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Comprehensive Dual-Mode Charging Systems for Lead-Acid Batteries in Electric Vehicles

Shruti Kumari[1], Noorul Islam[2], Avinash Kumar[3], Shweta Shukla[4], Abhay Sharma[5], Ayesha khan[6], Sumit[7]
[1-7]*Department of Electrical Engineering, Meerut Institute of Engineering and Technology, Meerut, India*

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Abstract: *The advancement of charging systems has played a pivotal role in the development and sustainability of electric vehicles (EVs). With an increasing demand for reliable and efficient charging mechanisms, dual-mode chargers have emerged as an essential component in managing the health and longevity of lead-acid batteries. These chargers operate in two distinct modes: boost mode and trickle mode, enabling optimized charging based on the battery's state of charge. This review paper delves into the working principles of dual-mode charging systems, specifically designed for 60V 16A lead-acid batteries, and explores their impact on battery performance, lifespan, and energy efficiency.*

Key Word*:Electric Vehicle; Lead-Acid Batterie; Battery Charger; Renewable energy; Uninterrupted Power Supply.*

I. Introduction

The rapid development of charging technologies has significantly contributed to the growth and sustainability of electric vehicles (EVs), with charging infrastructure playing a central role in enhancing EV adoption and operational efficiency[1,2,3,4]. Among the various charging solutions, dual-mode chargers have gained prominence due to their ability to manage the health and extend the lifespan of lead-acid batteries, a widely used battery type in smaller electric vehicles and backup power applications[6,7,8]. These chargers function in two distinct modes: **boost mode** and **trickle mode**, which allow for an adaptive charging process tailored to the battery's state of charge. In boost mode, the charger delivers a high current to quickly charge the battery, while in trickle mode, a lower, steady current is provided to maintain charge without overcharging, thus preventing damage[9,10]. This paper provides an in-depth analysis of the principles and operation of dual-mode charging systems designed specifically for 60V 16A lead-acid batteries. By reviewing relevant literature and experimental findings, this study explores the effects of these systems on key performance parameters, such as charge efficiency, battery longevity, and energy consumption[11, 12,13]. The impact of dual-mode charging on battery cycle life and energy storage capacity is also examined, with a focus on optimizing battery performance while minimizing environmental and operational costs. This review highlights the potential of dual-mode chargers to enhance battery health management strategies, contributing to more sustainable and cost-effective electric vehicle technologies[14,15].

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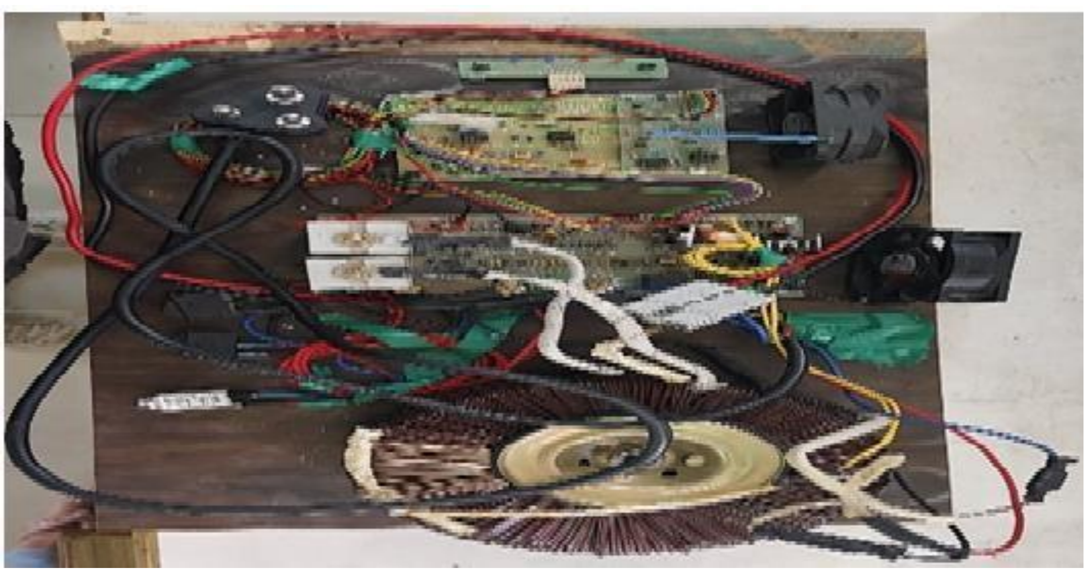

