrated into either the power supply or into the battery. Lithium ion batteries, which must incorporate smart regulators for charge control, typically incorporate regulator chips within the battery package.

The efficiency improvement from this change is difficult to calculate, because it occurs only during maintenance mode. But if the product is one that spends a significant period of time in maintenance mode (as most products do) the efficiency gains may be significant, as great as 10 percentage points on a 24-hour basis.

It should be noted that not all transistor-based linear regulators are smart regulators. It is the controls, not the transistor itself, which detects and shuts off charge to reduce wasted energy during maintenance charge. Furthermore, the smart regulator does not address the losses from magnetizing current in the input transformer of a linear power supply, and therefore would be much less effective in reducing power consumption if a linear power supply is used.

Replacing Linear Chargers with Switch Mode Chargers

Despite the various enhancements described above, overall efficiency for linear chargers will always be limited by the fact that a dissipative element – a resistor or transistor – is being used to control the dc charging current. The replacement of the linear charger with a switch mode charger would improve efficiency significantly because this dissipative element is eliminated entirely.

There are two types of switch mode charges, single-piece and multi-piece. The single-piece switch mode chargers are more difficult to design and manufacture than the multi-piece because they must be designed as a system tailored to meet the needs of a specific battery pack. Every new charger would need to be tested for regulatory approval and other engineering standards, making the redesign process relatively time intensive and costly.

Multi-piece chargers that employ a switch mode power supply in series with a dc-dc converter are simpler and less expensive to design. A switch mode power supply can be specified and purchased from a power supply manufacturer. A separate dc-dc converter can be used to regulate the charging current to the battery. Although this multi-piece approach (Figure 21) is not as efficient as using a single switch mode converter, it is much easier to specify and manufacture, since the dc-dc converter and other control components can be packaged with the battery-powered product or the battery itself. The system efficiency of the two-piece charger and battery system is approximately 50%, a significant improvement over the 10% efficiency estimated for a comparable linear charger.

