Hardware Related Influencing Factors and Optimization of Charging Efficiency

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Abstract. With the rapid popularization of portable electronic devices (such as smartphones and tablets) and the accelerating adoption of electric vehicles globally, the demand for fast, efficient, and stable charging solutions has become increasingly urgent. This paper focuses on analyzing the key hardware factors that determine charging efficiency, centering on two core components: chargers and batteries. For chargers, it evaluates three critical metrics—power conversion efficiency, heat dissipation capability (discussing overheating protection triggers and component aging risks), and output parameter stability (linking stability to charging continuity, safety, and device lifespan). For batteries, it explores how cell material ionic conductivity (lithium ion vs. lithium iron phosphate (LFP) batteries, electrolyte performance) and structural design (packaging, tab layout) influence ion/electron transfer efficiency. Based on these analyses, the paper proposes targeted optimization directions: using GaN/SiC materials for chargers, enhancing thermal management and output stability, and innovating battery materials (high nickel ternary, lithium manganese iron phosphate (LMFP), silicon carbon composites) and structures (lamination process, full tab design). The study acknowledges limitations, including the neglect of software, environmental factors, and cost considerations, and suggests future research focus on hardware and software integration.

Keywords: Chargers, Batteries, Materials

1 Introduction

Against the backdrop of the global electrification trend, portable electronics (smartphones, tablets) and electric vehicles have become integral to daily life and transportation. However, inefficient charging remains a critical bottleneck, its slow charging prolongs user waiting time, while low efficiency hardware wastes energy and shortens device lifespan. To tackle these challenges, this paper focuses on hardware centric solutions to enhance charging efficiency. It first systematically analyzes key hardware factors influencing efficiency, covering three core aspects of chargers (power conversion efficiency, heat dissipation, output stability) and two key dimensions of batteries (cell material ionic conductivity, structural design). Subsequently, it proposes targeted optimization strategies for both components, aiming to provide practical technical references for advancing high efficiency charging technology.

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S. Zhang (ed.), *Proceedings of the 2025 International Conference on Electronics, Electrical and Grid Technology (ICEEGT 2025)*, Advances in Engineering Research 292,
https://doi.org/10.2991/978-94-6463-986-5_93

2 Hardware Factors that Affect Charging Efficiency

2.1 Chargers

In terms of achieving fast charging, hardware optimization needs to consider the compatibility between the charger and the battery, so that they can work together to achieve the best results[1]. Next, let's first discuss the impact of the charger on the charging performance.

Power Conversion Efficiency. The power conversion efficiency of chargers is that chargers convert the input electrical energy into a form that can effectively charge the battery, and the proportion of this conversion is what we are referring to. The equation of the efficiency equals to the output efficiency divided by the input efficiency times 100%. Chargers with high efficiency can convert energy quickly, which will shorten the charging time. Additionally, high efficiency is beneficial for the energy conservation, therefore save users' budget.

Heat Dissipation. The heat dissipation capability directly determines the stability and upper limit of the fast-charging efficiency by influencing the working state of the charger components.

First, high temperatures will trigger an automatic protection mechanism, which will force the reduction of the fast-charging efficiency. When chargers are working, the internal chips will generate heat because of the transformation of current and voltage. The bad heat dissipation capability will accumulate heat and thus cause the temperature exceeds the safety threshold (generally 80-120°C), chargers will automatically start over heating protection, which will decrease the charging efficiency and prolong the charging time.

Second, long term poor heat dissipation will accelerate the aging of components and lead to a decrease in charging efficiency. The performance of the aged components declines, and they are unable to provide stable power output.

The Stability of the Output Parameters. A stable output parameter keeps the efficiency of charging stays in a steady power level. If the voltage and current won't fluctuate, chargers can continuously output peak power, avoiding the break off or slow down.

First, the stability of the output parameters avoiding safety risks. The stable parameters avert an abrupt increase of voltage to burn the components, or the instability of currents to trigger the short circuits.

Second, stable parameters extend the equipment's lifespan. A stable output enables the battery to charge within the safe range, reducing losses.

