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Impact of Smart Charging on the Reliability of Charging Infrastructure

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Summary

In the upcoming years, the implementation of smart charging strategies will be required to deal with the increasing number of electric vehicles (EVs). This paper investigates the impact of smart charging on the reliability and the lifetime of the charging infrastructure. An electro-thermal model of a high-power off-board charger was developed to estimate the thermal stress response of the switches on the applied smart charging current profile. The resulting junction temperature profiles were used to estimate the lifetime of the charger. The results showed that due to smart charging, the lifetime of the high-power off-board charger improved by a factor of 2.4 compared to a conventional uncoordinated charging strategy.

Keywords: smart charging, reliability, EVSE (Electric Vehicle Supply Equipment)

1 Introduction

Electric vehicles (EVs) are gaining more and more interest because of their potential to reduce worldwide pollution and counteract climate change. The lifetime of the drivetrain components of EVs is an important parameter that needs to be considered for a mass rollout. Accordingly, reliability assessments have recently gained a lot of interest in the scientific literature [1]. The power electronic converters (PECs) are in particular prone to failures as they are exposed to repetitive thermal stress due to temperature and load power variations [2]. Researchers have therefore studied the effect of different control strategies on the reliability of drivetrain PECs to extend their lifetime [3]. However, the reliability of the charging infrastructure, another important element for a mass rollout of EVs, has not been fully studied yet.

The increasing number of EVs (i.e., ~5 million new registrations are anticipated in 2022 worldwide) imposes an additional load on the distribution grid, which can lead to several grid power quality-related issues. Smart charging is generally considered the primary solution to overcome this challenge [4]. The charging process of EVs is actively scheduled and controlled to achieve specific objectives instead of directly charging EVs with the maximum power provided by the charging infrastructure. Many researchers have already addressed smart charging and assessed its (grid-related) technical and economic impact [5]. However, its impact on the lifetime of the charging infrastructure has still not been fully studied.

To this end, this paper investigates the impact of smart charging on the reliability and the lifetime of the charging infrastructure compared with conventional uncoordinated charging. An electro-thermal model of an off-board charger is developed to determine the thermal stress on the PEC from which the lifetime of the charger can be estimated. The rest of this paper is organised as follows. In Section 2, the methodology of the lifetime estimation is described in detail, including the system architecture, the controller design, the electro-thermal modelling and the reliability assessment. Section 3 shows the results of the lifetime estimation for both smart and conventional uncoordinated charging. Finally, the conclusions are presented in Section 4.

2 Methodology

To show the impact of smart charging on the lifetime of the charging infrastructure, a comparative reliability analysis between smart and uncontrolled charging was executed. As a starting point for this analysis, a charging current profile of each control strategy is used as the input of the electro-thermal model of the off-board charger, to estimate the thermal stress on the switches of the PEC. The resulting junction temperature profiles of the MOSFET and the diode are applied to a cycle counting algorithm to count the number of cycles to failures. This information is then used in Miner's accumulated damage rule to estimate the lifetime of the charging infrastructure. This approach is illustrated in Fig. 1 and will be explained in more detail in the next sections.

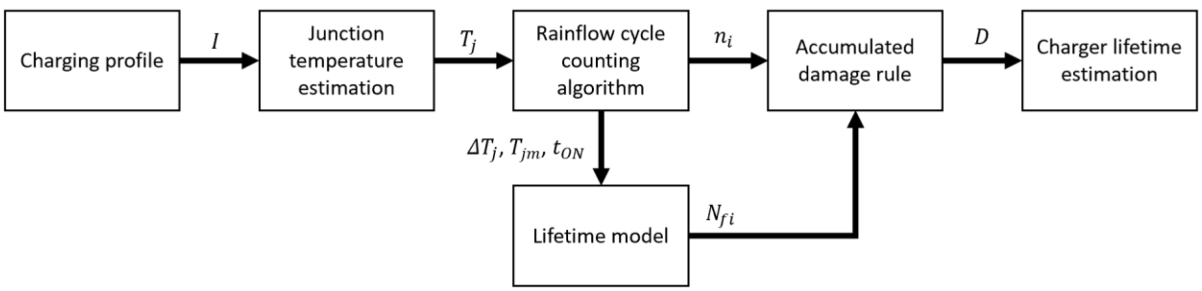


Figure 1: Lifetime estimation approach for charging infrastructure.