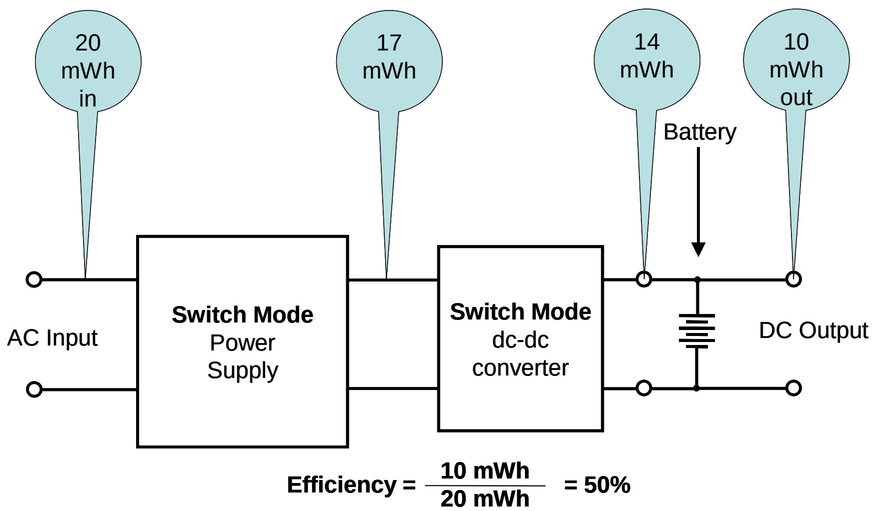


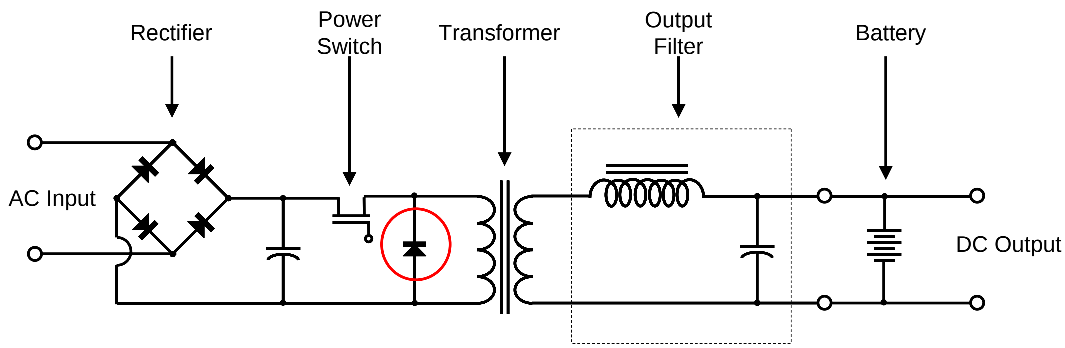
Figure 21. A two-piece charger with two switch mode components

Improving Efficiency in Switch Mode Chargers

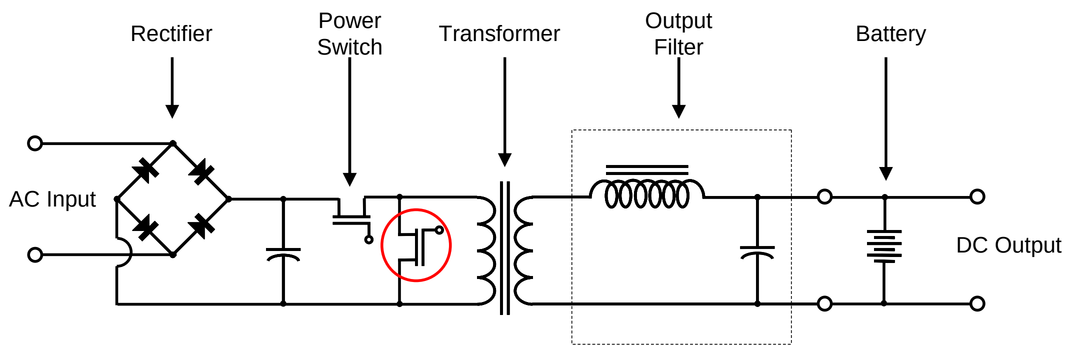
Although they are already more efficient than linear chargers, switch mode chargers can be made even more efficient with intelligent design techniques. The gains achievable for switch mode chargers are smaller and less certain than those to be gained from improving linear chargers. Many of the techniques described here are very cutting edge, and their full capabilities are not yet understood. These design strategies include synchronous rectification, resonant switching, and better switch design.

Synchronous Rectification

A large part of the inefficiencies in switch mode chargers occur in the diodes in the output rectifier. The replacement of diodes with metal oxide semiconductor field effect transistors (MOSFETs) can significantly reduce diode loss in most systems. Figure 22 illustrates this change in a single-stage switch mode power supply. The main drawback to using MOSFETs is the increased cost and complexity of integrating them with the system.



a



b

Figure 22. (a) Traditional diode-based secondary rectification (b) MOSFET-based synchronous rectification

Synchronous rectification works because the voltage drop across a MOSFET is much smaller than the drop across a diode. This translates to lower losses and increased efficiency.

At very small output powers (less than 10 W), the control power required by the MOSFET might exceed the gains achieved by replacing regular diodes. As a result, synchronous rectification may not be viable for chargers with very small power output or those with very small power output during maintenance mode. In the latter instance, it is possible to use hybrid chargers with diodes that operate during low power operation and MOSFETs that operate during high-power operation. Synchronous rectification has the potential to increase efficiency by as much as 10 percentage points on a 24-hour charging cycle, depending on the power rating of the charger.

Resonant Switching

Most switch mode chargers use pulse-width modulation (PWM) to efficiently convert power at higher voltages to power at lower voltages. Generally, the shorter the pulses –

that is, the higher the switching frequency – the more efficient the switch mode charger. Efficiencies of switch mode chargers generally increase up to about 30 to 50 kHz.

