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Reliability Analysis of AC-DC and DC-DC Converter Stages in Level-1 Electric Vehicle Chargers

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Abstract*— This study presents a reliability evaluation framework for Level-1 EV charger converter topologies, utilizing the MIL-HDBK-217 reliability prediction methodology. The framework evaluates three prevalent AC–DC power factor correction (PFC) topologies: conventional boost, bridgeless boost, and interleaved boost, alongside three isolated DC–DC converter configurations: conventional flyback, isolated half-bridge LLC resonant, and phase-shifted full-bridge center-tapped (PSFBCT) converters. Component failure rates are determined using MIL-HDBK-217 models for semiconductor devices, capacitors, magnetic components, and auxiliary elements. Converter-level reliability is examined using a series reliability structure, which facilitates the calculation of total failure rates and mean time between failures (MTBF). The results indicate that capacitors are the primary contributors to overall system failure rates and that reducing electrical stress enhances reliability performance. This framework offers a clear, practical way to evaluate and choose the most reliable converter designs for home EV charging.

Index Terms*— Electric Vehicle Charger, Reliability Analysis, MIL-HDBK-217F, MTBF, Level-1 Charging, PFC Converter, Flyback Converter, LLC Resonant Converter, PSFB Converter, Power Electronics Reliability.

I. INTRODUCTION

The transition toward sustainable transportation has led to increased interest in electric vehicles (EVs) as a means of reducing greenhouse gas emissions and limiting dependence on fossil fuels. Growth in EV deployment has intensified the demand for charging infrastructure capable of supporting reliable and efficient battery charging. Consequently, battery chargers constitute a critical component of EV ecosystems [1], [2]. Among the available charging technologies, Level1 chargers are widely used in residential settings because they can operate from standard single-phase utility outlets and typically require minimal installation effort and cost [1].

Conventional Level-1 EV chargers are commonly implemented using a two-stage power conversion architecture comprising an AC–DC power factor correction (PFC) stage followed by an isolated DC–DC converter. This configuration enables compliance with grid power quality requirements while providing regulated charging of the battery pack [1], [3]. The PFC stage is frequently realized using Boost, Bridgeless Boost, or Interleaved Boost converter topologies. For the isolated DC–DC stage, Flyback, LLC resonant, and Phase-Shifted Full Bridge (PSFB) converters are commonly employed due to their favourable efficiency characteristics and provision of galvanic isolation [1], [3].

Although the topologies have been extensively studied in terms of efficiency and power density, reliability has become a key design factor due to the expectation that charging systems will operate continuously over long service lifetimes [4]– [5]. Power electronic converters are prone to failures originating from semiconductor devices, capacitors, magnetic components, and thermal stresses, with capacitors and power semiconductors identified as the most failure-prone elements [4], [6]. As a result, reliability-focused design approaches and quantitative reliability assessment methods have received significant attention in EV charging applications [4], [7], [5]. Among these, the MIL-HDBK-217F handbook is the most widely used statistical framework for estimating component failure rates and system-level reliability in power electronic converters [5].

In response to the increasing demand for reliable EV charging infrastructure, this paper conducts a comparative reliability assessment of selected AC–DC and DC–DC converter topologies employed in Level-1 EV chargers. The MIL-HDBK217F part-stress methodology is applied to calculate and compare failure rates and mean time between failures (MTBF), with the objective of identifying the most reliable converter configurations for residential EV charging applications.

II. RELIABILITY ESTIMATION FRAMEWORK

A. Reliability Analysis

Reliability, efficiency and cost are all factors that impact system performance. The mean time between failures (MTBF) is an important reliability index that is the inverse of the failure rate. If there are no repair or maintenance strategies, then MTBF is equal to the expected lifetime [8]. The failure rate is the number of failures per unit of time (usually 1 million hours) of a system or component.