2.1 System architecture

The considered charging system in this research is a high-power off-board charger, used to charge medium duty EVs, consisting of a low-frequency isolation transformer, an LCL filter and a SiC-based active front end converter, where the three-phase incoming AC power is converted into a variable DC output power [6]. The converter has six switches, each consisting of a MOSFET and an anti-parallel body diode. The overall topology of the charger is depicted in Fig. 2. The specifications of the charger are listed in Table 1.

Table 1: Specifications of the considered off-board charger.

Parameter	Value
Maximum power (kW)	100
Switching frequency (kHz)	40
AC voltage (V)	400
DC bus voltage (V)	750
Power Electronic Module	SiC half bridge module

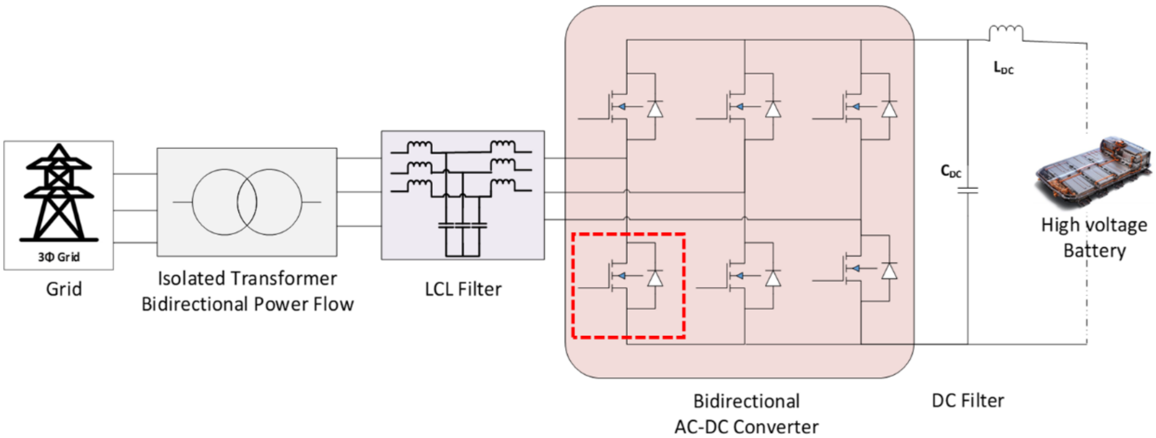


Figure 2: Topology of the off-board charger.

2.2 Controller design

A high-level charging management strategy, developed in [7], is used to generate a smart charging profile. The strategy provides an optimal charging schedule by minimizing the charging cost, while satisfying the limits and requirements from the EV driver and the utility grid. It manages to reduce the charging cost up to 10%. Furthermore, a low-level controller, designed in [6], is used to attain a fast-dynamic response and stability during charging operation. The constant current constant voltage (CC-CV) controller controls the DC current and voltage through AC side current control in a dq-reference frame as depicted in Fig. 3. Proportional integral (PI) controllers are used and tuned for the outer CC-CV control loop and inner current control loop (I_d and I_q). The state-space linear model of the converter is used to design the PI controllers. The closed-loop control design includes the sensors and PWM delays, i.e., 10 µs for voltage sensor (LEM DVC 1000-P), 3 µs for current sensor (ISB-425-A-802), and 0.5 µs for PWM. After a closed-loop analysis, the PI controller is tuned according to margins i.e., gain margin (*gM*) and phase margin (*PM*), and frequencies i.e., gain crossover frequency (ωcg) and phase crossover frequency (ωcp). The control parameters are depicted in Table 2.

