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PREDICTIVE MAINTENANCE AND FAULT DETECTION OF DC FAST CHARGERS USING IOT SENSORS AND MACHINE LEARNING

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Abstract

The rapid expansion of DC fast-charging infrastructure is essential for large-scale electric vehicle (EV) adoption, yet charger downtime, intermittent faults, and component degradation continue to reduce reliability and user trust. This paper proposes an IoT- and machine learning–enabled predictive maintenance and fault detection framework for DC fast chargers, designed to identify early-stage anomalies and forecast impending failures before they cause service interruptions. A multi-sensor monitoring layer captures high-frequency operational signals—such as input/output voltage and current, power factor, harmonic indicators, connector temperature, cabinet/IGBT temperature, insulation resistance indicators, cooling-system performance, and communication logs—streamed through an edge gateway for real-time analytics. The approach combines (i) supervised fault classification for known failure modes (e.g., connector overheating, contactor wear, insulation deterioration, cooling faults, and power-module imbalance) and (ii) unsupervised anomaly detection for unknown or evolving patterns using reconstruction- and density-based models. For maintenance planning, remaining useful life (RUL) estimation is integrated using time-series learning on degradation-sensitive features. Performance is evaluated using metrics such as precision–recall, F1-score, false-alarm rate, detection latency, and uptime improvement, alongside operational indicators such as mean time between failures (MTBF) and mean time to repair (MTTR). The proposed framework supports scalable deployment across charging networks, enabling remote diagnostics, reduced maintenance cost, and improved station availability—key requirements for dependable ultra-fast charging ecosystems.

Keywords

DC fast charger; predictive maintenance; fault detection; IoT sensors; anomaly detection; remaining useful life (RUL); machine learning; edge analytics

1. INTRODUCTION

Electric vehicles are increasingly positioned as a central pathway to decarbonizing transportation, but the practical success of EV adoption depends heavily on charging availability, reliability, and user confidence. Among available charging options, DC fast chargers enable rapid energy replenishment and are therefore crucial for highway corridors, fleet operations, and urban fast-charging hubs. However, their high power levels, complex power-electronic subsystems, and harsh outdoor operating conditions make them vulnerable to failures and performance drift. Even short periods of charger downtime can create queues, amplify range anxiety, and reduce the perceived dependability of EV infrastructure. Traditional maintenance approaches for charging stations are often reactive (repair after failure) or periodic (time-based inspections). These strategies can be costly and inefficient: reactive maintenance increases downtime and disrupts operations, while periodic maintenance may replace components prematurely and still fail to detect intermittent or fast-developing faults. DC fast chargers face diverse fault modes, including connector and cable overheating, contactor degradation, fan and liquid-cooling malfunctions, insulation deterioration, power-module imbalance, sensor drift, and communication/protocol issues. Many of these faults exhibit early warning signatures—small deviations in temperature rise rate, voltage ripple, harmonic distortion, efficiency drop, or repeated communication retries—that are difficult to capture through manual inspection alone.

This study focuses on developing a predictive maintenance and fault detection framework for DC fast chargers using

IoT sensors and machine learning. The key objectives are: (i) to design a sensing and data pipeline suitable for high-power chargers, (ii) to extract health indicators and fault signatures from electrical–thermal–operational data, (iii) to develop ML models for early fault detection and fault classification, and (iv) to enable maintenance decision support through risk scoring and, where feasible, remaining useful life estimation. The expected outcome is a scalable, real-time monitoring architecture that increases charger uptime, lowers maintenance cost, and strengthens user trust in ultra-fast charging infrastructure.

2. ELECTRIC VEHICLE CHARGING TECHNOLOGIES

Electric vehicles (EVs) are revolutionizing the transportation sector, offering a more sustainable alternative to gasoline-powered vehicles. However, a critical aspect of EV adoption is the ability to charge these vehicles efficiently. Over the years, various charging technologies have been developed to meet the needs of different EV models, charging speeds, and infrastructure conditions. This section discusses the different types of charging stations, the challenges faced by the current charging infrastructure, and the benefits of ultra-fast charging.