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If a system has different types of parts that can each fail on their own, and if the whole system fails when any one part fails, you can figure out the system's failure rate like this: The total system failure rate is calculated as

$$\lambda_S = \sum_{i=1}^{n} N_i \lambda_i \tag{1}$$

where λ_S denotes the overall system failure rate, N_i represents the number of components in the i^{th} category, λ_i is the failure rate of the i^{th} category of components, and n is the total number of component categories.

Most power electronic systems fail if any of the components fail. Therefore, it is crucial to be able to determine the failure probability of each component precisely. In this study, we use MIL-HDBK-217 to find these failure rates and consider extra stresses on the components [9].

B. MIL-HDBK-217

The variables and parameters used throughout this work are defined as follow in Table I.

Table I. Nomenclature for Reliability Calculations

Symbol	Description
λ_b	Base failure rate
π_T	Temperature factor
π_Q	Quality factor
π_E	Environment factor
π_S	Electrical stress factor
π_C	Contact construction factor
π_A	Application factor
π_{CV}	Capacitor factor
T_J	Junction temperature of the semiconductor device
T	Ambient temperature
P	Worst-case power dissipation of the device
θ_{JC}	Junction-to-case thermal resistance
V_S	Voltage stress ratio
S	Capacitor voltage stress ratio

- Diode (section 6.1 of [10]): The failure rate of a diode depends on the electrical stress it experiences, the temperature at its junction, and a few other factors that can speed up failure.

$$\lambda_P = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi_E$$
$$\lambda_b = 0.003$$
$$\pi_T = \exp\left[-3091\left(\frac{1}{298} - \frac{1}{273+T_J}\right)\right]$$
$$T_J = T + \theta_{JC} P$$
$$\pi_S = 0.054, \quad V_S \le 0.3$$
$$\pi_S = V_S^{2.43}, \quad 0.3 < V_S \le 1$$
$$\pi_C = 1, \quad \pi_Q = 5.5, \quad \pi_E = 1$$

- MOSFET (section 6.4 of [10]): For low frequencies (frequency ≤ 400 MHz), the total failure rate of MOSFETs is expressed as:

$$\lambda_P = \lambda_b \pi_T \pi_A \pi_Q \pi_E$$
$$\lambda_b = 0.012$$
$$\pi_T = \exp\left[-1925\left(\frac{1}{273+T_J} - \frac{1}{298}\right)\right]$$
$$T_J = T + \theta_{JC} P$$

$\pi_A = 10$, $P_r \ge 250$ W $\pi_Q = 5.5$, $\pi_E = 1$

- Film Capacitor (section 10.4 of [10]):

$$\lambda_P = \lambda_b \, \pi_{CV} \, \pi_Q \, \pi_E$$
$$\lambda_b = \left[0.00069\left(\frac{S}{0.4}^{5} + 1\right)\right] \times \exp\left(2.5\left(\frac{T+273}{398}\right)^{18}\right)$$
$$\pi_{CV} = 1.2C^{0.092}$$
$$\pi_Q = 20$$
$$\pi_E = 1$$

- Electrolytic Capacitor (section 10.15 of [10]):

$$\lambda_P = \lambda_b \, \pi_{CV} \, \pi_Q \, \pi_E$$
$$\lambda_b = 0.0028\left[\left(\frac{S}{0.55}\right)^3 + 1\right] \times \exp\left[4.09\left(\frac{T+273}{358}\right)^{5.9}\right]$$
$$\pi_{CV} = 0.32\, C^{0.19}$$
$$\pi_Q = 10$$
$$\pi_E = 1$$

- Inductor and Transformer (Section 11.1 of [10]): The baseline reliability of inductors and transformers is significantly higher than that of other components, most notably capacitors:

$$\lambda_P = \lambda_b \, \pi_T \, \pi_Q \, \pi_E$$
$$\lambda_b = \begin{cases} 0.00003 \\ 0.019, \end{cases} \text{,for inductors for transformers}$$
$$\pi_T = \exp\left[\frac{-0.11}{8.617 \times 10^{-5}}\left(\frac{1}{273+T} - \frac{1}{298}\right)\right]$$

