

# Robust Inner-Loop Control Design for a Single-Stage Single-Phase Onboard EV Charger with Uncertain Grid Impedance <sup>†</sup>

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## Abstract

Single-stage single-phase onboard electric vehicle (EV) chargers are popular owing to their simple structure and high efficiency. However, their performance during grid connection is highly dependent on grid impedance characteristics. In a real-world scenario, it is hard to determine the exact value of grid impedance because it varies over time. This creates a challenge for a controller design that is based on a certain value of impedance. In this paper, a robust current controller is presented for a single-stage single-phase onboard EV charger, considering both L-filter and uncertain grid impedance characteristics. A state-space model of a single-stage single-phase onboard EV charger incorporating grid impedance uncertainty is developed. Based on the uncertain model, an LMI-based robust current controller is designed considering both filter and grid impedance uncertainties. The robust current controller is presented by considering an uncertain model represented by a polytopic model with sixteen vertex systems. An all-pass filter is used to generate an orthogonal signal for a dq-frame implementation. Simulation results are presented to prove the robust current controller's performance and robustness during different grid impedance conditions.

**Keywords:** robust control; single-stage single phase EV charger; linear matrix inequality; uncertain grid impedance

## 1. Introduction

Significant growth has been observed in electric vehicles, and this has led to an increased need for efficient and reliable onboard chargers. Recently, single-stage single-phase AC/DC converters have received considerable attention because of their simple configuration and high efficiency. In a practical electric vehicle charger, a constant current constant voltage method is employed for battery charging. In this method, a constant current charger is used to increase the SOC of the battery, and after that, a constant voltage charger is employed to finish the charging process. The performance of an electric vehicle charger connected to a grid depends on the grid impedance [1,2]. In a practical network, it is difficult to determine the value of grid impedance because it varies over time because of changes in network configuration and network loading conditions. The interaction between the grid impedance and filter impedance can affect the current controller, and this can impact the current regulation and stability if not properly handled. In practical



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distribution networks, the grid impedance varies with feeder length, network topology, and loading conditions. Such variations can alter the converter-grid dynamics and degrade current regulation and power quality if the controller is designed using nominal parameters. Therefore, grid impedance uncertainty should be considered during the controller design stage.

The increasing deployment of battery-based energy storage systems and electric vehicles has motivated extensive research on intelligent control, digital modeling, and system reliability. Recent studies have emphasized the use of advanced control and monitoring techniques to improve battery safety, mitigate degradation phenomena, and enhance system performance through data-driven and model-based approaches [3,4]. In particular, digital modeling, intelligent regulation strategies, and interfacial engineering have emerged as effective tools for improving the operational stability and lifetime of modern electrochemical energy storage systems. Furthermore, battery charging management and overcharge protection have been recognized as important factors for ensuring long-term battery reliability and safety in practical applications [5]. These advances further justify the development of robust control strategies for EV charging applications under uncertain operating conditions.

Different control schemes have been proposed for grid-connected power converters and EV charger applications. The traditional proportional-integral (PI) controllers [6–8] have been widely used for grid-connected power converters due to their simplicity of implementation, especially with synchronous reference frame control. However, the PI controllers are normally designed based on nominal system parameters, which may not guarantee satisfactory control performance when system parameters vary or grid disturbances occur. To ensure satisfactory steady-state tracking of sinusoidal signals for single-phase grid-connected power converters, proportional-resonant (PR) controllers [9–11] have been widely used for their high gain at the fundamental frequency. However, the PR controllers may not be robust against system parameter variations and grid disturbances, especially for significant grid impedance changes. The deadbeat control [10,12] has been employed for grid-connected power converters, which can provide very fast current tracking by forcing the system states to reach their reference values within a few sampling periods. Although satisfactory dynamic performance can be achieved with the deadbeat control, the control performance heavily depends on the system modeling, which may degrade for system parameter variations and grid disturbances, especially for significant grid impedance changes. Model Predictive Control (MPC) [13–15] has also gained significant attention because of its ability to handle multivariable systems and system constraints, along with its ability to provide fast dynamic response. However, MPC has a high computational complexity and hence a higher implementation cost because it requires solving an optimization problem at every sampling instant. Various robust control strategies [16–18] have been proposed to improve stability and disturbance rejection in the presence of parameter uncertainty. However, most existing studies mainly consider uncertainties associated with converter-side components, while the effect of uncertain grid impedance is often neglected. In practical EV charging systems, grid impedance variations may affect current regulation, power quality, and system stability. Therefore, the development of a robust controller that explicitly considers grid impedance uncertainty remains an important research challenge.