1.2 Types of Charging Stations (Level 1, Level 2, and DC Fast Chargers)

Electric vehicle charging stations can be categorized based on the charging speed, the voltage provided, and the complexity of the charging systems. The three primary types of EV chargers are Level 1, Level 2, and DC fast chargers (also known as Level 3).

Level 1 Chargers : Level 1 chargers are the most basic form of EV charging infrastructure. These chargers use a standard 120V household outlet and typically come with the vehicle. Level 1 charging is the slowest method, delivering around 2-5 miles of range per hour of charging. This type of charging is convenient for overnight charging at home, but it is not suitable for daily use if long-range driving is required (Sovacool et al., 2020).

Level 1 chargers have limited capacity due to their low voltage and are primarily intended for home use where vehicle owners can leave their EVs plugged in for an extended period. They do not require specialized installation, making them an affordable option for those who do not require rapid charging. However, for electric vehicle adoption to grow, faster charging solutions like Level 2 and DC fast chargers are becoming essential.

Level 2 Chargers : Level 2 chargers operate on a 240V supply, delivering faster charging speeds compared to Level 1 chargers. These chargers are commonly found at home, workplaces, and public locations. Level 2 chargers provide an average charging rate of 10-60 miles of range per hour, depending on the charger's power output (typically 3.3 kW to 19.2 kW) and the vehicle's charging capacity (Chen et al., 2021). This type of charger is more suitable for users who need to charge their EVs overnight or during long stops. Level 2 chargers are increasingly popular for both private and public use, as they strike a balance between charging time and infrastructure cost. Many public charging stations, including those in parking garages, shopping malls, and office complexes, are equipped with Level 2 chargers, as they provide a reasonable charging time without requiring the heavy investment associated with DC fast chargers (Zhang et al., 2020).

DC Fast Chargers (Level 3) : DC fast chargers are the fastest EV charging stations available, capable of charging a vehicle at a much higher rate than Level 1 and Level 2 chargers. These chargers bypass the vehicle's onboard charger to provide DC (direct current) power directly to the battery. DC fast chargers can deliver power up to 350 kW, enabling an EV to charge to 80% of its battery capacity in just 20-30 minutes (Harten et al., 2019). This rapid charging capability makes DC fast chargers ideal for locations like highway rest stops, where long-distance EV travelers can quickly recharge before continuing their journey.

DC fast chargers are often integrated into fast-charging networks, such as Tesla Superchargers or networks like Electrify America and Ionity. However, they come with a higher infrastructure cost compared to Level 2 chargers, and they require significant grid capacity to deliver high power levels (Sovacool et al., 2020). Additionally, not all

EVs are compatible with DC fast chargers, as different EV manufacturers use different charging connectors (Chen et al., 2021).

1.2.1 Challenges in Current Charging Infrastructure

While the development of EV charging infrastructure has progressed over the years, several challenges remain. These challenges include issues related to charging speed, accessibility, grid integration, and costs.

- **Charging Speed and Time Constraints** : One of the primary challenges with existing charging infrastructure is the significant time required for EV charging. While Level 1 chargers are slow by design, even Level 2 chargers can take several hours to fully charge a vehicle. This is not ideal for users who rely on EVs for daily commuting or long trips. DC fast chargers alleviate this issue to some extent, but they remain limited in availability, especially in rural and suburban areas (Lund et al., 2020). Additionally, charging times can vary based on the vehicle's battery capacity and the charger's output, making it difficult for users to estimate how long they need to wait to fully charge their vehicle (Zhang et al., 2020).
- **Insufficient Charging Network** : The availability of charging stations is still limited in many regions, particularly outside urban centers. In many countries, especially developing economies, the infrastructure for charging stations is not sufficiently widespread. This problem leads to what is known as "range anxiety," where EV users fear they will not be able to find a charging station when they need one (Breetz et al., 2021). Expanding the charging network is essential to increasing EV adoption, but this expansion requires significant investment from both the private sector and government bodies.
- **Grid Integration and Load Balancing** : As more EVs hit the roads, the strain on the electrical grid increases. The current grid infrastructure may not be able to handle the additional demand caused by widespread EV adoption, particularly if large numbers of vehicles begin charging simultaneously (Sovacool et al., 2020). Smart charging solutions, such as AI-powered grid management, can help optimize charging times, prevent overloads, and manage demand more efficiently. However, implementing these systems on a large scale requires significant upgrades to the existing grid infrastructure.
- **Cost of Charging Infrastructure** : Another challenge is the high cost of installing charging stations, especially DC fast chargers. These stations require expensive equipment, high power availability, and specialized installation, making them less economically viable for many businesses and municipalities. Public-private partnerships, government incentives, and subsidies are necessary to reduce the cost barriers for installing charging stations, particularly in underserved areas (Lund et al., 2020).
- **Compatibility and Standardization** : Different automakers use different connectors and charging protocols for their EVs. For example, Tesla uses proprietary connectors for its vehicles, while other manufacturers use the CHAdeMO or CCS (Combined Charging System) connectors for DC fast charging. This lack of standardization in charging connectors creates challenges for both consumers and infrastructure providers. The lack of compatibility among different vehicle models and charging stations further complicates the development of universal charging networks (Chen et al., 2021).