$\pi_Q = 30$, $\pi_E = 1$

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The quality factor (π_Q) and environmental factor (π_E) are selected from the MIL-HDBK-217F reliability tables for typical operating conditions. As reported in [9], the environmental factor may exceed 300 under extremely harsh operating environments, resulting in a proportional increase in component failure rates. A safety factor (SF) of 100% is assumed, implying that semiconductor devices and capacitors are rated at twice their maximum operating voltage. The voltage stress ratio is expressed as

$$V_S = S = \frac{1}{1 + \frac{\mathrm{SF}}{100}}$$

which yields $V_S = S = 0.5$ for a safety factor of 100%. Under these conditions and an ambient temperature of 35°C, capacitors exhibit the highest failure rates among power electronic components, with electrolytic capacitors being the least reliable and inductors being the most reliable. Therefore, capacitor selection and proper sizing play a critical role in improving the overall reliability and lifetime of power electronic converters [9]. Table II shows the failure rates for different component categories, using the default values mentioned [9].

Table II: Component-Wise Failure Rates

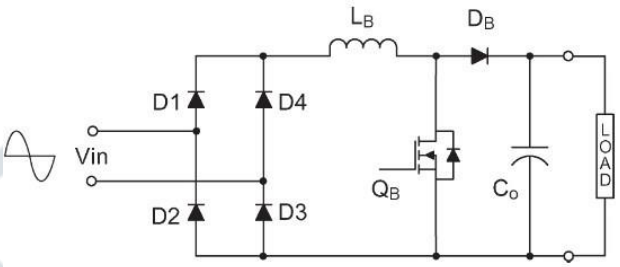
Component	Failure rate per 10^6 hours
Diode	0.0357
MOSFET	0.0814
Film Capacitor	0.3218
Electrolytic Capacitor	1.7609
Inductor	0.0001
Transformer	0.0655

III. SELECTED EV CHARGER TOPOLOGIES

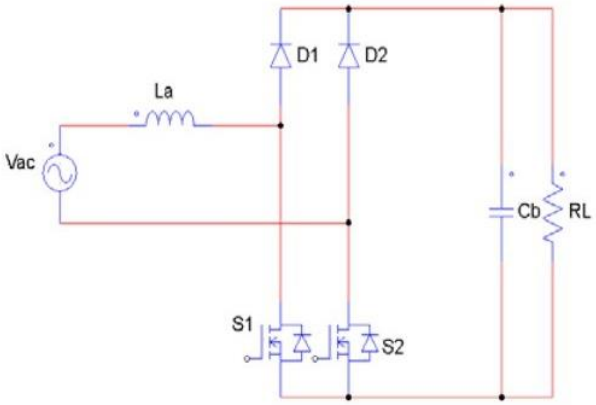
Electric vehicle (EV) charging systems usually include an AC-DC power factor correction (PFC) stage, followed by an isolated DC-DC converter stage. Together, these stages deliver regulated charging power to the battery pack. In Level1 charging applications, the charger connects to a single-phase residential utility supply and generally operates at low power levels. Consequently, converter efficiency, power quality, cost, and reliability are critical design considerations [1]. Given that EV chargers are expected to function for extended periods under diverse environmental and loading conditions, the reliability of the power electronic converters is a key performance metric.

From the range of charger architectures described in the literature, this study selects three AC–DC PFC topologies and three isolated DC–DC converter topologies for reliability evaluation. These arrangements are commonly used in low power and onboard EV charging applications because of their demonstrated efficiency and suitability for Level-1 charging requirements.