To address the aforementioned challenges, a robust control strategy for a single-stage single-phase onboard EV charger considering uncertain grid impedance is proposed. Unlike conventional PI-based current controllers that are designed using nominal system parameters and may experience performance degradation under grid impedance variations, the proposed method explicitly incorporates uncertainties associated with both the grid impedance and filter parameters into the controller design process. A polytopic uncertainty

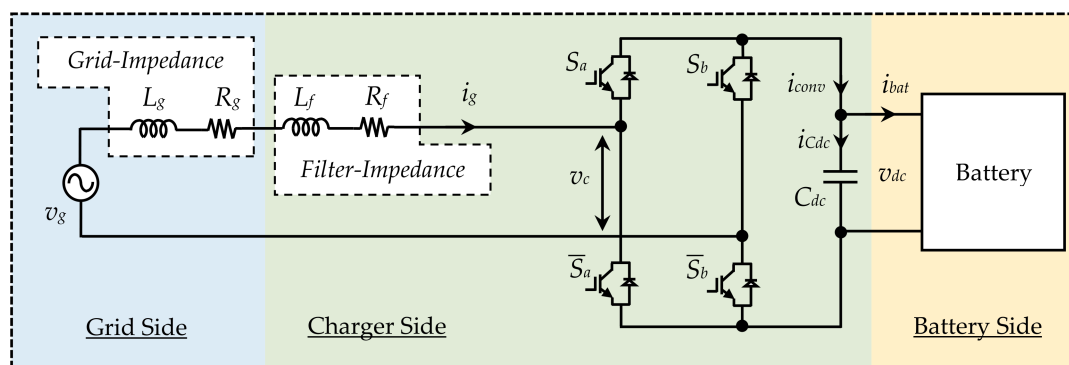
model is developed to represent these parameter variations, enabling the synthesis of an LMI-based robust inner-loop current controller that guarantees closed-loop stability over a predefined uncertainty range. In addition, the controller gains are systematically obtained through a convex optimization framework, avoiding the trial-and-error tuning commonly required in PI controller design. An outer-loop voltage controller is integrated to realize constant-current and constant-voltage battery charging operation. Furthermore, a digital all-pass filter is employed to generate orthogonal signals for dq-frame implementation in the single-phase system. Simulation results demonstrate that the proposed controller maintains stable operation under different grid impedance conditions while providing improved current regulation and lower current harmonic distortion compared with the conventional PI controller. The main contributions of this work are as follows: (1) development of an uncertain model of a single-stage single-phase EV charger considering both filter and grid impedance variations; (2) formulation of a polytopic uncertainty model for robust controller synthesis; and (3) design of an LMI-based robust current controller that guarantees closed-loop stability under predefined parameter variations.

## 2. System Modeling with Uncertainty

The single-phase charger considered in this work is connected to the grid through an interface inductor as shown in Figure 1. The grid impedance and filter impedance are represented by equivalent resistive and inductive components. Let  $v_g(t)$  denote the grid voltage,  $v_c(t)$  the converter pole voltage, and  $i_g(t)$  the grid current, respectively. The equivalent inductance and resistance seen by the converter are defined as

$$L_t = L_g + L_f \quad (1)$$

$$R_t = R_g + R_f \quad (2)$$



**Figure 1.** Topology of the single-stage single-phase EV charger including grid impedance and filter components.

Applying Kirchhoff's voltage law, the grid current dynamics can be expressed as

$$\frac{di_g(t)}{dt} = \frac{1}{L_t} (v_g(t) - R_t i_g(t) - v_c(t)). \quad (3)$$

Since the system is single-phase, an orthogonal signal generator is required to construct the  $\alpha\beta$  frame. In this work, a digital all-pass filter is used to generate a quadrature component of the current and voltage signals. This allows the formation of the artificial  $\alpha\beta$  frame and enables transformation to the synchronous rotating reference frame. To implement the dq transformation in the single-phase system, an orthogonal signal is

generated using a first-order digital all-pass filter. The transfer function of the filter is given by

$$G_{APF}(z) = \frac{\alpha + z^{-1}}{1 + \alpha z^{-1}} \quad (4)$$

where  $\alpha$  is determined according to the fundamental frequency and sampling period. The filter provides an approximately  $90^\circ$  phase-shifted signal at the fundamental frequency, enabling the construction of the orthogonal components required for the dq transformation.