Figure 1: Circuit diagram of Dual-Mode Charging Systems

II. Overview of Lead Acid Batteries

Lead acid batteries have been a cornerstone of energy storage solutions for over a century, primarily due to their affordability, robustness, and ability to deliver high currents, making them ideal for applications ranging from automotive to renewable energy storage. As one of the most widely used types of rechargeable batteries, lead-acid batteries power a broad range of devices, including electric vehicles (EVs), uninterruptible power supplies (UPS), backup systems for telecommunications, and off-grid renewable energy systems (Vetter et al., 2012).

a. Basic Composition and Functionality

A typical lead-acid battery consists of lead dioxide (PbO_2) as the positive plate, sponge lead (Pb) as the negative plate, and a sulfuric acid (H_2SO_4) electrolyte. During discharge, the battery undergoes a chemical reaction that converts the lead and lead dioxide plates into lead sulfate ($PbSO_4$), releasing energy. During charging, the process is reversed, and lead sulfate is converted back into lead and lead dioxide (Teplyakov et al., 2015

b. Advantages of Lead-Acid Batteries

Lead-acid batteries offer several advantages that have made them the preferred choice in many energy storage applications:
Cost-Effectiveness: One of the main reasons lead-acid batteries remain widely used is their lower initial cost compared to other battery chemistries, such as lithium-ion or nickel-metal hydride (NI-MH)where initial investment cost is a major consideration (Linden & Reddy, 2002).
Proven Track Record: Lead-acid batteries have been in use for over 150 years, and their technology is well-understood(Kordesch&Stresing, 2004).

c. Drawbacks of lead-Acid Batteries

Limited Energy Density: One of the key limitations of lead-acid batteries is their relatively low energy density compared to newer battery technologies like lithium- ion. This limitation affects the range of electric vehicles (EVs) and the overall weight and size of the battery packs in energy storage systems (Tarascon & Armand, 2001).

Cycle Life: Lead-acid batteries typically have a shorter lifespan compared to other battery chemistries, particularly if they are subjected to deep discharge cycles or are not properly maintained,they are consistently discharged to very low voltages or if overcharging occurs (Thackeray et al., 2012).

d. The role of charging system in Battery Health

The charging system plays a pivotal role in the health and longevity of lead-acid batteries. A poorly regulated charging system can lead to issues like overcharging, undercharging, and sulfation, each of which significantly reduces the battery's performance and lifespan.

Overcharging also leads to the production of hydrogen and oxygen gases, which can be hazardous if not vented correctly (Mori et al., 2008).

Undercharging: On the opposite side, undercharging occurs when the battery is not charged to its full capacity

e. Dual-Mode Chargers for lead-Acid

These chargers typically operate in two modes—boost mode and trickle mode—to provide the appropriate charging current based on the battery's state of charge.

Boost ModeThis mode is particularly beneficial in applications where downtime needs to be minimized, such as in electric vehicles (EVs) (Miller et al., 2012).

Trickle Mode: Once the battery reaches approximately 80% of its full charge, the charger switches to trickle mode, which provides a much lower current (up to 21A). Trickle charging allows the battery to be fully charged without the risks associated with overcharging. This mode is designed to maintain the battery at full charge while preventing the formation of lead sulfate crystals (Anderson et al., 2016).

