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Optimizing Laptop Charging Efficiency with the MPPT Algorithm in a Fast Charging System for USB-C PD (Power Delivery) Based Laptops

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The rapid advancement of portable electronic device technology, particularly laptops, necessitates a charging solution that is faster, more efficient, and compatible with diverse standards. The USB-C Power Delivery (USB-C PD) protocol has emerged as a universal charging standard due to its ability to support flexible voltage and current configurations. Nevertheless, the overall charging efficiency remains constrained by dynamic load behaviour, fluctuations in power sources, and the limitations of conventional power management techniques. This paper described the integration of a Maximum Power Point Tracking (MPPT) algorithm into a USB-C PD-based fast-charging system for laptops, aiming to enhance energy transfer efficiency between the power source and the device. The research methodology involves the design and simulation of a power management system incorporating MPPT, hardware prototyping, and performance evaluation based on efficiency, charging duration, and voltage stability metrics. Experimental results indicate that the implementation of the MPPT algorithm significantly improves charging efficiency, minimizes energy losses, and reduces charging time compared to conventional charging methods. The proposed approach not only contributes to the advancement of USB-C PD-based fast-charge technologies but also lays a foundation for future developments in intelligent, energy-efficient power management systems. These findings have broad potential applications in next-generation electronic devices that demand fast, adaptive, and sustainable charging solutions.
Keywords: MPPT, Fast Charging, USB-C Power Delivery, Energy Efficiency, and Laptop.

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1. Introduction

The rapid development of information and communication technology has driven an increasing demand for portable electronic devices with high performance and good energy efficiency. Among these devices, laptops play a crucial role not only for conventional office activities but also for work with high computing requirements, such as data processing, software development, and graphic design. Consequently, laptop energy consumption continues to increase, creating an urgent need for charging systems that are not only fast and efficient but also adaptable to various power supply standards (Solly et al. 2024).

The USB Type-C Power Delivery (USB-C PD) protocol has become the de facto international standard for charging modern devices due to its flexible voltage and current negotiation capabilities, with support for up to 20 V and 5 A (100 W). This flexibility enables faster charging while maintaining compatibility with a wide range of devices, from smartphones to high-performance laptops. However, despite these advantages, charging efficiency remains a major challenge. Varying load conditions, dynamic power consumption characteristics, and suboptimal power management strategies often hinder the optimal transfer of energy from the power source to the device.

To overcome these limitations, intelligent power management techniques are needed that can dynamically adjust the charging process according to system conditions. One promising method is the

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application of the Maximum Power Point Tracking (MPPT) algorithm, which has been widely used in renewable energy systems—particularly in photovoltaic applications—to maximize power extraction from variable sources. The MPPT algorithm works by tracking and maintaining the operating point at which the system produces maximum power. Applying this principle to a laptop fast charging system has the potential to improve power transfer efficiency by adjusting the characteristics of the source and load in real time, thereby reducing energy losses and shortening charging times.

Although various studies have addressed fast charging technology and power optimization in portable electronic devices, studies specifically examining the integration of MPPT algorithms in USB-C PD-based laptop charging systems are still relatively limited. Most previous studies have focused on conventional power regulation or fixed parameter optimization, which are not able to accommodate dynamic load variations that are the main characteristics of laptop usage. Therefore, this study aims to fill this research gap by examining the application of MPPT-based control in USB-C PD fast charging systems, with an emphasis on adaptive efficiency optimization under changing load conditions.

Overall, this study proposes an innovative approach through the integration of MPPT algorithm into a USB-C PD-based laptop fast charging system to improve energy transfer efficiency and charging performance. The results of this study are expected to make a significant contribution to the development of smart, efficient, and sustainable charging technologies, in line with global trends in power management and the development of environmentally friendly electronics.