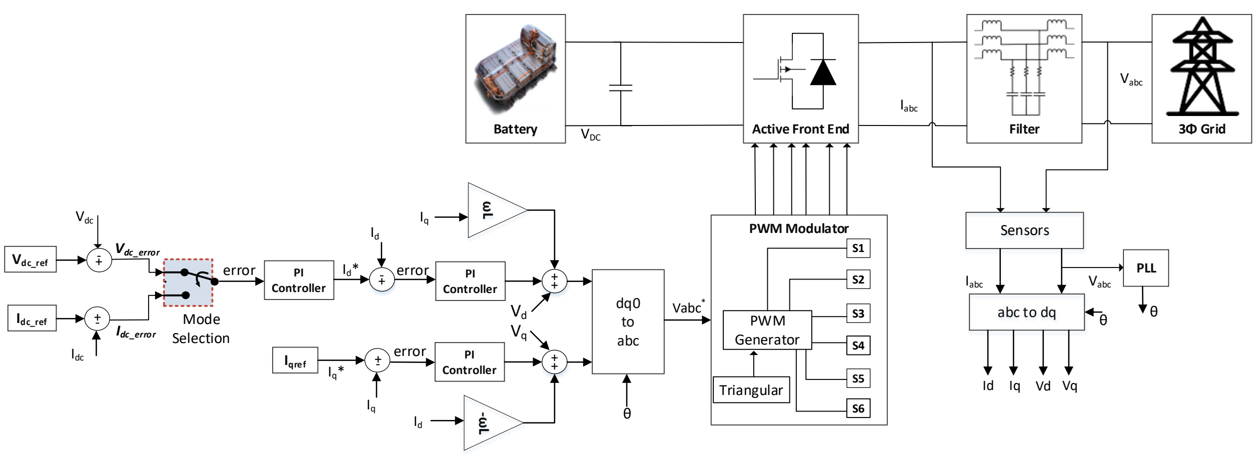


Figure 3: Diagram of the controller of the off-board charger.

Table 2: Control Design Parameters.

Controller	Control Parameters	gM (dB)	PM (deg)	ωcp (rad/s)	ωcg (rad/s)
Id / Iq Current Control	Kp = 1.8, Ki = 18411	43.9	65.1	1.51×10^4	7.86×10^5
Vdc / Idc Voltage / Current control	Kp = 0.25, Ki = 18	43.9	86.2	281	2.45×10^4

2.3 Electro-thermal modelling

A high-fidelity electro-thermal model of the charger is developed to estimate the thermal stress of the SiC power MOSFETs (and the body diode) (CAS300M17BM2) and their power losses. A universal loss model of a semiconductor, which describes the instantaneous power dissipation at a given junction temperature, is combined with a thermal model, which determines the temperature gradients inside the charging system by means of the power losses. Therefore, a coupled electro-thermal model ensures a high degree of accuracy [8].

The total power dissipated in the MOSFET comprises the switching losses and the conduction losses. The conduction losses occur when the semiconductor is turned on and can be represented as given in Eq. (1):

$$P_{cond(MOSFET)} = V_d\left(I, T_j\right) \cdot I \tag{1}$$

where V_d denotes the voltage drop over the MOSFET, which depends primarily on the conducted current I and the junction temperature.

The switching losses occur during the turn-on and turn-off transitions of the semiconductor and can be computed as the sum of the energy losses occurring during a switching transition, as given in Eq. (2):

$$P_{sw(MOSFET)} = P_{sw,on} + P_{sw,off} \approx f_{sw} \cdot \left(E_{sw,on}\left(I, V, T_j\right) + E_{sw,off}\left(I, V, T_{si}\right)\right) \tag{2}$$

where f_{sw} denotes the switching frequency and $E_{sw,on}$ and $E_{sw,off}$ denote the energy losses of the on-state and off-state respectively, which both mainly depend on the conducted current, the switched voltage and the junction temperature. Based on the power losses, the actual junction temperature can be estimated from Eq. (3)-(5):