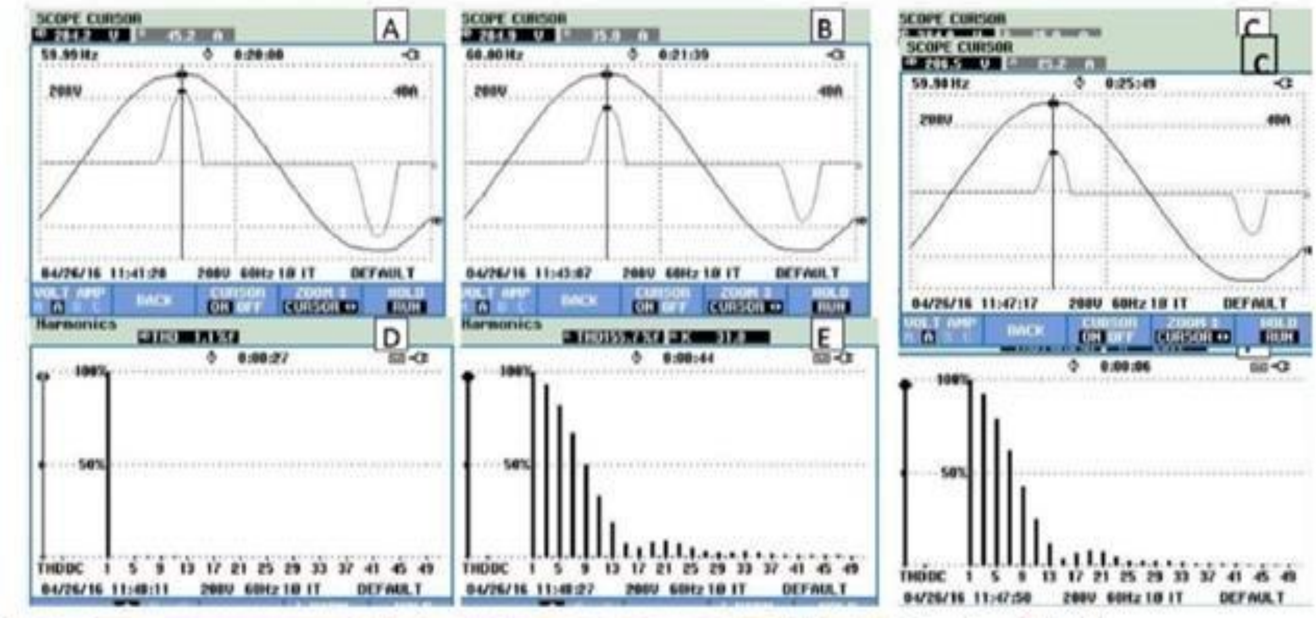

Figure 2: Charging & discharging

III. Dual-Mode Charging Systems

Working Principles Dual-mode charging systems are designed to optimize the charging process of lead- acid batteries by operating in two distinct modes: boost mode and trickle mode.

a. Boost Mode

In boost mode, the charger delivers a higher current (typically 11 Piyush Agrawal et al./ International journal of research in engineering and innovation (IJREI), vol 9, issue 1 (2025), 9-17. up to 16A

Operational Characteristics: During boost mode, the charger uses a high current to rapidly charge the battery. This high rate of current delivery accelerates the voltage rise in the battery

Applications: Boost mode is especially critical for applications where quick charging is essential, such as in electric vehicles (EVs), electric motorcycles. vehicle can be quickly returned to service, (Miller et al., 2012).

Advantages: The use of boost mode helps prevent significant downtime, which is vital for the vehicle's operation.It offers a practical solution to meet the need for high-demand charging cycles, such as those required in fleets or shared mobility services (Chakraborty et al., 2017).

b. Trickle Mode

Once the battery reaches a certain charge threshold (typically around 80%), the charger switches to trickle mode, which operates at a lower current rating (usually up to 21A). In this mode, the charger delivers a steady, controlled current to the battery, which is crucial for topping off the battery without overloading it.