2. Literature Review

Fast Charging

Fast charging is an advanced charging technology that aims to speed up the battery charging process by increasing the voltage and electric current values compared to conventional charging methods (Abdelsalam, A. et al, 2021). The main principle of fast charging is based on increasing the electric power supplied to the battery, which is mathematically expressed as $P = V \times IP = V \times I$. With a greater power supply, portable electronic devices such as laptops and smartphones can reach optimal charging levels in a shorter time. In general, standard charging only operates in the power range of 5–10 W, while fast charging technology can provide power up to 100 W or more, depending on the protocol used Ardiansyah, R., & Wibowo, B. (2020).

USB Type-C Power Delivery (USB-C PD) is currently the most dominant fast charging standard in modern electronic devices due to its ability to dynamically negotiate voltage and current up to 20 V and 5 A, resulting in a maximum power output of 100 W according to the PD 3.0 specification (Chen, X., & Liu, Y. 2018). . In addition, the USB-PD 3.1 standard extends this capability to 240 W, providing greater flexibility for high-power devices such as laptops Derdour, M., et al (2018). The intelligent power negotiation mechanism in USB-C PD ensures cross-device compatibility while maintaining safety, voltage stability, and charging efficiency.

In general, the fast charging process consists of three main stages: Constant Current (CC), Constant Voltage (CV), and Trickle Charge (Firdiansyah, A., & Prasetyo, H. 2021). In the CC stage, the charger provides a constant current while the voltage gradually increases, allowing the battery to quickly charge to approximately 60–70% of its total capacity. Furthermore, in the CV stage, the voltage is kept constant while the charging current gradually decreases to prevent overcharging and maintain battery cell stability. The final stage, trickle charge, applies a very small current to maintain the battery at full capacity and extend its lifespan. Various fast charging standards have been developed by the industry, such as Qualcomm Quick Charge, Oppo VOOC Flash Charge, Huawei SuperCharge, and Samsung Adaptive Fast

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Charging (Hamdani H et al, 2022). Nevertheless, USB-C PD remains the most universal and open standard because it supports interoperability between devices, flexible power negotiation, and scalability to high power levels.

However, the implementation of fast charging still faces several technical challenges. One major challenge is thermal management, as high charging currents generate excessive heat that can accelerate battery degradation and reduce system efficiency (Kusuma, DP, & Santoso, E. 2019). Other challenges include energy loss due to power conversion, voltage stability, battery lifespan, and compatibility between charging protocols (Muhammad, H. 2020).

To overcome these problems, an intelligent control strategy is needed, one of which is through the application of the Maximum Power Point Tracking (MPPT) algorithm. The MPPT algorithm was originally developed for renewable energy systems, specifically photovoltaic (PV) plants, to maximize power absorption from dynamic sources (Satria, B., & Aryza, S. 2025). MPPT works by adjusting the voltage and current values so that the system always operates at the maximum power point (Satria, B., & Aryza, S. 2025). When applied to a USB-C PD-based laptop fast charging system, MPPT has the potential to increase power transfer efficiency, reduce energy losses, and improve system stability.

The implementation of MPPT provides several key benefits, including increased energy efficiency through reduced power dissipation, accelerated charging times due to real-time power optimization, extended battery life by avoiding overcharge and undercharge conditions, and increased system reliability through adaptive voltage and current regulation to battery conditions. Thus, fast charging is a key technology in meeting the energy needs of modern portable computing devices. USB-C PD provides a safe and flexible high-power charging framework, while the integration of MPPT algorithm is a promising approach to improve efficiency and support smart and sustainable charging systems. This section provides a theoretical basis for efficiency optimization research on USB-C PD-based laptop charging systems using MPPT algorithm.

USB-C Power Delivery (PD)

USB Type-C Power Delivery (USB-C PD) is a universal power transfer protocol that enables bidirectional communication between a power adapter and a receiving device to determine optimal power requirements. This protocol supports dynamic voltage and current negotiation, allowing charging parameters to be automatically adjusted to device conditions during the charging process (Zhang et al., 2022). Therefore, USB-C PD is a highly suitable platform for implementing power optimization algorithms such as Maximum Power Point Tracking (MPPT).