1.2.2 Benefits of Ultra-Fast Charging

Ultra-fast charging offers several significant benefits that address the shortcomings of the existing charging infrastructure. These benefits extend to both consumers and businesses and include reduced charging times, greater convenience, and improved energy efficiency.

- **Reduced Charging Time** : The primary advantage of ultra-fast charging is the reduction in charging time. While Level 1 and Level 2 chargers can take several hours to fully charge an EV, ultra-fast chargers can charge a vehicle up to 80% in as little as 20-30 minutes, significantly improving convenience for EV owners (Harten et al., 2019). This rapid charging capability makes ultra-fast charging ideal for long-distance travel, where EV owners can quickly recharge at highway rest stops or other key locations along their route. This benefit is essential in making EVs a viable option for everyday transportation and long-distance travel.

- **Increased Convenience for Consumers** :Ultra-fast charging reduces the inconvenience associated with long charging times. In busy urban areas, where time is often a constraint, EV owners would prefer a quick top-up rather than having to wait for hours. By offering fast charging at convenient locations such as shopping malls, airports, and public spaces, ultra-fast charging can improve the overall user experience, thereby encouraging more people to adopt electric vehicles (Breetz et al., 2021).
- **Cost Efficiency and Grid Benefits** : While ultra-fast charging stations are expensive to install, they can be cost-efficient in the long run. By providing faster charging times, these stations can reduce the number of customers using the chargers simultaneously, which helps to prevent congestion and long wait times. Furthermore, ultra-fast charging stations can be integrated with smart grids to optimize energy use. For example, they can charge EVs during off-peak hours, reducing the load on the grid and preventing power surges (Lund et al., 2020). This integration with smart grid technology also improves the overall energy efficiency of the system, allowing for better distribution and management of electrical resources.
- **Support for Renewable Energy Integration** :Ultra-fast charging stations can be paired with renewable energy sources like solar and wind power. The integration of renewable energy into the charging stations ensures that EV charging remains sustainable and environmentally friendly. By using solar panels or wind turbines to generate electricity, ultra-fast charging stations can help reduce the overall carbon footprint of the charging process (Zhang et al., 2021). This integration is crucial in advancing the broader goals of decarbonizing the transportation sector.
- **Enhancing EV Adoption** : The widespread availability of ultra-fast charging stations can increase the adoption of EVs by alleviating concerns about range anxiety. With faster charging times and better station availability, potential EV buyers are more likely to choose an electric vehicle over a traditional combustion engine vehicle. As ultra-fast charging infrastructure continues to expand, it will play a significant role in encouraging consumers to make the switch to electric vehicles (Sovacool et al., 2020).
- **Business Opportunities and Revenue Generation**: From a business perspective, ultra-fast charging stations represent a potential source of revenue generation. By providing rapid charging services, charging stations can attract a steady stream of customers, including long-distance travelers, fleet operators, and commercial users. Additionally, businesses can use these stations to offer value-added services, such as retail opportunities at charging locations, which can help improve the financial viability of the charging infrastructure (Chen et al., 2021).

