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Control of a Vehicle-to-Grid Charging Dtation with a Double Integral Sliding Mode Controller

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Abstract. With the widespread adoption of vehicle-to-grid technology (V2G), bidirectional electric vehicle charging stations are now a necessity. These charging infrastructures allow injecting power from the electric vehicle (EV) to the grid in case the latter requires ancillary services. However, a robust control strategy is required to oversee the power transfer from or to the grid. In this regard, this paper investigates the performance of a double integral sliding mode controller used to control an isolated bidirectional dual active bridge converter. This latter is used in a DC-DC vehicle-to-grid charger due to its advantages. The purpose of the adopted control scheme in this paper is to maintain a stable DC-Bus voltage of 480 V while the EV injects power into the grid. The robustness of the proposed controller and its ability to achieve the desired performance were evaluated using a variable power profile. The simulation results yielded a response time of 0.03 seconds, an average voltage error of 0.7V, and a maximum error of 8V. This demonstrates the robustness and tracking performances of the proposed controller, and thus its suitability for V2G charging stations.

Introduction

By overcoming the limitations of charging infrastructure availability and lengthy charging time, EVs are becoming the norm in the transportation sector [1]. Their growing adoption has provided tremendous economic and ecological benefits, including reducing greenhouse gas emissions and dependency on fuel [2]. Nevertheless, their successful integration into the electrical power system remains a challenge. From the power-grid perspective, EVs are considered huge loads that need to be managed to prevent destabilizing the power system [3]. Among the solutions proposed in the literature to address the challenge of integrating EVs, Vehicle-to-grid technology stands out as the most practical and effective [4]. V2G enables two-way power transfer between the EV and the grid through dedicated charging stations (CS) equipped with bidirectional DC-DC converters, as illustrated in Fig. 1. This allows EVs to participate in ancillary services provision [5].

Since power injection to the grid is involved, the power converters of the V2G-CS need to be meticulously controlled so that the quality of the injected power complies with grid code requirements. In this regard, the first stage of the V2G-CS, which consists of DC-DC converters, must be controlled to stabilize and regulate the DC-Bus voltage. To serve this purpose, several controllers were proposed in the literature, including conventional linear control schemes such as PID and its variants[6][7]. However, due to the limited performance of these latter when faced with sudden and quick load changes, nonlinear approaches such as sliding mode and backstepping

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controllers were proposed as alternatives [8][9]. Sliding mode control in particular has been heavily investigated by virtue of its robustness against modeling uncertainties and parameter variations [10][11]. Improved variants of the SMC, such as the integral sliding mode control (ISMC), were also proposed. The ISMC ensures robustness from the initial time by introducing an integral term in the sliding surface, which eliminates the reaching phase of the SMC, thereby improving overall robustness[12].