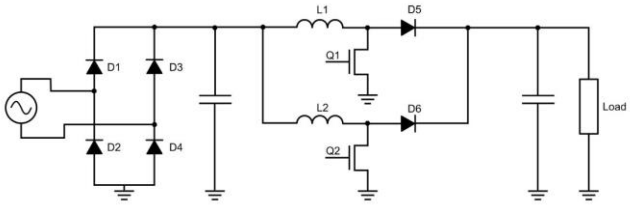
The AC–DC stage consists of three principal topologies: (i) the Conventional PFC Boost Converter, which remains one of the most commonly implemented front-end PFC solutions because of its relatively simple control structure and ability to maintain a high power factor [11]; (ii) the Bridgeless PFC Boost Converter, which removes the input diode bridge to reduce conduction losses and improve conversion efficiency [12]; and (iii) the Interleaved Boost PFC Converter, which employs multiple parallel boost cells operated with phase shifted switching signals to reduce input-current ripple and distribute thermal loading across semiconductor devices [13]. The isolated DC–DC stage is commonly implemented using three converter topologies. The Conventional Flyback



(a) Conventional PFC Boost Converter



(b) Bridgeless PFC Boost Converter



(c) Interleaved Boost PFC Converter

Fig. 1. AC–DC Charger Topologies

Converter is widely used in low-power charging applications owing to its simple configuration and low component count [14]. The Isolated Half-Bridge LLC Resonant Converter utilizes soft-switching operation to reduce switching losses and device stress, thereby improving conversion efficiency [15]. The Phase-Shift Full-Bridge

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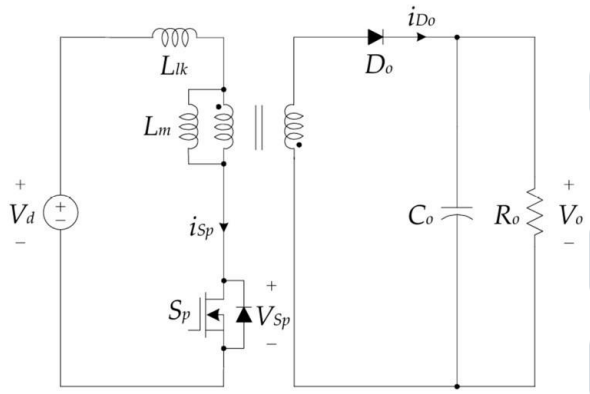
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Center-Tapped (PSFB-CT) Converter provides galvanic isolation, accommodates higher power levels, and enables zero-voltage switching (ZVS), which contributes to improved efficiency and reduced switching stress [16].

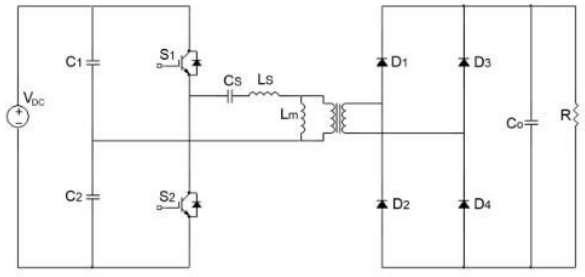
The circuit configurations of the selected AC–DC and DC–DC converter topologies are illustrated in Figs 1- 2. These six topologies form the basis of the reliability assessment presented in this paper.

IV. RESULTS

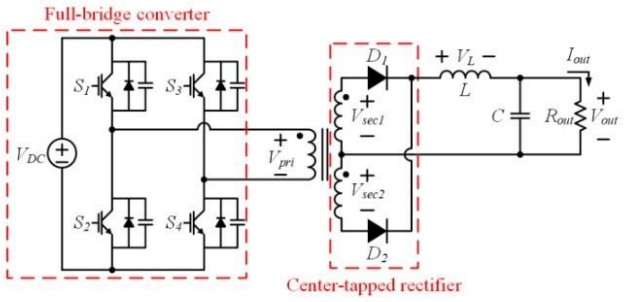
The reliability of the selected Level 1 EV charger designs was assessed using component failure-rate data obtained from MIL-HDBK-217. For each design, the overall system failure rate was calculated by summing the failure rates of individual components, weighted according to their quantities within the system. The Mean Time Between Failures (MTBF) was subsequently determined as the reciprocal of the total failure rate.



(a) Conventional Flyback Converter



(b) Isolated Half Bridge LLC Resonant Converter



(c) PSFB Center-Tapped Converter

Fig. 2. DC–DC Charger Topologies

Table III. Reliability Indices of AC–DC Topologies

Topology	Failure Rate	MTBF (hrs)	5-Year Reliability
Conventional PFC Boost	2.0209	494829	0.9153
Bridgeless PFC Boost	1.9952	501203	0.9163
Interleaved Boost PFC	3.8990	256476	0.8430

System reliability over a five-year operating period was estimated using an exponential reliability model.