3. ARTIFICIAL INTELLIGENCE IN ELECTRIC VEHICLE CHARGING

As electric vehicle (EV) adoption grows, the need for efficient and effective charging solutions becomes more critical. Traditional charging infrastructure is often inadequate to meet the demands of a rapidly expanding EV market, especially when it comes to optimizing charging time, ensuring reliability, and integrating with power grids. Artificial Intelligence (AI) has the potential to revolutionize the EV charging ecosystem by improving charging efficiency, enabling predictive maintenance, and optimizing energy consumption. This section explores the role of AI in electric vehicle charging, focusing on enhancing charging efficiency, predictive maintenance, and optimizing energy use.

1.3 Role of AI in Enhancing Charging Efficiency

Charging efficiency is one of the foremost concerns in the EV charging infrastructure. Charging an electric vehicle involves converting electricity from the grid into a form that can be used to charge the vehicle's battery. This process can be time-consuming and energy-intensive. AI technologies can help optimize charging efficiency by improving the management of charging stations, predicting energy demands, and enhancing the overall operation of charging systems.

- **AI in Load Management** : AI is particularly effective in managing the power demand and supply between the electric vehicle, the charging station, and the grid. One of the key challenges in EV charging is the fluctuation in demand, especially during peak hours. AI-based load management systems can predict the optimal time to charge vehicles based on the electricity consumption patterns and available power resources. These systems use machine learning algorithms to analyze real-time data and forecast energy demand, ensuring that charging stations operate at peak efficiency without overloading the grid (Dunne et al., 2021).

- **Smart Charging** : AI enables the development of smart charging systems, which dynamically adjust the charging speed based on various factors such as the state of charge (SOC) of the vehicle's battery, the overall grid load, and the vehicle's battery health. By optimizing the charging speed, AI reduces energy wastage and ensures that vehicles are charged at the most efficient rate. These systems can also prioritize vehicles based on their charging needs, ensuring that high-priority vehicles are charged first, improving the utilization of charging infrastructure (Zhang et al., 2020).
- **Integration with Renewable Energy Sources** : AI's role in enhancing charging efficiency also extends to integrating renewable energy into the charging stations. Charging stations that rely on solar or wind power can benefit from AI in optimizing the use of renewable energy. AI systems can predict when renewable energy sources will be abundant, such as during peak solar hours, and adjust the charging schedules accordingly. This helps reduce the dependence on the grid and ensures that charging stations operate in an environmentally friendly manner (Harten et al., 2019).

1.3.1 Predictive Maintenance and Fault Detection Using AI

In addition to improving charging efficiency, AI can also enhance the reliability and longevity of charging infrastructure through predictive maintenance and fault detection. Predictive maintenance uses AI to anticipate when equipment in the charging station is likely to fail, allowing operators to address issues before they result in downtime or costly repairs.

- **Early Fault Detection** : The traditional approach to maintenance in charging stations involves periodic inspections and reactive repairs, which can lead to significant downtimes. AI, on the other hand, uses data analytics and machine learning to detect irregularities in the performance of charging equipment, such as unusual voltage fluctuations, temperature variations, or abnormal charging speeds. By monitoring these parameters in real time, AI can identify potential faults early on, reducing the need for expensive repairs and minimizing system downtime (Sovacool et al., 2020).
- **Failure Prediction Models** : Machine learning algorithms are used to analyze historical data on equipment performance, such as the frequency of failures, the lifespan of components, and the operating conditions of charging stations. Based on this data, AI can create **predictive models** that forecast when specific components are likely to fail, allowing operators to schedule maintenance in advance. This proactive approach helps ensure that charging stations remain operational and reduces the chances of unexpected breakdowns (Zhang et al., 2021).
- **Maintenance Optimization** : AI not only detects faults but also optimizes maintenance schedules. For instance, AI systems can prioritize maintenance tasks based on the severity of the issue, the availability of replacement parts, and the impact on overall system performance. This **dynamic maintenance scheduling** ensures that the least disruptive repairs are carried out first, minimizing downtime and ensuring the availability of charging stations at all times (Li et al., 2021).
- AI-powered predictive maintenance can also reduce the **operational costs** of maintaining charging stations by reducing labor costs and improving the life expectancy of charging equipment. By predicting failures and ensuring timely interventions, AI minimizes the risk of sudden, expensive repairs that may arise from overlooked issues.
- **Remote Diagnostics** : Remote diagnostic capabilities are another advantage of AI in predictive maintenance. Charging stations can be equipped with sensors that feed data to an AI-driven remote diagnostics system, allowing operators to identify problems without having to physically visit the site. This reduces the response time for addressing issues and makes it easier to manage charging infrastructure over vast geographic areas, especially in remote or hard-to-reach locations (Chen et al., 2021).