2.2 Batteries

The Iconic Conductivity Rate of the Battery Cell Materials. Battery charging and discharging involve the movement of ions between the positive and negative electrodes, accompanied by the transfer of electrons. Positive and negative electrodes made of different materials would lead to disparate ionic conductive abilities. For instance, batteries consist of lithium ions can diffuse rapidly, move from positive to negative quickly. This type of batteries can tolerate higher currents and realize the fast-charging process. In contrast, LFP batteries have lower charging rate compared to the lithium ions batteries.

In addition, electrolyte also has impact on the charging of batteries. The electrolyte is like the path for ions to transfer, and the high conductivity of electrolyte means that the resistance to ion migration is lower, allowing ions to move more smoothly between the positive and negative electrodes, thereby improving the charging and discharging efficiency of the battery.

Structural Design of the Battery. One of the major limiting factors for charging efficiency is the heat generated during the charging process. During charging, due to the high current, a large amount of heat is generated inside the battery due to the resistance of ion migration and electron conduction. If the heat cannot be effectively dissipated, the battery management system (BMS) will implement low power protection, directly reducing the actual charging efficiency. Different packaging forms can result in differences in heat dissipation, which has a significant impact on charging efficiency.

Another crucial factor that affects the charging efficiency is the fluency of electron conductivity. During charging, the external current needs to pass through the battery tab to enter the battery cell. If the design of the tab causes significant resistance in the electronic conduction, it will generate a large amount of heat, which not only wastes electrical energy but also triggers a power reduction, thus forming a vicious cycle.

3 Optimization direction of chargers

3.1 Energy Loss

Power devices are the core components for electric energy conversion in chargers. Their performance directly affects the energy conversion loss. There are 2 major ways for power loss, which are conduction loss and switching loss. For metal oxide semiconductor field effect transistors (MOSFET), the conduction loss follows the equation below:

$$P_{cond} = \mathrm{I}^2 \times \mathrm{R}_{\mathrm{DS\ (on)}} \tag{1}$$

And for diodes and insulated gate bipolar transistor (IGBT), there is the equation:

$$P_{cond} = V \times I \tag{2}$$

On the switching loss aspect, the power loss can be divided into switching on and switching off, and here are the equations:

$$P_{on} = 0.5 \times V_{DC} \times I_{load} \times t_{on} \times f_{sw} \tag{3}$$

$$P_{off} = 0.5 \times V_{DC} \times I_{load} \times t_{off} \times f_{sw} \tag{4}$$

In these 4 equations, the on resistance, time taken to turn on and off and switching frequency are different due to different semiconductors.

Table 1. Key Parameters of Si, SiC and GaN[2]

Materials	$R_{DS(on)}$	V_f(V)	t_{on} (ns)	f_{sw} (MHz)
Si	10-100	0.6-1.5	50-500	0.5-1
SiC	1-10	1.2-2.0	5-50	5-50
GaN	5-50	1.5-3.0	1-10	10-100

The Table 1 above gives the specific quantities relate to equations of Si, SiC and GaN. Clearly, by comparing these 3 semiconductors, we can easily find that SiC and GaN perform better than the traditional material Si. Usually, some great GaN chargers can reduce the energy dissipation which mainly cause by on resistance and switching time, those with high efficiency can decrease the energy lost more than 20%[3].

3.2 Enhancement of Heat Dissipation Hardware

During fast charging, even if the power device losses decrease, heat will still be generated. If the heat cannot be dissipated in time, the increase in charger temperature will trigger over heating protection (reducing power), which will affect the charging efficiency.

When the charger temperature exceeds 100°C, the rate of overheating protection activation increases by 60%, and prolonged high temperature will accelerate the aging of capacitors by a factor of 3[4]. The evidence strongly reveals that the heat dissipation capacity determines the upper limit of charging stability.

The equation below describes the heat passes through solid materials:

$$Q = \lambda \times A \times \triangle T/d \tag{5}$$

Here, λ represents thermal conductivity, which is determined by different materials.