Unlike conventional charging systems that use a fixed voltage, USB-C PD enables real-time power profile negotiation between the charger and the load device, such as laptops, smartphones, and tablets. This approach allows for more precise power delivery according to the device's actual needs without overloading internal components (Lee & Park, 2021). In the latest specification, USB-PD 3.1 with the Extended Power Range (EPR) category, this system is capable of supporting power transfers of up to 240 W, far exceeding the 100 W limit of the previous generation (USB Implementers Forum, 2023).

USB-C PD operation utilizes the Configuration Channel (CC pin) communication line to exchange data and detect power roles between devices. In general, the USB-C PD operational process consists of three main stages. The first stage is handshaking, which is the initial negotiation process to determine the appropriate voltage and current combination, such as 5 V/3 A, 9 V/3 A, or 20 V/5 A (Kumar et al., 2020). The second stage is dynamic power adjustment, where the system continuously regulates the power supply based on battery conditions to prevent excessive current and excessive temperature increases

(Choi & Kim, 2022). The third stage is support for bidirectional power flow, which allows a device to function as both a power source and receiver, for example, a laptop charging a smartphone or vice versa (Rahman et al., 2023).

This high level of flexibility makes USB-C PD a standard for cross-device charging in the modern electronics ecosystem. In addition to charging, the USB-C interface also supports high-speed data transmission and video signals over a single cable, thus acting as an integrated solution for power and digital communication needs (Tan & Li, 2024). In the context of this research, USB-C PD plays a crucial role due to its adaptive and efficient nature, which enables the implementation of MPPT algorithms to optimize power transfer without compromising system safety and voltage stability. The integration of USB-C PD and MPPT is expected to produce a smarter, more efficient, and more reliable laptop charging system.

Table 1.USB-C Power Delivery (PD) Standard with Multiple Power Level Support

PD Version	Voltage Range	Maximum Power
USB PD 2.0	5V, 9V, 15V, 20V	Up to 100W
USB PD 3.0	5V – 20V (dynamic)	Up to 100W
USB PD 3.1	28V, 36V, 48V	Up to 240W

The latest USB Power Delivery standard (USB-PD 3.1) enables charging of high-performance laptops and workstations, as well as other power-hungry devices, through a single USB-C interface. This technology is gradually replacing conventional power adapters (USB-IF, 2023; Zhang & Lee, 2022). This development marks significant progress towards a universal, efficient, and compact power delivery system in the modern electronic device ecosystem. Key advantages of USB-C Power Delivery include:

a. Universality– One USB-C cable can be used to charge multiple types of devices, such as smartphones, laptops, monitors, and cameras, thus increasing compatibility while reducing cable waste (Rahman et al., 2023).
b. High Speed Charging– With power support of up to 240 watts, USB-C PD is capable of charging gaming-class laptops and other high-power devices (Kumar & Choi, 2022).
c. Flexibility– Dynamic voltage and current negotiation mechanisms enable adaptive power delivery according to device needs, thereby preventing damage and improving system performance (Tan & Li, 2024).
d. Efficiency– Optimal current and voltage regulation reduces conversion losses and improves energy transfer efficiency (Lee et al., 2021).
e. Future-Oriented Design– The ongoing standardization process by the USB Implementers Forum (USB-IF) ensures USB-C PD compatibility with future devices and technologies (USB-IF, 2023).

Despite its various advantages, the implementation of the USB-C PD system still faces a number of technical and practical challenges, including:

a. Cable Quality– Not all USB-C cables are designed to handle high currents up to 5 A, which can degrade performance or pose a safety risk (Park & Kim, 2022).
b. Device Compatibility– Some devices only support certain power profiles, resulting in inconsistent charging performance (Chen et al., 2021).
c. Thermal Management– At high power levels (100–240 W), overheating is still a major issue affecting system reliability (Zhang & Wei, 2023).
d. Production cost– Certified USB-C PD chargers and cables tend to be more expensive than conventional charging solutions (Rahman et al., 2023). USB-C PD is a key technological foundation in the development of laptop fast charging systems. When combined with the

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Maximum Power Point Tracking (MPPT) algorithm, this system offers several important benefits, including:

1. Increased Efficiency– The MPPT algorithm ensures that the input power always adjusts to the optimal battery charging needs dynamically (Sahu & Mishra, 2022).
2. Battery Life Extension– Better power regulation reduces thermal stress and slows battery degradation (Lee et al., 2021).
3. Reduced Charging Time– Continuous power optimization enables maximum energy transfer and shorter charging cycles (Kumar & Choi, 2022). Thus, this study positions USB-C PD as a core technology in MPPT-based fast charging architectures, with the goal of achieving high efficiency, thermal stability, and adaptive performance in modern laptop charging systems.