The dq transformation is defined as

$$\mathbf{i}_{dq}(t) = \mathbf{T} \mathbf{i}_{\alpha\beta}(t) \quad (5)$$

$$\text{where } \mathbf{T} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix}, \mathbf{i}_{dq} = \begin{bmatrix} i_{g,d} \\ i_{g,q} \end{bmatrix} \text{ and } \mathbf{i}_{\alpha\beta} = \begin{bmatrix} i_{g,\alpha} \\ i_{g,\beta} \end{bmatrix}.$$

The converter dynamics in the dq frame can therefore be written as

$$\dot{\mathbf{i}}_{dq}(t) = \mathbf{A}_c \mathbf{i}_{dq}(t) + \mathbf{B}_c v_{dc}(t) \mathbf{m}_{dq}(t) + \mathbf{v}_{g,dq}(t) \quad (6)$$

$$\text{where } \mathbf{A}_c = \begin{bmatrix} -R_t L_t^{-1} & \omega \\ \omega & -R_t L_t^{-1} \end{bmatrix}, \mathbf{B}_c = \begin{bmatrix} -(2L_t)^{-1} & 0 \\ 0 & -(2L_t)^{-1} \end{bmatrix}, \mathbf{v}_{g,dq} = \begin{bmatrix} v_{g,d} \\ v_{g,q} \end{bmatrix}, \mathbf{m}_{dq} = \begin{bmatrix} m_d \\ m_q \end{bmatrix}$$

represents the modulation signals and  $v_{dc}$  is the DC-link voltage.

The DC-link capacitor dynamics are given by

$$C_{dc} \frac{dv_{dc}(t)}{dt} = i_{conv}(t) - i_{bat}(t). \quad (7)$$

For digital implementation, the system model is discretized using a forward Euler approximation with sampling period  $T_s$ . The resulting discrete-time model can be expressed as

$$\mathbf{x}_{k+1} = \mathbf{A}_d \mathbf{x}_k + \mathbf{B}_d \mathbf{u}_k + \mathbf{w}_k \quad (8)$$

$$\text{where } \mathbf{A}_d = \mathbf{I}_2 + T_s \mathbf{A}_c, \mathbf{B}_d = T_s \mathbf{B}_c, \mathbf{w}_k = T_s \mathbf{v}_{g,dq}, \mathbf{x} = \begin{bmatrix} i_{g,d} & i_{g,q} \end{bmatrix}^T, \mathbf{u} = \begin{bmatrix} m_d & m_q \end{bmatrix}^T.$$

In practical distribution networks, the grid impedance is not constant and may vary due to network reconfiguration, line impedance changes, and loading conditions. Therefore, the parameters  $R_g$ ,  $L_g$ ,  $R_f$ , and  $L_f$  are assumed to vary within the known bounds ( $\rho > 1$ ).

$$\rho^{-1} R_g < R_g < \rho R_g \quad (9)$$

$$\rho^{-1} L_g < L_g < \rho L_g \quad (10)$$

$$\rho^{-1} R_f < R_f < \rho R_f \quad (11)$$

$$\rho^{-1} L_f < L_f < \rho L_f \quad (12)$$

The uncertain parameters  $R_g$ ,  $L_g$ ,  $R_f$ , and  $L_f$  are bounded within predefined minimum and maximum values. Since each uncertain parameter has two extreme values, the uncertainty set contains ( $2^4 = 16$ ) possible parameter combinations. Let  $(\mathbf{A}_{d,i}, \mathbf{B}_{d,i})$ , ( $i = 1, 2, \dots, 16$ ) denote the state-space matrices corresponding to the sixteen extreme combinations of the uncertain parameters. Consequently, the uncertain system matrices  $(\mathbf{A}_d, \mathbf{B}_d)$  belong to the following polytopic uncertainty set [19]:

$$\Psi = \left\{ \sum_{i=1}^{16} \rho_i (\mathbf{A}_{d,i}, \mathbf{B}_{d,i}) \mid \sum_{i=1}^{16} \rho_i = 1, \rho_i \geq 1 \right\}. \quad (13)$$

Therefore, the uncertain system can be represented as a convex combination of sixteen vertex systems, where each vertex corresponds to a unique combination of the minimum and maximum values of  $R_g$ ,  $L_g$ ,  $R_f$ , and  $L_f$ . This polytopic representation is employed for the synthesis of the proposed robust controller. Furthermore, the uncertainty coefficient  $\rho$  determines the allowable variation range of the uncertain parameters around their nominal values. Larger values of  $\rho$  correspond to wider parameter variations and are used to evaluate the robustness of the proposed controller under different operating conditions.

### 3. Robust Control and Outer Voltage Control Design

For the purpose of robust current regulation in the presence of uncertainties in the grid impedance, an integral state feedback controller is used [20]. The controller is based on the discrete-time state-space model, considering the uncertainties in the grid and the filter parameters.

#### 3.1. Inner-Loop Robust Control Design

To achieve accurate reference tracking, an integral state is introduced as

$$\mathbf{z}_{k+1} = \mathbf{z}_k + (\mathbf{i}_{ref,k} - \mathbf{i}_k). \quad (14)$$

The augmented state vector is defined as  $\mathbf{x}_a = [\mathbf{x} \ \mathbf{z}]^T$ .