Table 2. The thermal conductivity of 3 types of heat dissipation materials[5]

Type of heat dissipation material	Thermal conductivity (Typical range)	Unit
Graphene heat dissipation film	1500-5000 (Typical: 2000-3000)	W/(mK)
Traditional aluminum sheet	200-240 (Typical: 237)	W/(mK)
Liquid metal	400-800 (Typical: 600-700)	W/(mK)

Table 2 provides different thermal conductivities among 3 types of heat dissipation materials, by comparing the numerical values, the best performance can be easily found. The graphene heat dissipation film has explicitly higher thermal conductivity, so it can be used in chargers.

Another way to improve heat dissipation is on the aspect of structure. These are the 2 significant dimensions:

First, optimizing the layout of the heating components. Separating high heating components in chargers from capacitors, resistors and other components that has low tolerance to heat, avoiding the convergence of heat, or using heat sink for heating components individually, reducing the diffusion to surroundings. The separation of the heating element and the structural design of the aluminum heat conducting support can reduce the internal temperature of the charger by 18℃[6].

Second, enhancing heat dissipation structure's heat conduction. Using metallic conduction braces like aluminum to expand heat dissipation areas. Filling high thermal conductivity materials between the heating element and the casing to reduce the contact thermal resistance and enable the heat to be conducted to the outside more quickly.

3.3 Output Parameter Stability Optimization

The optimization of the output parameter stability of the charger lies in ensuring that the voltage and current remain accurate and without abnormal fluctuations under conditions such as load changes and fluctuations through hardware design and software algorithms. When the voltage fluctuation exceeds ±0.5V, the risk of battery short circuit increases by 45% and the equipment lifespan shortens by 20%[7].

Aspect of Hardware: Create Stable Output. Power supply topology structure: Adopting an efficient resonant/synchronous topology. For example, modern generations have superior advantages over traditional "linear power supplies" or "flyback topologies". They prefer to choose the inductor-inductor-capacitor (LLC) resonant topology or the synchronous rectification topology.

The LLC topology utilizes the resonant characteristics of inductors and capacitors to automatically stabilize the energy conversion efficiency when the grid voltage fluctuates, reducing the transmission of input side fluctuations to the output side. Synchronous rectification replaces traditional diodes with MOSFETs with low on resistance, thereby reducing voltage losses during the rectification process.

The output end needs to be equipped with low impedance and high frequency characteristic filtering capacitors or inductors to form an "inductor-capacitor (LC) filtering network". The core function is to filter out the high frequency noise in the current.

Solid state capacitors should be preferred over liquid electrolytic capacitors. The equivalent series resistance (ESR) of solid-state capacitors is lower, enabling them to quickly absorb the high frequency noise in the output current (such as the 100kHz or higher noise generated by MOSFET switching during fast charging); at the same time, "high frequency ceramic capacitors" are connected in parallel to filter both high frequency and low frequency noise.

Selecting shielded power inductors to reduce electromagnetic radiation generated by the inductor during operation and minimize interference to other components. At the same time, ensure the stability of the inductance value.

Aspect of Software: Dynamic Adjustment and Precise Control. By reading the voltage/current data from the hardware sampling circuit through software, high precision sampling can monitor the output parameters at a high frequency, ensuring the timely capture of even the slightest fluctuations.

Second, Dynamic Proportional Integral Derivative (PID) regulation bases on sampled data, the adjustment quantity is calculated using the PID algorithm, and the switching frequency/duty ratio of the power switch tubes in the hardware is controlled in real time to quickly correct the deviation.

4 Optimization Direction of Batteries

4.1 Innovation in Battery Cell Materials

Positive Electrode. In traditional ternary materials, cobalt is costly and scarce in resources, which limits the increase in energy density. Different materials lead to different conductivity. High conductivity electrolytes can increase the lithium-ion migration rate by 30%, while the ion diffusion coefficient of LFP batteries is only 60% of that of ternary lithium batteries[8]. High nickel ternary materials (such as NCM811, NCA, with a nickel content of ≥ 80%) can significantly increase the lithium-ion storage capacity by increasing the nickel content, thereby greatly enhancing the battery's energy density.

Manganese Iron Phosphate (LMFP): LMFP has higher safety and longer cycle life compared to LFP. However, its voltage plateau is relatively low (about 3.2V), which limits its energy density. LMFP is developed by introducing manganese elements into LFP, raising the voltage plateau to approximately 4.1V. This results in a 20%-30% increase in energy density (reaching 180-200Wh/kg), while maintaining the excellent safety and low-cost advantages of LFP. Experimental data shows that the energy density of the NCM811 cathode material can reach 290 Wh/kg, and the cycle life of the LMFP material exceeds 3000 times[9].