Energy Efficiency in Charging Systems and Control System Theory

Energy efficiency in a charging system is defined as the ratio of the energy actually stored in the battery to the total energy supplied from the power source (Zhang et al., 2022). Charging efficiency is influenced by several key factors, including:

1. DC-DC power converter quality, which determines the magnitude of electrical energy conversion losses (Rahman & Choi, 2021).
2. Voltage and current stabilityduring the charging process, which affects the consistency of energy transfer (Lee & Tan, 2023).
3. Thermal managementon batteries and charging devices, as excessive temperature increases can reduce efficiency and accelerate battery degradation (Wang et al., 2021).

The integration of the MPPT algorithm is expected to minimize these losses by ensuring the power converter always operates at the optimal point of the current-voltage (I–V) curve, thereby maximizing energy transfer efficiency (Kumar et al., 2023). Modern laptops generally use lithium-ion batteries, which have high energy density, long cycle life, and are compatible with fast charging technology (Chen & Li, 2022). However, these batteries are highly sensitive to excessive voltage and current, requiring a Battery Management System (BMS) to maintain safe operating limits. Within this framework, the charging process can be viewed as a feedback control system, where the MPPT plays a role in increasing adaptability by adjusting voltage and current parameters in real time to maintain maximum power transfer (Sahu & Mishra, 2022).

In general, a control system is a mechanism designed to regulate and direct a process to achieve desired operational objectives (Ogata, 2021). In the context of battery charging, a control system functions to maintain current and voltage within safe and efficient limits (Park et al., 2023). This system utilizes feedback signals from battery voltage, current, and temperature sensors, which are then processed by a controller—such as a microcontroller or digital processor—to regulate the power converter to operate at optimal conditions (Lee & Zhang, 2022). Some common control methods used in modern charging systems include:

Open Loop Control

1. Works without sensor feedback.
2. Using fixed charging parameters (e.g. constant voltage or current).
3. Limitations: less adaptive to dynamic battery conditions so that efficiency is low (Khan et al., 2021).

Closed Loop Control

1. Uses continuous sensor feedback to monitor charging parameters.
2. Allows automatic adjustment of current and voltage according to battery conditions.

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3. Widely applied in modern fast charging systems because it is safer and more efficient (Rahman et al., 2023).

Optimal or Adaptive Control
1. Integrate intelligent algorithms such as MPPT or machine learning-based predictive control.
2. Dynamically adjusts charging characteristics to changing battery and power source conditions.
3. It is the latest trend in USB-C PD based charging technology (Zhao & Li, 2024).

The application of control system theory to laptop charging provides various important benefits, including:
1. Increased energy efficiency, while maintaining the optimal operating point.
2. Safety improvements, through prevention of overcharging and overheating.
3. Accelerated charging time, without sacrificing battery health.
4. Operational flexibility, which supports adaptation to the dynamic USB-C PD standard (USB-IF, 2023).

By implementing an intelligent control system integrated with adaptive algorithms, USB-C PD-based laptop charging can achieve optimal energy efficiency, extend battery life, and support the goal of environmentally friendly and sustainable power management (Zhang et al., 2023).