The control law is formulated as

$$\mathbf{u}_k = -\mathbf{K}_a \mathbf{x}_{a,k} \quad (15)$$

where  $\mathbf{K}_a = [\mathbf{K}_c \ \mathbf{K}_i]$  contains feedback and integral gains.

To guarantee closed-loop stability under parameter uncertainty [21], the controller gains are determined using an LMI-based optimization framework. A quadratic Lyapunov function is selected as

$$V_k = \mathbf{x}_{a,k}^T \mathbf{P} \mathbf{x}_{a,k}, \mathbf{P} > 0 \quad (16)$$

where  $\mathbf{P}$  is a symmetric positive definite matrix. The stability condition requires the Lyapunov function to decrease at every sampling instant as

$$\Delta V_k = V_{k+1} - V_k < 0. \quad (17)$$

Considering the augmented closed-loop system for each vertex of the uncertainty model,

$$\mathbf{x}_{a,k+1} = (\mathbf{A}_{a,i} - \mathbf{B}_{a,i} \mathbf{K}_a) \mathbf{x}_{a,k} \quad (18)$$

the Lyapunov stability condition becomes

$$(\mathbf{A}_{a,i} - \mathbf{B}_{a,i} \mathbf{K}_a)^T \mathbf{P} (\mathbf{A}_{a,i} - \mathbf{B}_{a,i} \mathbf{K}_a) - \mathbf{P} < 0 \quad (19)$$

To convert the nonlinear matrix inequality into a convex optimization problem, the following variable substitutions are introduced:

$$\mathbf{X} = \mathbf{P}^{-1}, \mathbf{Y} = \mathbf{K}_a \mathbf{X}. \quad (20)$$

Using these substitutions and applying the Schur complement, the stability condition can be transformed into the following LMI form:

$$\begin{bmatrix} \mathbf{X} & (\mathbf{A}_{a,i} \mathbf{X} - \mathbf{B}_{a,i} \mathbf{Y})^T \\ \mathbf{A}_{a,i} \mathbf{X} - \mathbf{B}_{a,i} \mathbf{Y} & \mathbf{X} \end{bmatrix} > 0 \quad (21)$$

where  $i = 1, 2, \dots, 16$  represent the sixteen vertex systems of the polytopic uncertainty model.

Using these substitutions, the stability condition can be transformed into an equivalent LMI formulation that can be solved using semidefinite programming tools such as YALMIP [22]. After solving the optimization problem, the controller gain matrix is recovered as

$$\mathbf{K}_a = \mathbf{Y}\mathbf{X}^{-1}. \quad (22)$$

The resulting controller guarantees robust stability and accurate current tracking performance for all admissible parameter variations.

### 3.2. Outer Voltage Control Design

In addition to the inner-loop robust current controller, an outer-loop voltage controller is implemented to regulate the DC-link voltage of the converter [23]. The outer control loop generates the reference current required for maintaining the desired DC voltage level.

The voltage regulation objective is defined by the voltage tracking error

$$e_v(t) = V_{CV}(t) - v_{dc}(t) \quad (23)$$

where  $V_{CV}$  is the reference DC-link voltage and  $v_{dc}$  is the measured DC voltage.

A proportional–integral (PI) controller is used to generate the q-axis current reference

$$i_q^{ref}(t) = K_{pv} e_v(t) + K_{iv} \int e_v(t) dt \quad (24)$$

while the d-axis reference current is set to zero to ensure unity power factor operation.

$$i_d^{ref}(t) = 0. \quad (25)$$

For digital implementation with sampling period  $T_s$ , the PI controller can be expressed as

$$i_{q,k}^{ref} = K_{pv} e_{v,k} + K_{iv} \zeta_{v,k} \quad (26)$$

where the integral state is updated by

$$\zeta_{v,k+1} = \zeta_{v,k} + T_s e_{v,k}. \quad (27)$$

The outer-loop voltage controller employs a conventional PI regulator to generate the reference current for the inner-loop current controller. Since the voltage loop exhibits slower dynamics than the current loop, its bandwidth is selected to be significantly lower than that of the inner current loop to ensure proper time-scale separation and avoid undesirable interactions between the two control loops. The PI gains are tuned to achieve a stable voltage response with negligible steady-state error during the battery charging process.