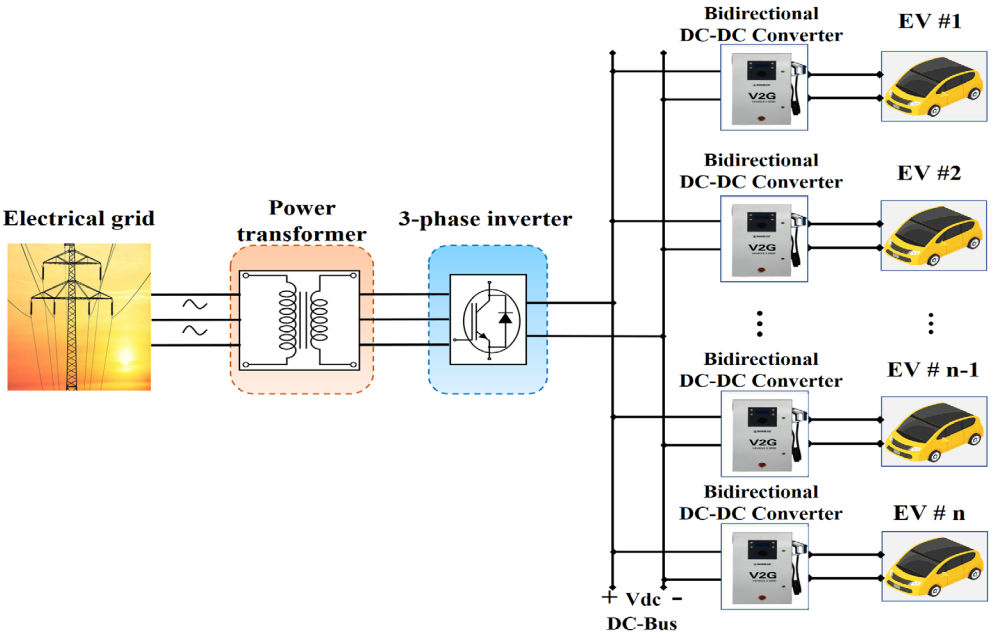


Fig 1. *Typical structure of V2G-CS*

In this manuscript, a double integral sliding mode controller (DISMC) with DPC approach is employed to control the DC-Bus voltage of an isolated bidirectional dual active bridge converter (IBDAB) used as the DC-DC charger of the V2G-CS. The DISMC builds on the robustness improvements of the ISMC by adding a second integral term, which results in better steady-state accuracy and smoother dynamics. The adoption of the IBDAB is based on its advantages, namely galvanic isolation between the EV and the DC-bus, and high-power density, among others. The goal of the DISMC is to maintain a stable DC-Bus voltage while the EV is injecting power into the grid. This is crucial since within the same station several DC-DC chargers can share the same DC-bus as presented in Fig. 1. The DC-Bus is connected to the grid via a three-phase power inverter, and if the DC-bus voltage is not stable, this can result in harmonics in the power system, which may be detrimental to the grid.

The rest of this paper is organized as follows; section two details the IBDAB modeling process, followed by the design of the controller in Section three. While the simulation results and their discussion are presented in section four. Finally, this paper ends with a conclusion.

The isolated bidirectional dual active bridge DC-DC converter (IBDAB)

The inherent advantages of the IBDAB, such as safety with galvanic isolation, zero voltage switching, current and voltage control, high efficiency, and high conversion ratio, make this converter ideal for EV charging. Due to its bidirectional capability, the IBDAB can either charge the EV from the DC-Bus or inject power back to this latter, which is convenient for the V2G applications. Nevertheless, to ensure an efficient power flow in both directions, a robust and reliable control strategy must be designed. Since the controller used in this study (DISMC) is model-based, an accurate and reliable model of the DAB converter is developed in this section.

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Fig. 2 shows the configuration of the DAB converter in which V_b and V_{dc} are the voltages on the EV side and the DC-bus side, respectively. The circuit topology of the converter consists of eight semiconductor switches (S_1, …, S_8) forming two symmetric H-bridges, connected to the primary and secondary sides of a high-frequency transformer. Filtering capacitors (C_b and C_{dc}) are inserted on each side of the converter to smooth out the voltage and reduce the ripples. L_k represents the equivalent inductance which accounts for both the transformer's leakage inductance and auxiliary inductors. In addition, an inductor L_b is added to smooth out the current on the EV side. In this paper, the high voltage (HV) side of the DAB converter is connected to the DC-bus, whereas the low voltage side (LV) is interfaced with the EV, and n represents the transformer ratio.

Using the single-phase-shift modulation control, the duty cycle of the switches is kept at 50%. On each side, the upper and lower switches of the same bridge conduct in a complementary manner, and those of the diagonal positions are simultaneously conducting. Whereas, the conducting interval between the primary and secondary sides is defined as DT_s, where Ts is the half-switching period and $D = \frac{\delta}{\pi}$ represent the phase-shift ratio with δ indicating the phase-shift angle. This latter determines the average and the direction of the power flow of the DAB converter according to the following equation:

$$P_o = \frac{V_b V_{dc}}{2nf_s L_k} D(1-D) \tag{1}$$

Where f_s is the switching frequency and D is ranged between -1 and 1 ($-\frac{\pi}{2} < \delta < \frac{\pi}{2}$).