Above these frequencies, however, other sources of energy loss begin to become an issue. The most important loss is the *switching loss*, which occurs when the semiconductor switch turns off and on. The loss is proportional to the instantaneous voltage and current at the moment of switching. As the switch turns on and off more often (that is, as the switching frequency increases), the greater the switching losses. High efficiencies can be sustained at high frequencies through the use of *resonant switching*, a special technique in which the circuit is designed to turn the power switches on or off at either zero voltage or zero current, helping to maintain high efficiency even at very high frequencies[7].

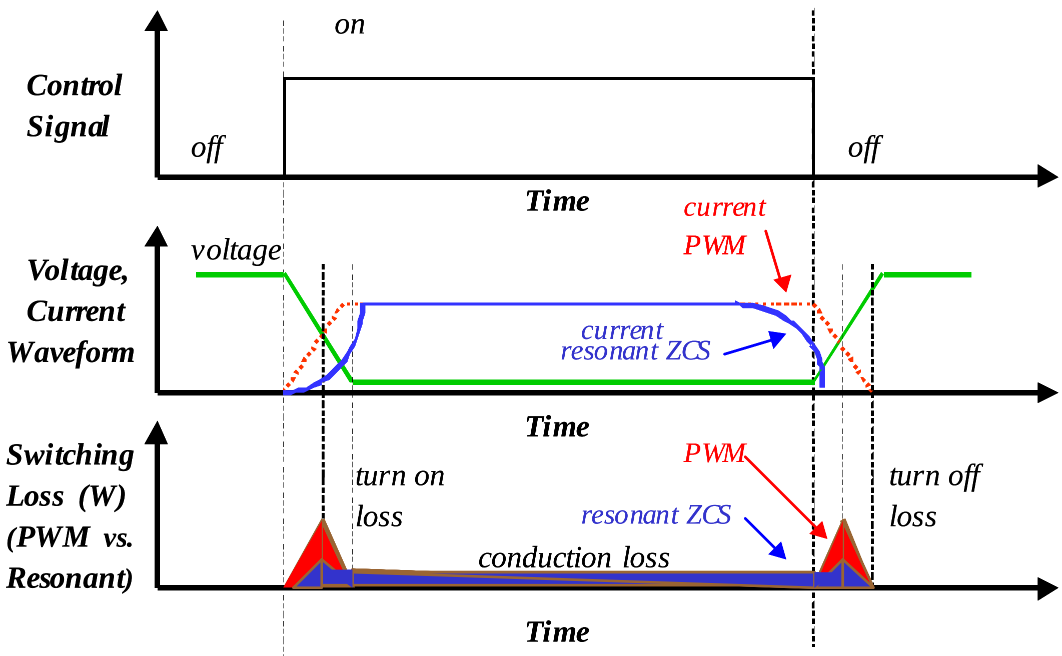


Figure 23. Comparing switching losses of resonant switching with regular PWM

Resonant switching involves the addition of sophisticated controls and a few passive components to the switching design to induce resonance conditions. The use of resonant switching rarely makes sense for switch mode chargers operating at fairly low voltages (below 200 V) and low power levels (below 2 kW), since an increase in frequency rarely results in much of an increase in efficiency for such chargers.

For larger switch mode chargers, however, the story is different. Such chargers typically use somewhat different topologies, such as full-bridge converters, which benefit more significantly from higher operating frequency. The additional controls and components may be more justified in this case, since the energy saved is much larger in real terms and as a fraction of the energy passing through the charger. Resonant switching can help improve efficiencies by as much as 8 to 12 percent on a 24-hour cycle basis.

[7] Ibid.

More Efficient Switches

Since a large part of the losses associated with switch mode chargers appear in the semiconductor switch, any effort to improve efficiency must look at more efficient switches. Constant advances in switching technology have made such switches possible. However, these switches are not always used in manufactured products because of the costs to redesign the electronics and retool existing manufacturing. For manufacturers to act on these innovative technologies there must be a clear market pull towards products using these switches, whether for efficiency purposes or superior performance in some other way[8]. The efficiency improvement in using new switches is difficult to quantify as it depends on both the type of switch as well as the design of the charger. Future technologies may allow great improvement in efficiency. An estimated efficiency improvement of 10 percentage points may be achievable with existing technology.