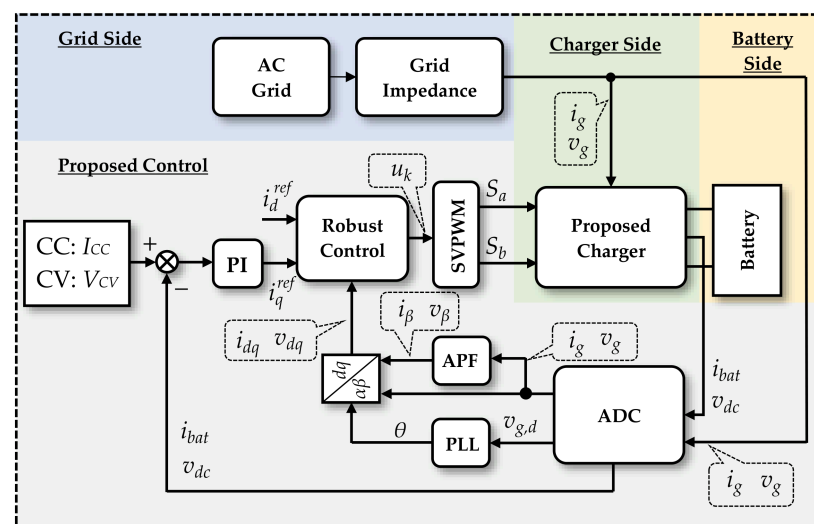
## 4. Simulation Results

In this section, the simulation results will be illustrated to verify the effectiveness of the proposed controller under various practical conditions, considering uncertain grid impedance. The controller performance is evaluated using MATLAB/Simulink (2021b) and PSIM (v9.0.3) simulation environments. The LMI optimization problem is formulated using the YALMIP (R20181012) toolbox and solved offline using the SeDuMi (v1.02) solver to obtain the robust controller gain. The obtained gain is then implemented in PSIM for time-domain verification. The digital controller is executed with a sampling period of 0.1 ms. The simulation parameters used in this study are presented in Table 1.

**Table 1.** Simulation parameters of the single-stage single-phase EV charger.

| Parameter                           | Symbol   | Value        |
|-------------------------------------|----------|--------------|
| Converter filter inductance         | $L_f$    | 3 mH         |
| Converter filter resistance         | $R_f$    | 0.1 $\Omega$ |
| Grid inductance                     | $L_g$    | 4 mH         |
| Grid resistance                     | $R_g$    | 0.1 $\Omega$ |
| Grid voltage (rms)                  | $v_g$    | 230 V        |
| Sampling period                     | $T_s$    | 0.1 ms       |
| Constant-current charging reference | $I_{CC}$ | 15 A         |
| Constant-voltage charging reference | $V_{CV}$ | 450 V        |

Figure 2 shows the overall control structure of the proposed EV charger. The grid voltage and current are processed through a PLL and an all-pass filter to enable dq-frame transformation for the single-phase system. The outer PI controller regulates the DC-link voltage based on the CC–CV charging strategy, while the inner-loop robust controller regulates the grid current. The control signals are then applied to the converter using SVPWM.



**Figure 2.** Block diagram of the proposed control structure for the single-stage single-phase EV charger.

Table 2 shows the variations in grid and filter parameters for evaluating the robustness of the suggested controller. In this table, five different cases are considered for evaluating the robustness of the proposed controller by varying the filter inductance  $L_f$ , filter resistance  $R_f$ , grid inductance  $L_g$ , and grid resistance  $R_g$  over a wide range of values. The variations in these parameters represent different grid impedance scenarios that could occur due to the variation in grid network topology. This will help to assess the robustness of the suggested controller using the LMI technique.

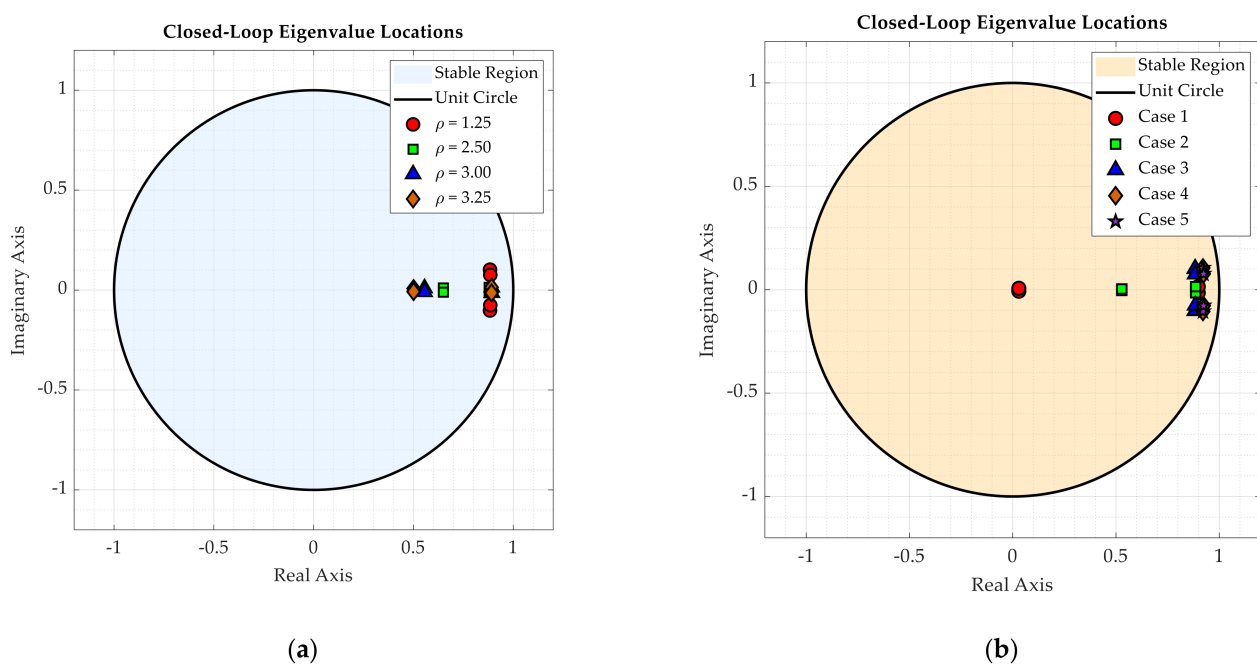
**Table 2.** Parameter variations used to evaluate the robustness of the proposed controller.