Operational Characteristics: In trickle mode, the battery is charged at a much slower rate compared to boost mode. This lower current helps to prevent overcharging, as the battery's voltage gradually increases without the stress of rapid charging. It starts minimizing the risk of gassing, where the electrolyte produces harmful gases (Mori et al., 2008).

Applications: Trickle charging is used during the final phase of charging when the battery is near full capacity. This mode is essential in applications where battery longevity and health are critical, such as in UPS systems, solar energy storage, and automotive batteries (Thackeray et al., 2012).

Advantages: Trickle charging is a key strategy for maintaining battery health over the long term. By avoiding overcharging, trickle mode minimizes the risk of sulfation, which occurs when lead sulfate crystals accumulate on the plates during incomplete charging cycles (Yu et al., 2015).

c. Auto-Cut Feature

One of the most significant features of modern dual-mode charging systems is the auto-cut function, which automatically halts the charging process once the battery reaches full charge. This feature is critical in preventing overcharging.

Operational Characteristics: This system helps maintain the optimal voltage and temperature during charging, reducing the risk of damage to the battery's internal components (Pletcher et al., 2009). 12 Piyush Agrawal et al./ International journal of research in engineering and innovation (IJREI), vol 9, issue 1 (2025), 9-17.

Advantages: The primary advantage of the auto cut feature is its ability to safeguard the battery's integrity. Overcharging can result in the loss of electrolyte, corrosion of the battery plates, and the breakdown of the internal structure, all of which significantly reduce the efficiency and lifespan of the battery (Miller et al., 2012).

Applications: The auto-cut feature is particularly beneficial in high-usage applications such as electric vehicles and grid-connected energy storage

d. Summary of Dual-Mode Charging System Benefits

The dual-mode charging system, consisting of boost mode, trickle mode, and the auto-cut feature, offers numerous benefits for lead-acid battery management:

Faster Charging: Boost mode enables quick recharging of the battery, particularly when it is deeply discharged.

Improved Battery Health: Trickle mode ensures that the battery is maintained in a fully charged state without the risk of overcharging, which helps to prolong the battery's lifespan.

IV. Impact on Battery Health and Longevity

The health and longevity of lead-acid batteries are deeply influenced by the charging method employed. Lead-acid batteries, while widely used due to their cost- effectiveness and reliability, are highly sensitive to charging parameters such as current, voltage, and charging duration.

a. Overcharging and its impact on Battery Health

One of the most significant risks to battery health is overcharging. Overcharging occurs when the charger continues to deliver current to the battery even after it has reached its full charge capacity. In lead-acid batteries, this can lead to several detrimental effects:

Overheating: When the battery is accelerate the degradation of the battery's internal components. The internal resistance increases, leading to higher temperature build-up, which can eventually result in thermal runaway (Srinivasan & Santhanagopalan, 2012).

Gas Generation: Lead-acid batteries use sulfuric acid as an electrolyte, and overcharging causes the electrolyte to decompose into hydrogen and oxygen gases. These gases can accumulate within the battery, leading to gas evolution and possible venting, which reduces the efficiency of the battery and can also cause damage to the battery casing or the surrounding environment (Linden & Reddy, 2002).

Loss of Capacity: In severe cases, overcharging can cause plate corrosion and eventually result in a total 13 Piyush Agrawal et al./ International journal of research in engineering and innovation (IJREI), vol 9, issue 1 (2025), 9- 17. loss of capacity (Li et al., 2017).

b. Sulfation and its effect on Battery Efficiency

Sulfation is another significant issue that can negatively impact lead- acid battery performance and longevity. Sulfation occurs when the battery is undercharged, or the charging process is too slow to fully charge the battery. Sulfation can cause a permanent capacity loss if not addressed promptly (Yu et al., 2015).

Undercharging: If a battery is not charged sufficiently, especially when it is frequently maintained at low charge levels, the lead sulfate crystals can form and harden. In extreme cases, the crystals can permanently damage the plates and make the battery unable to accept a full charge. Quick Charging in Boost Mode.