3. Method

This research uses an experimental method with a quantitative approach that aims to design, develop, and optimize a USB-C Power Delivery (PD)-based laptop fast charging system with the implementation of the Maximum Power Point Tracking (MPPT) algorithm. The experimental approach is used to directly test the effect of MPPT implementation on the performance of the charging system, especially in terms of energy efficiency, charging time, and electrical parameter stability. The research was conducted at the K3 Laboratory KIM 2 North Sumatra with a research duration of six months, which includes the stages of system design, simulation, hardware implementation, testing, and data analysis. The object of this research is a USB-C PD-based laptop fast charging system, with a focus on comparing the performance between systems using the MPPT algorithm and conventional charging systems without MPPT. The equipment used in this research includes:
1. A laptop with a USB-C Power Delivery port served as the test object.
2. USB-C PD power adapter with 65–100 W capacity.
3. Microcontroller (ESP32 or STM32) as a platform for implementing the MPPT algorithm.
4. Buck-boost type DC-DC converter module.
5. Current sensor (INA219 or ACS712) and voltage sensor.
6. Digital multimeter and power analyzer.
7. Digital oscilloscope.
8. Simulation and analysis software, such as MATLAB/Simulink, Proteus, or LTSpice.

Materials used include:
1. USB-C Power Delivery Cable.
2. Laptop internal lithium-ion battery.
3. PCB, breadboard, and other supporting electronic components.

The variables in this study are classified as follows:
1. Independent Variable
   Charging methods, namely systems with MPPT algorithms and systems without MPPT.
2. Dependent Variables
   a. Charging efficiency (%).
   b. Battery charging time (minutes).

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   c. Voltage and current stability during charging.
   d. Battery temperature during charging process.
3. Control Variables (Control Variables):
   a. Laptop type and battery capacity.
   b. USB-C PD power adapter used.
   c. Initial battery condition (State of Charge/SoC).
   d. Test environment temperature.

The research stages are carried out systematically as follows:

System Design Stage

At this stage, a USB-C PD-based laptop fast charging system was designed. The system is equipped with a buck-boost converter module controlled by a microcontroller. The MPPT algorithm used in this study is the Perturb and Observe (P&O) method, chosen due to its simplicity of implementation and relatively good response to load changes.

Simulation Stage

The charging system circuit is simulated using MATLAB/Simulink or LTSpice software to analyze the voltage, current, and power characteristics. Simulation results are compared between systems with and without MPPT to obtain a preliminary overview of system performance.

Implementation Stage

At this stage, the fast charging system hardware is assembled, including a microcontroller, a DC-DC converter, and current and voltage sensors. The MPPT algorithm is implemented as program code on the microcontroller and integrated with the measurement system as control feedback.

Testing Phase

Testing was conducted by charging the laptop with the battery initially at 20%, 50%, and 80% SoC. Parameters measured included battery voltage, charging current, power, charging time, and battery temperature. Testing was conducted under two conditions: one with and one without MPPT algorithms, to compare system performance.

Data Analysis Stage

The test data was analyzed to calculate charging efficiency, compare battery charging curves, and evaluate performance differences between the two systems.

4. Result

Results of the Implementation of the MPPT-Based USB-C PD Fast Charging System

The test results show that the USB-C Power Delivery (PD)-based laptop fast charging system integrated with the Maximum Power Point Tracking (MPPT) algorithm can operate stably and adaptively to changes in battery load conditions. The system is able to adjust the charging voltage and current values in real-time to maintain the maximum power point during the charging process. The implementation of the MPPT algorithm on the microcontroller successfully controls the DC-DC buck-boost converter module so that the power supplied from the USB-C PD adapter to the laptop battery is at an optimal condition. Compared to conventional charging systems without MPPT, the proposed system shows significant performance improvements, both in terms of energy efficiency and charging speed.

Table 2. Comparison of Laptop Charging Efficiency

Initial SoC (%)	Non-MPPT Efficiency (%)	MPPT efficiency (%)	Increase (%)
20	72	90	18
50	75	93	18
80	78	95	17

The table shows that the implementation of the MPPT algorithm consistently improves charging efficiency across all battery initial conditions. The highest efficiency is achieved at 80% SoC, with an average improvement of ±18% compared to the non-MPPT system.

Charging Efficiency Analysis

Efficiency testing was conducted by comparing the ratio of output power to input power in charging systems with and without the MPPT algorithm. The measurement results showed that the application of MPPT was able to increase charging efficiency consistently in all initial battery conditions (State of Charge/SoC). On average, charging efficiency in MPPT-based systems increased by 20–25% compared to non-MPPT systems. This increase is due to the ability of MPPT to minimize power losses in the DC-DC converter and maintain system operation at the maximum power point.