| Parameter          | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|--------------------|--------|--------|--------|--------|--------|
| $L_f$ [mH]         | 0.50   | 0.75   | 3.00   | 4.50   | 6.00   |
| $R_f$ [ $\Omega$ ] | 0.03   | 0.05   | 0.10   | 0.15   | 0.20   |
| $L_g$ [mH]         | 1.00   | 2.00   | 4.00   | 6.00   | 8.00   |
| $R_g$ [ $\Omega$ ] | 0.03   | 0.05   | 0.10   | 0.15   | 0.20   |

The parameter ranges listed in Table 2 are selected to represent practical operating conditions in EV charging systems. The filter parameters are varied to account for component

tolerances, while the grid impedance is varied over a wider range to represent both strong grid and weak grid conditions that may arise from differences in feeder length, network topology, and loading conditions.

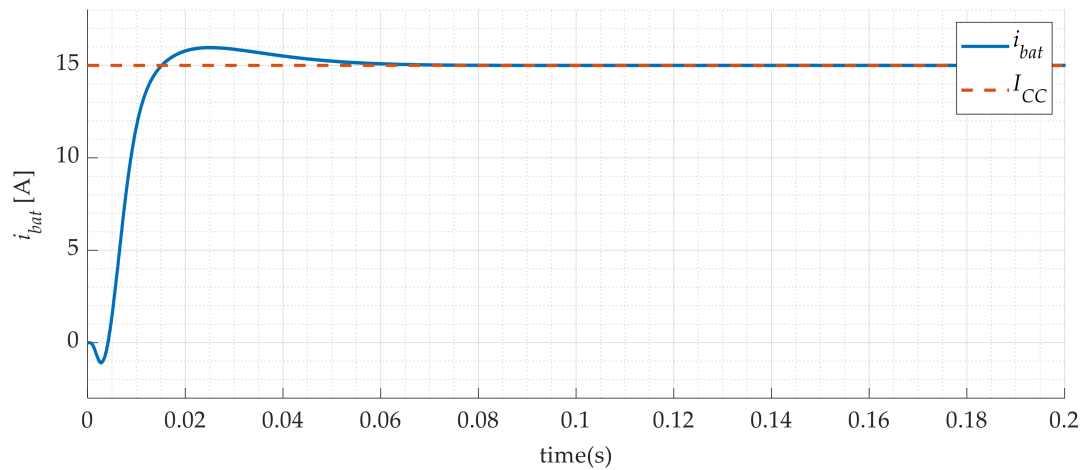
Figure 3a shows the system's eigenvalue locations under various levels of uncertainty in relation to the system's parameters. From the diagram, it is clear that all the eigenvalues are contained within the unit circle. This implies that the system is stable even in the presence of parameter uncertainty. Figure 3b shows the system's eigenvalue locations under various levels of uncertainty in relation to the system's parameters, with the range of uncertainty set to  $\rho = 1.25$ , as shown in the diagram. From the diagram, it is clear that all the eigenvalues are contained within the unit circle. This implies that the system is stable even in the presence of parameter uncertainty.