The evaluated converter topologies were classified into two categories: AC–DC and DC–DC converters. The AC–DC category includes the conventional PFC boost, bridgeless PFC boost, and interleaved boost PFC converters. The corresponding reliability metrics are presented in Table III. Among these topologies, the bridgeless PFC boost converter exhibits the lowest failure rate, at 1.9952 failures per million hours (10^6 h), compared with 2.0209 failures per million hours for the conventional PFC boost converter. As a result, the two configurations achieve comparable five-year reliability values of 0.9163 and 0.9153, respectively. In contrast, the interleaved boost PFC converter is characterized by a higher failure rate of 3.8990 failures per million hours, corresponding to an MTBF of 256,476 hours and a five-year reliability of 0.8430.

Table IV. Reliability Indices of DC–DC Topologies

Topology	Failure Rate	MTBF (h)	5-Year Reliability
Conventional Flyback	1.9437	514,482.69	0.9184
Isolated Half-Bridge LLC	5.9758	167,341.61	0.7697
PSFB Center-Tapped	2.2235	449,741.40	0.9072

The DC–DC stage comprises the conventional flyback converter, the isolated half-bridge LLC resonant converter, and the PSFB center-tapped converter. Table IV summarizes the computed reliability indices for these topologies. Overall, the conventional flyback converter is the most reliable topology, with the lowest failure rate of 1.9437 failures per million hours, the highest mean time between failures (MTBF) of 514,482.69 hours, and a 5-year reliability of 0.9184. The PSFB centertapped converter shows intermediate reliability, with a failure rate of 2.2235 failures per million hours and a 5-year reliability of 0.9072. In contrast, the isolated half-bridge LLC resonant converter has the poorest reliability, with the highest failure rate of 5.9758 failures per million hours, the lowest MTBF of 167,341.61 hours, and the lowest 5-year reliability of 0.7697 among the

assessed topologies

The results indicate that converter reliability is strongly influenced by both the number of components and the characteristics of the passive elements employed, particularly electrolytic capacitors. Topologies containing fewer highly stressed components exhibit lower aggregate failure rates and correspondingly higher mean time between failures (MTBF). Based on the five-year reliability assessment, the conventional flyback converter and the bridgeless power factor correction (PFC) boost converter achieved the highest reliability among the topologies considered within their respective stages. In contrast, the isolated half-bridge LLC resonant converter exhibited the lowest reliability performance of the evaluated designs. These findings suggest that reliability should be considered alongside efficiency, power density, and cost in the selection and design of electric vehicle (EV) charger topologies.

V. CONCLUSION

This study appraises the reliability of six Level 1 EV charger topologies utilizing component failure-rate data from the MIL-HDBK-217 standard. The total failure rate for each topology was determined through parts-count accumulation, which subsequently enabled the calculation and comparison between their Mean Time Between Failures (MTBF) and 5year reliability indicators.

The results show that reliability depends a lot on the chosen topology and how many components are under stress. For AC to DC converters, the bridgeless PFC boost converter had the best reliability, with the conventional PFC boost converter close behind. The interleaved boost PFC converter had a higher failure rate and lower 5-year reliability. For DC-to-DC converters, the conventional flyback converter was the most reliable. The isolated half-bridge LLC resonant converter had the lowest MTBF and the worst 5-year reliability. The PSFB center-tapped converter performed between these options.

The results suggest that converter topologies with lower component counts are associated with improved long-term reliability. In certain cases, electrolytic capacitors represent a substantial contribution to the overall failure rate, thereby reducing system reliability. These findings indicate that reliability should be evaluated alongside efficiency, power density, and cost when selecting electric vehicle charger topologies. The proposed framework can also be extended to other electric vehicle charging architectures to support comparative reliability assessments.

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