Slow Charging: While a slower charging process, such as trickle charging, is essential during the final stages of charging, if the battery is charged too slowly over a prolonged period, the likelihood of sulfation increases. This is particularly the case if the battery remains in a partially charged state for extended periods (Mori et al., 2008).

c. The Role of Dual Mode Chargers in Battery

Health Optimization Dual-mode charging systems work by intelligently adjusting the charging current throughout the battery's charging cycle, which helps to balance the need for fast charging with the importance of maintaining the battery's health. These chargers optimize the charging process by following two key strategies:

Quick Charging in Boost Mode: The boost mode provides a rapid charge when the battery is in a low state of charge. This mode is effective at bringing the battery up to approximately 80% of its full capacity. Rapid charging in this mode reduces the time spent in a low charge state, which minimizes the risk of sulfation, a common issue with undercharged batteries (Thackeray et al., 2012).

Controlled Charging in Trickle Mode: Once the battery reaches a significant charge level (usually around 80%), the charger switches to trickle mode, which provides a much slower, more controlled charge to top off the battery. This gradual charging process ensures that the battery reaches its full capacity without the risks associated with overcharging. The trickle mode prevents the battery from being subjected to excessive current flow, which could otherwise lead to heat buildup, gas generation, and internal damage (Miller et al., 2012).

V. Benefits of Dual-Mode Chargers

These chargers provide a tailored approach to charging, ensuring that the battery is not only recharged efficiently but also maintained in optimal condition throughout its lifecycle. Below, we explore the key benefits of dual-mode chargers in greater detail. 14 Piyush Agrawal et al./ International journal of research in engineering and innovation (IJREI), vol 9, issue 1 (2025), 9-17.

a. Increased Charging Efficiency

One of the most significant advantages of dual- mode chargers is their ability to increase charging efficiency by adapting the charging method based on the battery's state of charge. In a typical lead-acid battery charging cycle, the battery goes through different stages, starting from a low state of charge and progressing toward full capacity. The dual-mode charger operates in boost mode during the initial stages, providing a high current to charge the battery rapidly. This is particularly beneficial in applications where quick turnaround times are needed, to top off the battery.

b. Prevention of Overcharging

Overcharging occurs when the charger continues to provide current to the battery even after it reaches full charge, causing the battery to overheat, release gases, and suffer from permanent capacity loss. Overcharging can also result in excessive heat buildup within the battery, which leads to the degradation of internal components, electrolyte loss, and in extreme cases, the possibility of thermal runaway (Srinivasan & Santhanagopalan, 2012).

c. Cost- Effectiveness

Cost is always an important factor when evaluating the practicality of charging systems, particularly in industries that rely on large numbers of batteries, such as electric vehicles (EVs) and backup power systems.Lead-acid batteries are relatively inexpensive compared to alternative battery chemistries, making them an attractive option for many applications.

d. Environmental Benefits

In addition to their economic advantages, dual-mode chargers also offer environmental benefits. By extending the lifespan of lead-acid batteries, dual-mode chargers which reduce the frequency of battery disposal, which in turn minimizes the environmental impact of battery waste. Lead acid batteries contain hazardous materials such as lead and sulfuric acid, which can pose significant environmental risks if not disposed of properly (Srinivasan & Santhanagopalan, 2012).

VI. Challenges and Future Directions

Despite the numerous benefits of dual mode charging systems, several challenges need to be addressed to further optimize their performance and enhance their adoption across various applications.

a. Battery Compatibility

One of the primary challenges facing the widespread adoption of dual-mode chargers is their compatibility with different types of batteries. While dual mode chargers are optimized for lead-acid batteries, their effectiveness and efficiency with other battery chemistries, such as lithium-ion or nickel-metal hydride (NiMH), remain uncertain. The charging requirements of each battery type can vary significantly.

b. Technological Advancements

For instance, artificial intelligence (AI) and machine learning (ML) could play a role in predicting the optimal charging current and voltage based on factors such as the battery' state of health (SOH), temperature, and ambient conditions (Miller et al., 2012).