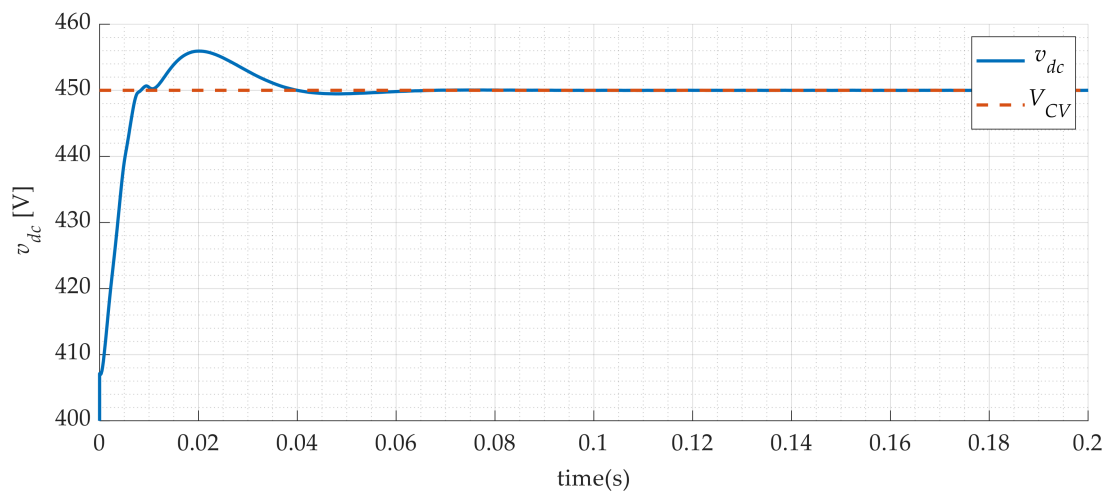
**Figure 3.** Closed-loop eigenvalues in the z-plane: (a) eigenvalue locations for different uncertainty levels relative to the nominal system; (b) eigenvalue distribution for uncertainty range  $\rho = 1.25$  under parameter variations.

Figure 4 illustrates the transient response of the battery charging current under the constant-current charging mode. It can be observed that the charging current accurately tracks the reference value of 15 A with a smooth transient response and negligible steady-state error. The result demonstrates that the proposed control strategy is capable of maintaining the desired charging current while preserving stable operation of the converter.

Figure 5 shows the transient response of the DC-link voltage under constant-voltage (CV) operation. It can be observed that the DC-link voltage successfully reaches the reference value of 450 V with a smooth transient response and a small overshoot during the startup period. After the transient interval, the voltage converges rapidly to its reference value with negligible steady-state error. The result demonstrates that the outer-loop PI controller, together with the proposed robust inner-loop current controller, is capable of maintaining stable DC-link voltage regulation despite the presence of grid and filter parameter uncertainties.



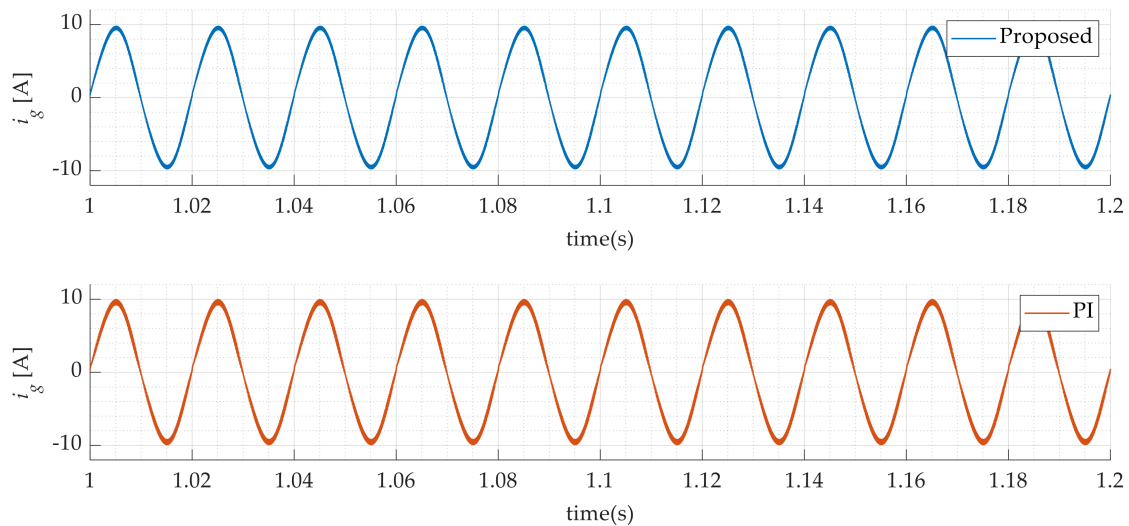
**Figure 4.** Transient response of the battery charging current under constant-current (CC) operation.