$$T_j = T_a + \Delta T_{sa} + \Delta T_{js} \tag{3}$$

$$\Delta T_{sa} = Z_{th(sa)} \cdot \sum P_n \tag{4}$$

$$\Delta T_{js} = P_n \cdot Z_{th(js)n} \tag{5}$$

where T_j is the junction temperature, ΔT_{sa} is the heatsink to the ambient temperature drop, ΔT_{js} is junction to the heatsink temperature drop, $Z_{th(sa)}$ is the heatsink thermal resistance, $Z_{th(js)n}$ is junction to heatsink thermal resistance and P_n are the power losses of nth MOSFET or diode in the converter.

2.4 Reliability assessment

The electro-thermal model of the charger provides junction temperature profiles of the MOSFET and the body diode based on the charging profile which is used as input. To convert the thermal stress profile into a regular thermal cycle that is used to estimate the lifetime, a modified rainflow cycle counting algorithm is applied, which estimates the number of cycles, the amplitude of the temperature swing, the pulse duration of the MOSFETs and the mean junction temperature. This information is then used in a lifetime model to compute the number of cycles to failure for both the MOSFET and the body diode as expressed in Eq. (6):

$$N_f = A \cdot (\Delta T_j)^{\alpha} \cdot (ar)^{\beta_1 \Delta T_j + \beta_0} \cdot \left[\frac{C + (t_{ON})^{\gamma}}{C+1}\right] \cdot e^{\left(\frac{E_a}{k_b \times T_{jm}}\right)} \cdot f_{diode} \tag{6}$$

Here, N_f denotes the number of cycles to failure. ΔT_j is the amplitude of the temperature swing is, t_{ON} is the pulse duration of the MOSFETs and T_{jm} is the mean junction temperature, which are all obtained from the rainflow cycle counting algorithm. A = 3.4368e^{14}, C = 1.434, α = -4.923, β_0 = -1.942, β_1 = -9.012e^{-3} and γ = -1.208 are model parameters, ar = 0.31 is the bond wire aspect ratio, k_b = 8.6173 eV/K is the Boltzmann constant, E_a = 0.066 eV is the activation energy and f_{diode} = 0.6204 is the body diode impact factor.

The accumulated damage of different thermal stress levels for the MOSFET and the body diode can be calculated by using the Miner linear damage rule, as given in Eq. (7):

$$D = \sum_{i=1}^{k} \frac{n_i}{N_{fi}} \tag{7}$$

where D is the accumulated damage, n_i is the number of cycles, obtained from the rainflow cycle counting algorithm for a specific thermal stress level i and N_{fi} the number of cycles to failure at that particular stress level.

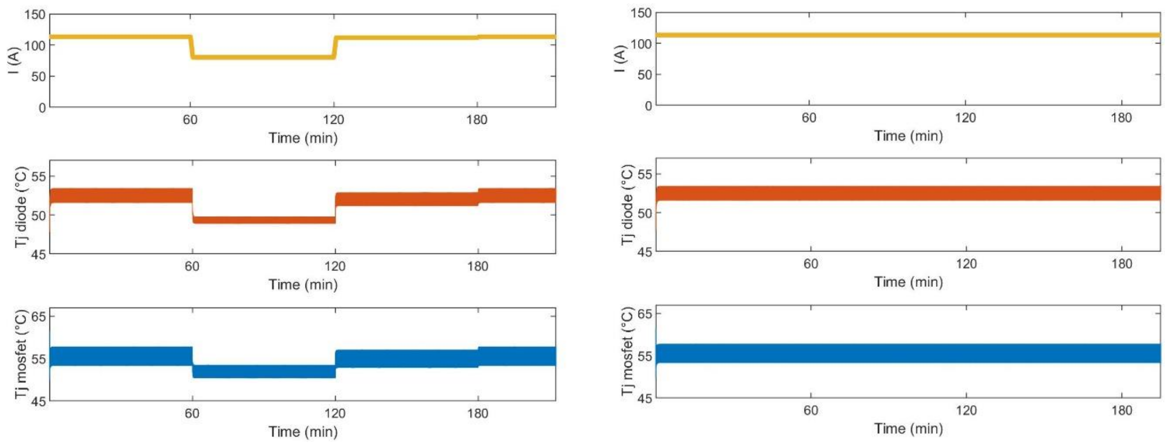
In this paper, it is considered that only the switches contribute to the reliability performance of the off-board charger, as they are responsible for about one third of the failures of PECs [9]. Therefore, the charger only depends on the reliability of the six SiC MOSFETs and six anti-parallel body diodes. Furthermore, it is considered that all MOSFETs and body diodes behave the same as the lower MOSFET and diode pair, as shown by the red dashed square in Fig. 2.