General Strategies for Improving Battery Charger System Efficiency

The strategies below can be used to improve battery charger system efficiency are applicable to any charger system, regardless of charger topology and battery type.

More Efficient Batteries

Batteries are important to consider when improving charger efficiency because they suffer energy losses twice: once during charge and once during discharge. As a result, employing a high-quality battery can yield measurable efficiency gains.

Some gains in battery efficiency may be made through improvements in battery design or manufacturing. For example, batteries may be designed to have lower voltage drops through improved inter-cell connections. Such changes generally have relatively minor effects on efficiency.

The most effective way to improve battery efficiency is to switch to more efficient battery chemistries. For example, lithium ion batteries have properties that make them more energy efficient in practice than nickel-cadmium and nickel-metal hydride batteries. The lithium ion cell has an inherently higher coulombic efficiency than NiCd and NiMH cells. Lithium ion batteries also operate at a higher voltage per cell than nickel-cadmium and nickel-metal hydride batteries. This means that one-third the number of cells is required in a lithium ion battery operating at the same voltage, reducing losses from contacts and interconnects between cells. Finally, lithium ion batteries also have a lower self-discharge rate than nickel-cadmium and nickel-metal hydride batteries. This means lithium ion batteries require less in the way of energy during maintenance charge.

The main disadvantage of lithium ion batteries in these markets is their relatively high cost. This cost has been falling rapidly, however, and many analysts expect the cost of lithium ion to fall to the same level or even below the costs for nickel-cadmium and nickel-metal hydride equivalents by 2010.

[8] Ibid.

Until recently, lithium ion batteries were best-suited for relatively low-power applications such as electronics; they could not deliver the high currents necessary for power tools and similar motor-driven equipment. Since 2004, new high-power lithium ion batteries have been released in several new markets, including the power tool and hybrid electric vehicle markets.

Despite these advancements, lithium ion faces an up-hill struggle in markets such as UPS, electric vehicles, and motive power, in which lead-acid batteries are dominant. Lead-acid batteries also have relatively low self-discharge and relatively high-voltage cells, such that the advantages of lithium ion batteries are less attractive in these markets. The extremely low cost of lead-acid batteries, along with their relative ruggedness and simplicity, makes them very difficult to replace in these applications.

Reducing Fixed Power Consumption

Energy losses in a battery charger system can be divided into two types: *variable losses*, which are dependent on the size of the load and change with state-of-charge, and *fixed losses*, which are not dependent on load size. Fixed losses occur in fans, control circuits, and magnetic components. These losses are particularly significant when the output power is low, such as during maintenance mode and no-battery mode. During active charge mode, other losses tend to dominate. The efficiency gains vary with the time the product spends in maintenance mode and no-battery modes. For products that normally spend a significant portion of their time in these two modes, improvement in full-cycle charging efficiency can be large, perhaps as high as 10 percentage points over 24 hours.

Lower Charge Rate

Efficiency can be improved by reducing the rate of charge. In general if the rate of charge is decreased, both the losses within the charger and the losses within the battery will decrease, resulting in overall improved efficiency. The efficiency gain is at the expense of recharge time. A lower charge current naturally means that it will take longer for the battery to recharge; however, lower charge rates can increase the full-cycle battery charger system efficiency by as much as 5 to 15 percentage points over 24 hours[9].

Increasing Battery Charger System Voltage

Even more substantial gains in efficiency – up to 20 percentage points for a 24-hour charge cycle – can be realized through a systems approach that addresses the entire application, in addition to the battery and charger. A simple example is the use of higher voltages to power a given device. Resistive losses within the charger, battery, and device itself are all related to the square of the current while the current is inversely proportional to the voltage (double the voltage equals half the current). In theory, doubling the

---

[9] Note that some commercially available “fast chargers” are advertised as more efficient than conventional chargers. These claims are often reasonable for the charger without the battery, as the fast charger (inevitably a switch mode charger) is usually compared to a linear or ferroresonant charger. When the battery is included in the efficiency calculation, some of the efficiency advantages of fast chargers are lost, as the high charging rate results in poorer battery efficiency.

voltage would reduce resistive losses by a factor of four during both charging and operation.