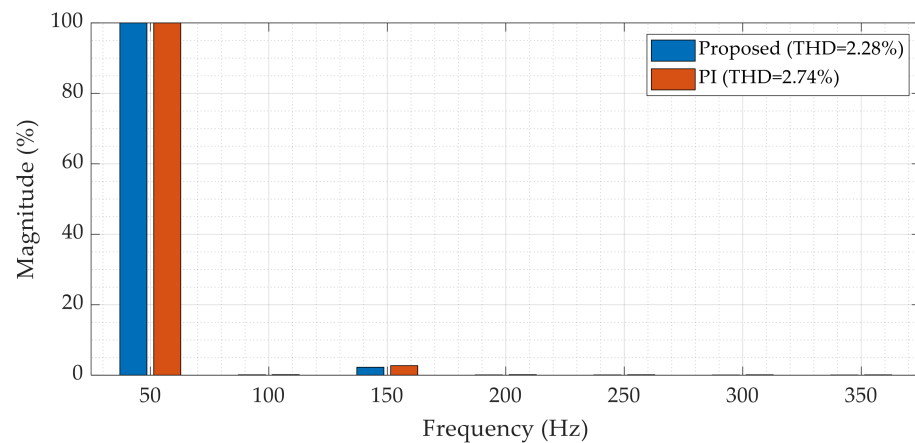
**Figure 5.** Transient response of the battery charging voltage under constant-voltage (CV) operation.

Figure 6 presents the steady-state grid current waveforms obtained using the proposed robust controller and a conventional PI controller under the same operating conditions. The PI controller is selected as a benchmark because it is one of the most widely adopted current control methods in practical EV charger applications due to its simple structure and ease of implementation. As shown in the figure, both controllers achieve sinusoidal current regulation; however, the proposed controller produces a smoother current waveform with reduced distortion. This improvement is attributed to the explicit consideration of grid impedance uncertainty in the controller design process, which enhances the robustness of current regulation under parameter variations.

Figure 7 compares the harmonic spectra of the grid current for the proposed robust controller and the conventional PI controller. The total harmonic distortion (THD) achieved by the proposed controller is 2.28%, whereas the PI controller results in a THD of 2.74%. This corresponds to a reduction of approximately 16.8% in current harmonic distortion. The lower THD demonstrates the ability of the proposed controller to maintain higher power quality despite the presence of grid impedance uncertainty. Furthermore, both controllers satisfy the commonly accepted grid-current quality requirement of less than 5% THD; however, the proposed controller exhibits superior harmonic performance, indicating its effectiveness for EV charger applications operating under uncertain grid conditions.



**Figure 6.** Steady-state grid current waveforms obtained using the proposed robust controller and the conventional PI controller.



**Figure 7.** Comparison of grid-current harmonic distortion under the proposed robust controller and conventional PI controller.

The simulation results demonstrate the effectiveness of the proposed robust control strategy for the single-stage single-phase EV charger. The controller performance is evaluated under different grid and filter parameter variations, as presented in Table 2. The closed-loop eigenvalue analysis confirms that all poles remain within the unit circle, ensuring system stability over the considered uncertainty range. Moreover, the proposed controller achieves accurate charging current regulation and improved grid-current quality. Compared with the conventional PI controller, the proposed method provides a smoother current waveform and lower current harmonic distortion, demonstrating its suitability for EV charger applications subject to uncertain grid impedance conditions.

From an implementation perspective, the proposed controller is suitable for real-time digital control platforms because the LMI optimization is performed offline during the controller design stage. As a result, only the state-feedback control law is executed online, which requires simple matrix multiplication at each sampling instant. Therefore, the computational burden is relatively low and can be accommodated by commonly used DSPs and microcontrollers for power electronic applications. However, accurate current and voltage measurements, as well as reliable generation of the orthogonal signals for dq-frame transformation, are important factors that may influence control performance in practical implementations.

## 5. Conclusions

In this paper, a robust inner loop current controller has been proposed for a single-stage single-phase onboard EV charger in the presence of uncertain grid impedance. First, the state-space representation of the charger has been developed by incorporating both grid impedance and filter impedance. Then, an LMI-based robust controller has been proposed by utilizing the polytopic uncertainty representation. This ensures closed-loop stability over a predefined range of parameter uncertainty. Moreover, a digital all-pass filter has been utilized to obtain an orthogonal signal. This has enabled the application of the dq-frame controller in the single-phase system. Simulation results were obtained under various grid impedance uncertainties. It has been shown that the proposed controller ensures closed-loop stability along with reliable current regulation in the presence of significant parameter uncertainty. This confirms the proposed controller's robustness in grid-connected EV charger applications. As future work, the proposed controller will be experimentally evaluated using a real-time digital control platform.

**Author Contributions:** Conceptualization, S.I. and C.C.; methodology, C.C.; software, S.I.; validation, S.I., M.S. and S.S.; formal analysis, S.I. and C.B.; investigation, M.S. and C.B.; resources, M.S.; data curation, C.B.; writing—original draft preparation, S.I.; writing—review and editing, C.C.; visualization, S.S. and C.B.; supervision, C.C.; project administration, S.S.; funding acquisition, C.C. All authors have read and agreed to the published version of the manuscript.

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