A failure in any of these components also cause the charger to fail immediately. As a result, the total system-level reliability can be represented as a series network of the reliability of the individual components as expressed in Eq. (8).

$$R_{charger} = D_{MOSFET}^{6} \cdot D_{Diode}^{6} \tag{8}$$

3 Results

The charging profiles and the corresponding junction temperature profiles of the diode and the MOSFET, generated by the electro-thermal model, for both smart and conventional uncontrolled charging are shown in Fig 4. The ambient temperature is considered to be 45^{0}C, as the charging manufacturers are more interested in the reliability assessment of chargers at worst-case ambient temperature.



(a) (b)

Figure 4: Charging current and corresponding junction temperature of diode and MOSFET for (a) smart charging and (b) uncontrolled charging.

For a high-power off-board charger, at the worst ambient temperature, the point of interest in reliability is R_{90}, showing a 90% reliability percentile [10]. Fig. 5 illustrates the system-level reliability percentile R_{90} for the the considered smart and uncontrolled charging profiles. For uncontrolled charging, the 90% reliability percentile is reached after almost 12 years, while for smart charging, it is reached after 28.4 years. Thus, the system-level reliability of the charger improves with a factor of 2.4 for smart charging in comparison with conventional uncontrolled charging. This can be explained due to the fact that the smart charging profile reduces the junction temperature of the MOSFET and the diode during charging, resulting in a positive impact on the overall lifetime of the charger.

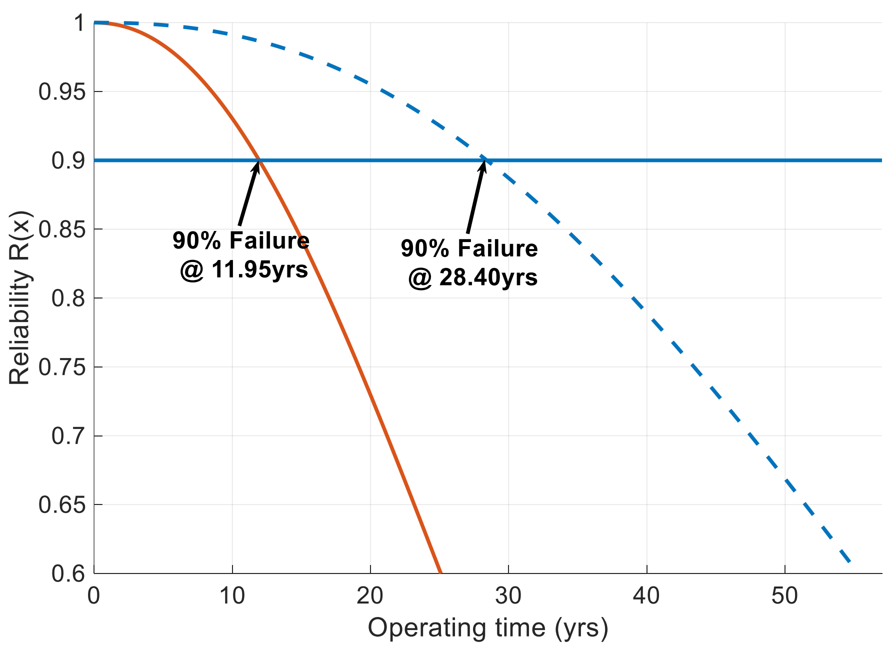


Figure 5: Lifetime curve of a high-power off-board charger for smart (dashed blue line) and uncontrolled charging (solid orange line) profiles.