Hysteresis Charging

Hysteresis charging is a form of maintenance charge that keeps batteries near a fully charged state while maintaining a relatively high efficiency. During hysteresis charge, the battery voltage is allowed to float between a high and low set point. When the high set point is reached during charge, the charge current is shut off. After a period of time the battery voltage will fall due to self-discharge until the low set point is reached. At this time the charger turns back on, but instead of charging with a small current, a relatively large current is used to quickly bring the battery voltage and state-of-charge back to the high set point. Because charging occurs at a higher power level, the conversion efficiency of the power supply circuitry is relatively high.

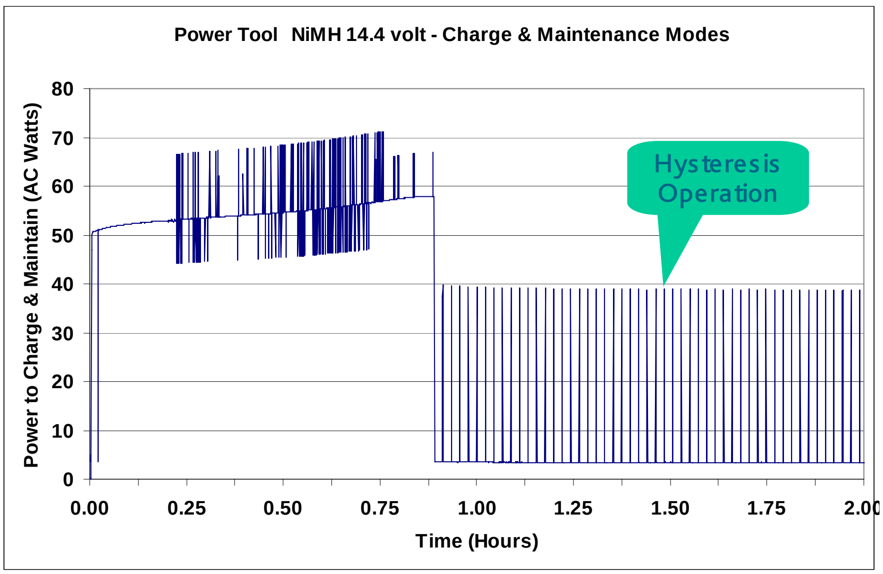


Figure 24. A power tool charger with a hysteresis charge algorithm during maintenance mode

The use of hysteresis charge does not adversely affect the performance or life of most batteries and actually may help enhance product life over traditional float charging. The efficiency improvement feasible with hysteresis charging is heavily dependent on the percentage of time that the product spends in maintenance mode. For a 24-hour full-cycle charging operation, efficiency improvement may be as high as 25 percentage points. .

Battery Sensing Circuitry to Reduce No-Battery Mode Power Consumption

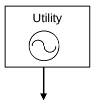
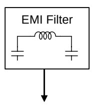
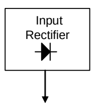
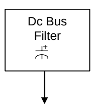
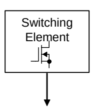
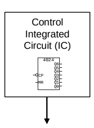
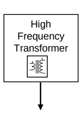
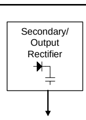
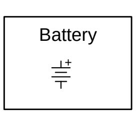
Battery sensing circuitry can also be used to turn off the charging circuitry when a battery is absent from the charger, eliminating the losses associated with the no-battery mode. When a discharged battery is first connected, the energy remaining within the battery is used to close the switch and reconnect utility power to the charger system, initiating the charging process. The battery sense switch might be designed with complex logic tied to the charge control circuitry, or may be a simple physical switch that disengages when the battery is not connected to the charger. Such circuitry is already used in most lift truck battery chargers.