Eq. 1 shows that the quantity of power transferred, from one side to another, depends also on the switching frequency and the equivalent inductance. Furthermore, based on Eq. 1, the value of D that yields the maximum power is $D = \frac{1}{2}$ ($\delta = \frac{\pi}{2}$), accordingly P_{max} is given as follows

$$P_{max} = \frac{V_b V_{dc}}{8nf_s L_k} \tag{2}$$

To enable the DAB converter to transfer power from the EV to the DC-bus, the phase-shift ratio (D) must be positive, and vice versa (charging). Therefore, the value of D can be divided into two sub-equations:

$$D = 0.5 - \sqrt{0.25 - \frac{2nf_s L_k}{V_b V_{dc}} P_o} \ , P_o > 0 \tag{3}$$

$$D = -0.5 + \sqrt{0.25 + \frac{2nf_s L_k}{V_b V_{dc}} P_o} \ , P_o < 0 \tag{4}$$

As a result, for a given value of V_b, V_{dc}, f_s and L_k, the transferred power P_o can be directly controlled by the phase shift according to the nonlinear relationship shown in Eq. 1. Thus, in this paper, a robust control approach is designed to compute the appropriate value of the phase shift that can supply the desired power.

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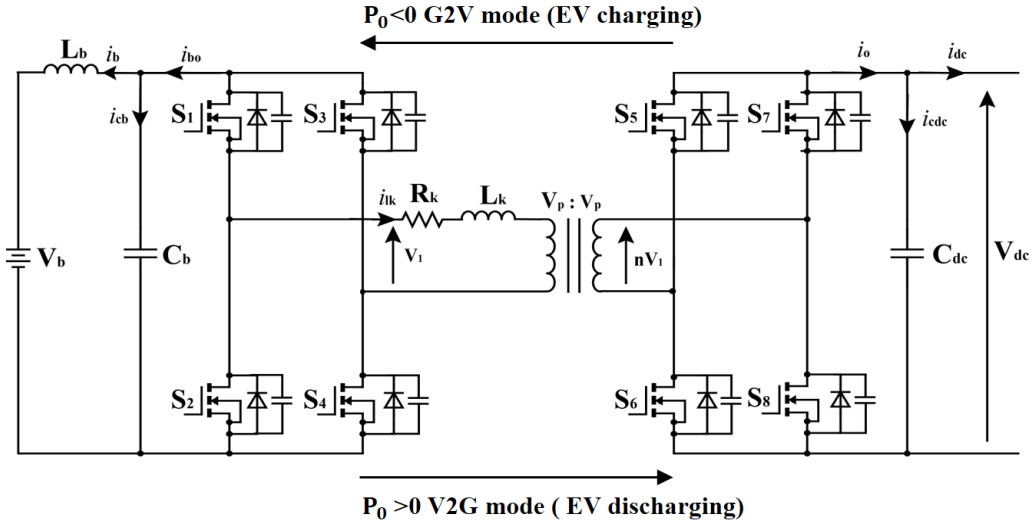


Fig 2. *DAB converter*

Design of the DC-Bus voltage controller

In this study, a double integral sliding mode controller (DISMC) with DPC approach is applied to control the power flow from the EV to the grid while maintaining a stable DC-Bus voltage. This is achieved by computing the phase shift δ that corresponds to the required power.

The DISMC is an enhanced version of the sliding mode control (SMC). The controller relies on the mismatch between the reference and the measured DC-bus voltages to derive a corresponding power P_o (Eq. 1) that nullifies this error. Afterward, the computed power is translated into the phase shift ratio D using Eq. 3.

The voltage error used by DISMC is denoted as follows:

$$e_v = V_{ref} - V_{dc} \tag{5}$$

Where V_{ref} is the DC-bus voltage reference. To efficiently eliminate the steady-state error in the conventional SMC and single integral SMC, a double integral sliding surface s_v is used instead of a single integral sliding surface:

$$s_v = C_1 e_v + C_2 \int e_v \, dt + C_3 \iint e_v \, dt \tag{6}$$

C_1, C_2, and C_3 are positive constants representing the gains of the sliding surface. Taking the derivative of Eq. 6:

$$\dot{s}_v = C_1 \dot{e}_v + C_2 e_v + C_3 \int e_v \, dt \tag{7}$$

As mentioned previously, the phase shift will be generated according to the transferred power P_o, which is used as the control signal of the DISMC to regulate the DC-bus voltage. The dynamic equation of the power across the capacitor $P_{C_{dc}}$ can be expressed as follows:

$$P_{C_{dc}} = C_{dc} V_{dc} \frac{dV_{dc}}{dt} = P_o - P_{dc} \tag{8}$$

Where P_{dc} is the power that is injected into the grid via the three-phase inverter, which is defined as:

$$P_{dc} = V_{dc} I_{dc} \tag{9}$$

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Thus, the dynamic equation of the DC-bus voltage can be expressed as follows:

$$\frac{dV_{dc}}{dt} = \frac{P_o}{C_{dc}V_{dc}} - \frac{I_{dc}}{C_{dc}} \tag{10}$$

Being that the purpose of the controller is to obtain a stable DC-bus voltage, thus $\dot{V}_{ref} = 0$. As a result, by substituting $\frac{dV_{dc}}{dt}$ in Eq. 7 by its expression in Eq. 10, the new $\dot{s}_v$ is denoted as:

$$\dot{s}_v = -C_1\left(\frac{P_o}{C_{dc}V_{dc}} - \frac{I_{dc}}{C_{dc}}\right) + C_2 e_v + C_3 \int e_v \, dt \tag{11}$$

Next, the equivalent control law is obtained from Eq. 11 by solving $\dot{s}_v = 0$, which yields the following control signal, with ε_V is a positive constant:

$$P_{o\,(eq)} = I_{dc}V_{dc} + \frac{C_2}{C_1} C_{dc}V_{dc}e_v + \frac{C_3}{C_1} C_{dc}V_{dc} \int e_v \, dt + C_s \tanh\left(\frac{S_v}{\varepsilon_V}\right) \tag{12}$$

Being that the 'sign' function is responsible for the chattering effect due to its discontinuity, the hyperbolic tangent function 'tanh' is used in this work to achieve a smoother control law. To discern the existence of the DISMC, the following Lyapunov function is chosen:

$$V_v = \frac{1}{2}{s_v}^2 \tag{13}$$

Accordingly, the first derivative of the Lyapunov function V_v is formulated as:

$$\dot{V}_v = -C_s|s_v| < 0 \tag{14}$$

This implies that the controller reaches the sliding surface boundary $|s_v| < \varepsilon_V$ on a finite time, and that it is asymptotically stable under the condition of $C_s > 0$. The dynamics of the controller and the convergence time of V_{dc} to the reference V_{ref} are imposed by setting appropriate gains $C_1 > 0$, $C_2 > 0$, and $C_2 > 0$.

Discussion

The performance of the double integral sliding mode controller is evaluated in this section. The areas that are investigated in this section are: 1) The response time of the controller and 2) The stability of the DC-bus voltage, since the latter will result in a stable output power injected into the grid. The parameters of the IBDAB converter, as well as the information on the EV adopted in the simulations are listed in Table 1.

Table 1. *Simulation parameters*

Parameter	Value	Parameter	Value
Nissan Leaf battery capacity	40[kWh]	Capacitors Cb, Cdc	2 [mF], 3 [mF]
Transformer's primary and secondary voltages	380[V], 480[V]	Inductance Lk, Lb	0,102[μH] 0,5[mH]

To evaluate the response time and robustness of the controller, the demanded power by the grid is instantaneously changed from P_1=44.5 kW to P_2= 7.7 kW at T=3s, and from P_2 back to P_1 at T=6s as shown in Fig. 3. Based on the results presented in Fig. 4, it is clear that the response time of the controller is satisfactory, bringing back V_{dc} to its nominal value in 0.03 seconds compared

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to 0.055 seconds when using the classical PID. Furthermore, the DISMC was able to maintain the DC-Bus voltage constant at V_{dc} = 480V with an average error of less than 0.7 V and a maximum error of 8 V, occurring during the transitions in the demanded power from P_1 to P_2 and vice versa. When compared to PID, which yielded an average error of 0.8 V and a maximum error of 25 V at identical time instants, it is evident that the DISMC is superior. This validates the robustness of the controller and its capability to stabilize the voltage regardless of the sudden changes in the injected power.