4 Conclusions

Smart charging will become crucial when dealing with large fleets of EVs in the future. Therefore, in this paper, a reliability analysis is executed to examine the impact of smart charging on the lifetime of a high-power off-board charger and to compare it with uncoordinated charging. An electro-thermal model, including switching and conduction losses, is developed to estimate the junction temperature of the MOSFETs and the anti-parallel body diodes of the power electronic converter, the main component of the charger prone to failure, based on a smart and uncoordinated charging current profile. The resulting temperature profiles are used in a rainflow cycle counting algorithm to count the number of thermal cycles, a lifetime model to compute the number of cycles to failure and Miner's linear damage rule to calculate the accumulated damage and finally the system-level reliability. The results show that smart charging improves the lifetime of a high-power off-board charger with a factor 2.4 compared to uncoordinated charging. It can thus be concluded that smart charging is not only beneficial in terms of charging cost and grid impact, but also increases the lifetime of the charging infrastructure.

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References

[1] F. H. Gandoman *et al.*, "Status and future perspectives of reliability assessment for electric vehicles," *Reliab. Eng. Syst. Saf.*, vol. 183, pp. 1–16, Mar. 2019.

[2] M. Andresen, K. Ma, G. Buticchi, J. Falck, F. Blaabjerg, and M. Liserre, "Junction Temperature Control for More Reliable Power Electronics," *IEEE Trans. Power Electron.*, vol. 33, no. 1, pp. 765–776, Jan. 2018.

[3] A. Zhaksylyk, S. Chakraborty, E. Abramushkina, T. Geury, M. El Baghdadi, and O. Hegazy, "Comparative Analysis of Traction Inverter Controllers for the Mission-Profile Oriented Reliability and Performance Evaluation in Electric Vehicles," *2021 16th Int. Conf. Ecol. Veh. Renew. Energies, EVER 2021*, May 2021.

[4] J. García-Villalobos, I. Zamora, J. I. San Martín, F. J. Asensio, and V. Aperribay, "Plug-in electric vehicles in electric distribution networks: A review of smart charging approaches," *Renew. Sustain. Energy Rev.*, vol. 38, pp. 717–731, Oct. 2014.

[5] Q. Wang, X. Liu, J. Du, and F. Kong, "Smart Charging for Electric Vehicles: A Survey from the Algorithmic Perspective," *IEEE Commun. Surv. Tutorials*, vol. 18, no. 2, pp. 1500–1517, Apr. 2016.

[6] H. Rasool *et al.*, "Design Optimization and Electro-Thermal Modeling of an Off-Board Charging System for Electric Bus Applications," *IEEE Access*, vol. 9, pp. 84501–84519, 2021.

[7] B. Verbrugge *et al.*, "Real-time Scheduling and Optimization Algorithm for a High-Level Charging Management System of Electric Buses," *Energies*, 2022.

[8] S. Chakraborty *et al.*, "Scalable Modeling Approach and Robust Hardware-in-the-Loop Testing of an Optimized Interleaved Bidirectional HV DC/DC Converter for Electric Vehicle Drivetrains," *IEEE Access*, vol. 8, pp. 115515–115536, 2020.

[9] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, "An industry-based survey of reliability in power electronic converters," *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1441–1451, May 2011.

[10] S. Chakraborty *et al.*, "Real-Life Mission Profile Oriented Lifetime Estimation of a SiC Interleaved Bidirectional HV DC/DC Converter for Electric Vehicle Drivetrains," *IEEE J. Emerg. Sel. Top. Power Electron.*, 2021.

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