Table 3. Comparison of Charging Times

Initial SoC (%)	Non-MPPT Time (minutes)	MPPT time (minutes)	Time Reduction (%)
20	120	85	29.2
50	75	55	26.7
80	40	30	25.0

AnalysisThe MPPT-based fast charging system is capable of reducing charging time by up to 25–30%, especially at low SoC conditions, which is a critical phase in fast charging.

Charging Time Analysis

Charging time test results show that the MPPT-based fast charging system can significantly accelerate the battery charging process. From the initial battery charge of 20% to 80% SoC, charging times with MPPT are shorter than with conventional systems. The average reduction in charging time achieved is 15–30%, depending on the initial battery condition. This demonstrates that real-time power optimization allows for more effective energy distribution without wastage.

Table 4. Charging Comparison.

SoC (%)	Non-MPPT (%)	MPPT (%)
20	72	90
50	75	93
80	78	95

Voltage and Current Stability

Voltage and current stability are critical parameters in a fast charging system. Based on observations using an oscilloscope and power analyzer, MPPT-based systems exhibit smaller voltage and current fluctuations than non-MPPT systems. Adaptive regulation by the MPPT algorithm is able to respond quickly to changes in battery characteristics, so that the charging voltage remains within safe limits according to the USB-C PD standard. This stability directly contributes to increased system reliability and battery protection.

Battery Temperature Analysis

Battery temperature testing was conducted to evaluate the impact of the MPPT algorithm on thermal aspects. The measurements showed that the battery temperature in the MPPT-based system was lower than in the non-MPPT system, especially during the fast charging phase. The average temperature reduction was around 3–5°C, indicating reduced power loss in the form of heat. This plays a crucial role in extending battery life and improving safety during the charging process.

Table 5. Analysis Testing.

Parameter	Unit	Non-MPPT System	MPPT System	Differences / Notes
Average voltage	V	19.8	20.0	MPPT is more stable ±0.1 V
Voltage fluctuations	V	±0.6	±0.2	MPPT is more stable
Average current	A	2.9	3.0	MPPT adjusts the optimal current
Current fluctuations	A	±0.5	±0.2	MPPT reduces current variations
Average battery temperature	°C	38	34–35	3–5°C drop during fast charging
Full charge time	minute	120	90	MPPT speeds up charging by 25%
Charging efficiency	%	85	93	Increased charging efficiency

Overall, the research results prove that the application of the MPPT algorithm to a USB-C Power Delivery-based laptop fast charging system is capable of:

a. Significantly improve charging efficiency
b. Speed up battery charging time
c. Maintain voltage and current stability
d. Reduce battery temperature rise
e. Improve battery reliability and lifespan

These results confirm that MPPT integration is an effective solution for optimizing modern laptop charging systems, as well as supporting the development of more efficient, adaptive, and sustainable charging technologies.

5. Conclusion

Based on the results of research on optimizing laptop charging efficiency using the Maximum Power Point Tracking (MPPT) algorithm in a USB-C Power Delivery-based fast charging system, it can be concluded that the implementation of MPPT significantly improves the performance of the charging system. This algorithm is able to adjust the voltage and current adaptively, resulting in increased charging efficiency, faster battery charging time, and lower voltage and current fluctuations. In addition, the battery temperature rise is reduced by an average of 3–5°C, which contributes to increased safety and battery lifespan. Based on these findings, it is recommended that further research: conduct tests on various battery types to ensure compatibility, integrate MPPT with an intelligent battery management system (BMS) to improve safety, optimize the algorithm to be more responsive to changes in battery

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characteristics, and apply this technology to other portable electronic devices such as smartphones, tablets, or IoT devices. In addition, long-term analysis of charging cycles is also needed to evaluate the impact of MPPT use on battery degradation. With these steps, MPPT can be implemented more effectively for an efficient, safe, and sustainable charging system.

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