The addition of battery sensing circuitry requires some additional hardware. The cost of the switch is somewhat related to the size of the charger: the higher the direct current the more expensive the switch. Nevertheless, the costs are small compared to the overall cost of the charger, and the potential for energy savings represents a reasonable payback opportunity. For those products that do not already have such switches, the potential for savings is considerable: no-battery mode power consumption may be cut by up to 90%.

Best-in-Class Efficiency: A Design Example

In order to demonstrate how these techniques come together in a design, Table 3 outlines a conceptual design of an efficient switching battery charger system that employs a 3.6 volt, 1600 mAh lithium ion battery that achieves the upper limit of efficiency at 70%.

Table 3. Basic building blocks of a switch mode battery charger system and their associated characteristics (Estimated for a 3.6 V, 1600 mAh lithium ion battery).

Circuit Block Diagram	Component Description	Charge Mode Losses	Maintenance Mode Losses	No-Battery Mode Losses	Energy Budget Example (%)	Techniques to Improve Efficiency
	The utility supplies alternating current (ac) at 115 volts.				100.0	
	Serves to block electrical noise generated by the switching element from propagating back onto the utility.	Low	Low	Low	99.5	
	Converts ac voltage to dc voltage using one or more diodes.	Low	Low	Low	98.5	Low loss diodes. SiC components
	Reduces the ripple of the rectified voltage using capacitors to create high voltage dc.	Low	Medium	Medium	98.0	Choose capacitors designs that have a low equivalent series resistance (ESR).
	Converts high voltage dc to pulse width modulated (PWM) dc to effectively change the energy content of the dc voltage.	High	Medium	Medium	94.0	Design the charger to minimize the difference in voltage between the input and output of the switch. Charge using as little current as possible. Use high-efficiency switch.
	Generates all the control signals required for the feedback loops and gate driver circuit. In the maintenance and no battery mode these losses could dominate the overall losses.	Low	High	High	92.5	Digital control, high level of integration of various components into a single chip. Use power switches with lower gate drive requirement. Provide low-impedance drive for the switching element.
	Used for isolation between input and output and to further reduce the dc voltage level to the output dc voltage level.	Low	High	High	90.0	Optimize the design of the transformer for the application.
	Aids in regulating low voltage dc using one or more Schottky diodes.	High	Low	Low	88.0	Use MOSFETs instead of diodes (e.g., synchronous rectification)
	Stores electrical energy in a chemical form. Electrical and thermodynamic losses depend on the current rates during charge and discharge, as well as temperature,	High	High	N/A	70.0	Use lithium ion battery; charge at mild temperatures and low charge rate

Summary

There are significant opportunities to improve the efficiencies of battery charger systems in use today. At present, inefficiencies in the charger and battery often consume more electricity than the product they power. There are millions of battery charger systems in operation worldwide, and therefore substantial energy savings are achievable by reducing or eliminating these inefficiencies.

Several methods can be used to achieve higher efficiency in battery charger systems, including:

- Higher voltage systems
- Use of switch mode power supplies
- Use of synchronous rectification
- Use of improved semiconductor switches
- Use of lithium-ion batteries
- Charge and discharge at lower current rate
- Disconnect charger from grid when no battery is present.

Table 4 summarizes the degree to which efficiency can be improved for today's various charger topologies.

Table 4: Potential for Efficiency Improvements in Charger Topologies

Topology	***Typical Efficiency Range (%)***	***Estimated Improved Efficiency Range***
Linear	2% - 30%	20% - 40%
Switch Mode	40% - 60%	50% - 70%
Ferroresonant	25% - 50%	45% - 55%
SCR	30% - 55%	45% - 60%

At a time when many common battery charger systems have measured efficiencies of less than 15%, comparable systems with overall efficiencies of 65% or greater are technically feasible. The technical path to higher efficiency is clear. It is now necessary to develop the policies that will encourage and accelerate the market adoption of the technologies and practices that can reduce battery charger energy consumption cost-effectively, while preserving the essential convenience of these products that has made them popular.