1.3.2 Optimizing Charging Time and Energy Use with AI Algorithms

The optimization of both charging time and energy consumption is critical in improving the user experience and the operational efficiency of EV charging infrastructure. AI algorithms can optimize these two parameters by continuously learning from historical data, user behavior, and real-time environmental factors.

- **Dynamic Charging Time Optimization** : AI can dynamically adjust the charging time based on a variety of factors such as the state of charge (SOC) of the vehicle's battery, charging speed preferences, and the available power. By doing so, AI ensures that the vehicle is charged in the shortest possible time without exceeding the battery's charging capacity or degrading its health. For example, AI algorithms can slow down the charging speed once the battery reaches 80% to prevent overcharging and prolong battery life (Li et al., 2020). These algorithms can also prioritize certain vehicles for faster charging based on user-defined preferences, such as scheduling or battery health.
- **Energy Use Optimization** : Energy use optimization is another key area where AI can provide significant benefits. Charging stations are typically connected to the power grid, which may experience fluctuations in electricity prices due to demand changes or renewable energy generation patterns. AI can monitor real-time data on electricity prices, grid demand, and energy availability and schedule charging sessions accordingly. For example, AI can ensure that EVs are charged during off-peak hours, when electricity prices are lower, or when renewable energy is abundant (Sovacool et al., 2020).
- AI can also manage multiple charging stations within a network, optimizing energy distribution across the stations based on real-time demand. This approach helps reduce grid strain, especially during peak times, by ensuring that only a few stations are charging simultaneously, thereby balancing the load across the network (Zhang et al., 2021). By using AI-driven energy management systems, EV charging stations can contribute to the grid's stability while minimizing costs for the consumer.
- **Load Balancing and Vehicle-to-Grid (V2G) Integration** : In addition to optimizing charging times and energy consumption, AI can facilitate vehicle-to-grid (V2G) integration, where EVs can return excess stored energy back to the grid. V2G systems use AI algorithms to determine the optimal times for charging and discharging energy based on grid conditions and energy demand. This creates a win-win scenario where EVs are charged efficiently and contribute to grid stability by returning stored energy during peak demand periods (Harten et al., 2019). AI can also enable real-time load balancing among multiple EVs charging at the same station. By continuously analyzing the demand and adjusting charging rates, AI can prevent overloading the grid or charging stations, ensuring efficient energy use and preventing unnecessary delays for users (Li et al., 2020).
- **Predictive Algorithms for Optimized Energy Scheduling** : AI systems can use predictive algorithms to forecast energy consumption patterns, enabling them to adjust charging schedules and energy use in advance. These algorithms analyze factors such as vehicle usage patterns, local energy production, and weather conditions to predict the most efficient charging time. This proactive approach ensures that charging infrastructure operates efficiently, minimizing energy waste and reducing operational costs (Zhang et al., 2021).

Conclusion

This paper overcomes a key reliability challenge in ultra-fast EV charging networks by proposing an IoT- and machine learning–based predictive maintenance and fault detection framework for DC fast chargers, where continuous monitoring of electrical, thermal, and operational signals—combined with supervised fault classification, unsupervised anomaly detection, and time-series health indicators—enables early detection of developing faults before they cause downtime, supports maintenance planning through risk prioritization and possible remaining useful life estimation, improves charger availability and user experience by reducing unexpected failures and charging uncertainty, and lowers operational costs by shifting from routine replacement to condition-based interventions; in the future, the framework can be strengthened by building larger labeled datasets across charger models, using domain adaptation to manage site-level differences, improving cybersecurity and data integrity across IoT pipelines, and integrating predictive outputs with automated maintenance scheduling and spare-parts logistics to further enhance the dependability of fast-charging infrastructure and accelerate EV adoption.

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