Table 3. The energy density range of cathode materials[10]

Cathode Materials	Energy Density Range (Wh/kg)
High Ni Ternary (NCM811)	250-280 (Up to 302 for mass produced cells by Gotion High Tech
Lithium Manganese Iron Phosphate (LMFP)	180-200
Mid Ni Ternary (NCM523)	180-210

Low Ni Ternary (NCM111)	140-160

The table above shows the energy density range of 4 cathode materials, 3 of them are made of Ni. The advantage of NCM811 and other materials with nickel can be found, and the table also demonstrates the benefit of LMFP.

Negative Electrode. Natural graphite has a high crystallinity, a theoretical specific capacity of 372 mAh/g, and a low cost. By combining GaN devices with graphene heat dissipation films, the overall conversion efficiency of the charger can be stabilized at over 95%, and it can operate continuously for 2 hours without triggering overheating protection[11]. However, its cycle stability and rate performance need to be optimized through coating and other processes and are widely applied in consumer electronics and battery power sources.

Artificial graphite is prepared from raw materials such as petroleum coke and needle like coke. Its structure is controllable. Its cycle life (usually more than 1000 times) and rate performance are superior to those of natural graphite. It is currently the core material for the negative electrode of battery power sources.

The theoretical specific capacity of Si is extremely high (4200 mAh/g), which is more than 10 times that of graphite, significantly enhancing the energy density of batteries.

By combining silicon with carbon materials (such as graphite, amorphous carbon), both the high capacity of silicon and the ability of carbon to inhibit volume expansion and enhance conductivity are retained. This is the current mainstream research direction for silicon based negative electrodes, with specific capacities typically ranging from 800 to 1500 mAh/g.

4.2 Improvement in Battery Structure Design

Lamination Versus Coiling Process Optimization. The coiling process has high production efficiency, but the electrode distribution is prone to being uneven, resulting in significant differences in local current/temperature; the lamination process has more uniform electrodes, which can reduce internal resistance and improve cycle and rate performance, but the traditional lamination process has low efficiency.

Optimization of Battery Tab and Cathode Electrodes. The battery tab is the "bridge" that connects the cell to the outside. The cathode electrode is responsible for the internal current conduction. Optimizing its structure can reduce internal resistance and enhance fast charging capability.

On the aspect of full battery tab design, traditional cells only have battery tab on two sides. Full tabs are evenly distributed on the electrode, changing the current flow from "single sided entry" to "uniform entry from multiple sides", which can reduce internal resistance by more than 30% and be suitable for high-rate fast charging. The current effect of the traditional bilateral tab design leads to an increase of 25% in local resistance, while the optimized tab layout can enhance the heat dissipation efficiency by 15%[12].

Through an experimental comparison of the electrode terminal design, it was found that the full electrode terminal layout can reduce the internal resistance of the battery by 35% and increase the charging rate by 20%[13].

Lightweight copper foil/aluminum foil cathode electrodes use ultra-thin copper foil (with a thickness reduced from 10 um to 6 um) or composite cathode electrodes, while maintaining conductivity, can reduce the weight of the cell and improve energy density.

5 Conclusion

The whole paper talks about what hardware factors affect charging efficiency and how to improve them. It points out that for chargers, three key things matter: how well they convert electricity, how well they dissipate heat (poor heat dissipation slows charging and ages parts), and how stable their output voltage/current is (stability ensures safety and efficiency). For batteries, it's about the material's ability to let ions move.

To improve, use better charger materials like GaN/SiC, enhance heat dissipation, and stabilize output; for batteries, use new materials (like high nickel or LMFP) and optimize structures. Hardware optimization must consider the compatibility between the charger and the battery; otherwise, the efficiency improvement may be compromised.

Meanwhile, there are some limitations. For example, it ignores software and environmental factors and doesn't talk about either cost or production. In the future, the development on fast charging should mainly focus on better materials, hardware and software integration, and balancing cost and reliability to my perspective.

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