c. Scalability and Cost

Another challenge that may limit the widespread adoption of dual-mode chargers is the scalability and cost of integrating these systems into large-scale operations. For instance, in electric vehicle (EV) fleets or renewable energy storage systems, a large number of batteries may need to be charged simultaneously. While dual-mode chargers provide excellent benefits in terms of battery health and charging efficiency, scaling these systems to accommodate multiple batteries at once can introduce logistical and economic challenges.

d. Environmental Considerations

Finally, as the demand for sustainable energy solutions grows, future developments in dual-mode charging systems must also take into account their environmental impact. While dual-mode chargers contribute to energy savings and improved battery longevity

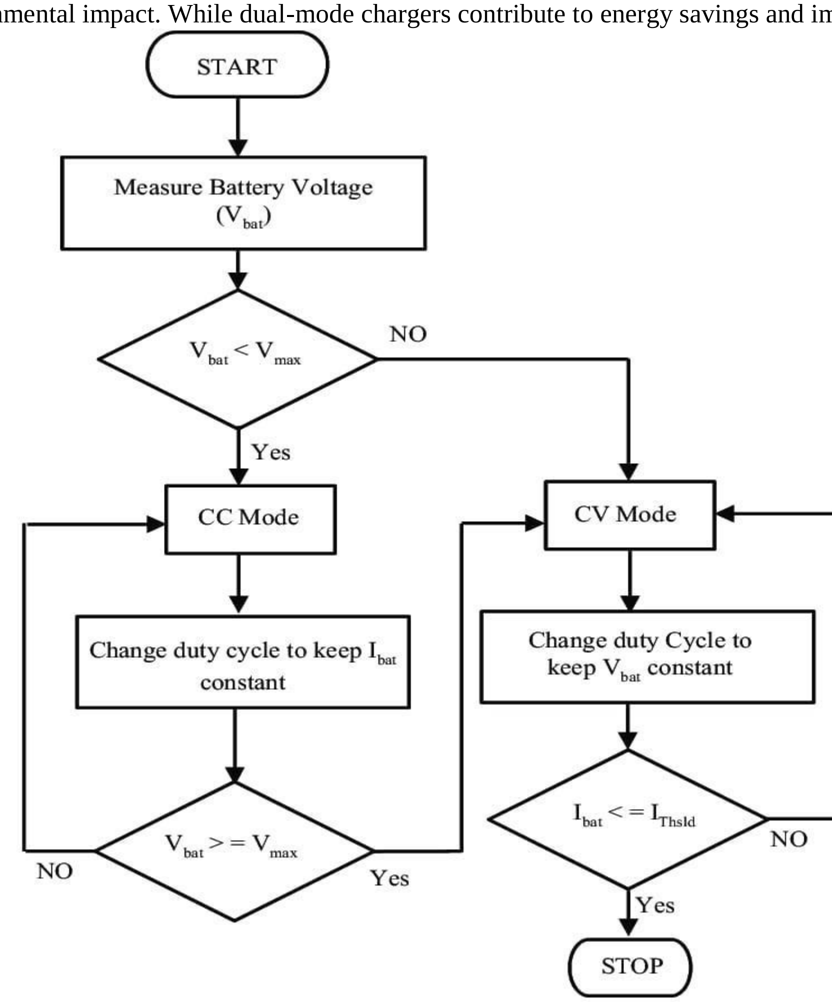

Figure 3: Flow Chart Dual-Mode Charging Systems

V. Conclusion

4 Dual-mode chargers have emerged as a key technological advancement in the efficient and safe charging of lead-acid batteries, particularly in the context of electric vehicles (EVs) and renewable energy storage systems. Traditional charging systems often rely on a single, fixed charging rate. In contrast, dual-mode chargers optimize the charging process by adjusting the current based on the battery's state of charge, ensuring that lead-acid batteries perform at their best over extended periods."

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