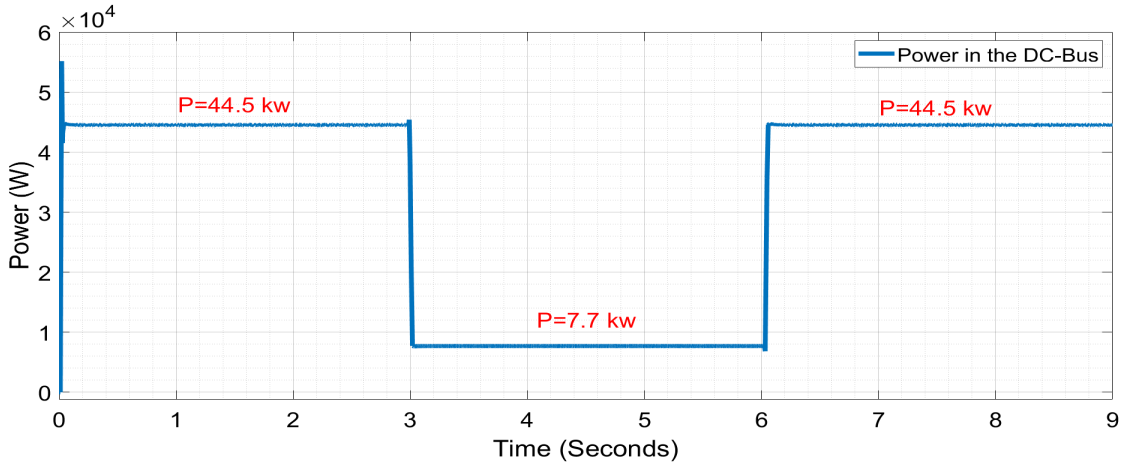


***Fig 3**. Injected power into the DC-bus*

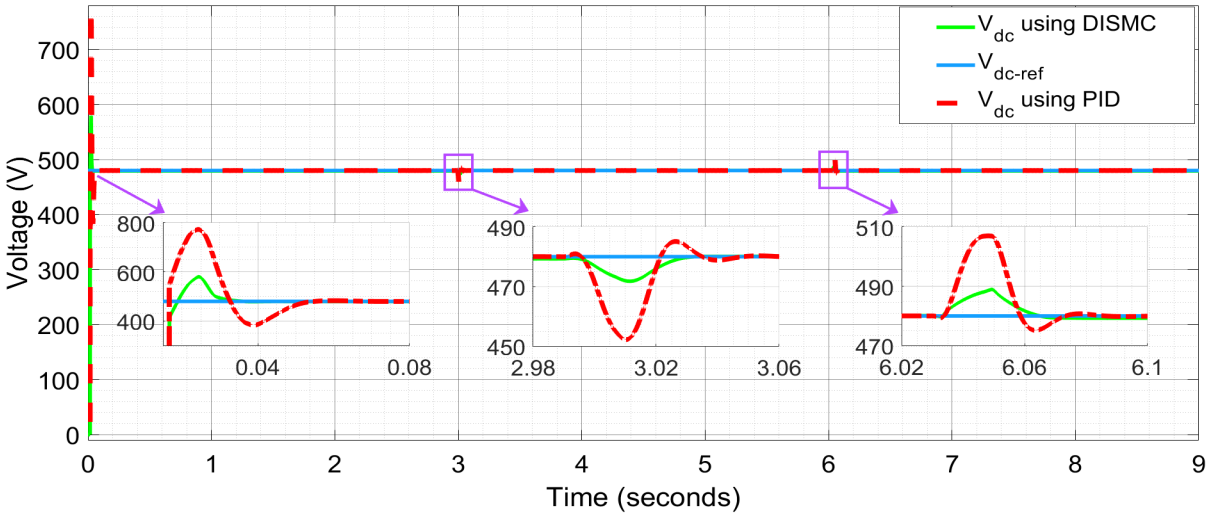


***Fig 4**. Evolution of the DC-Bus voltage*

As a result of injecting power to the DC-Bus, the EV battery state of charge given in Fig. 5 is decreasing. The slopes of the SOC reflect the amount of power withdrawn from the EV. The SOC in Fig. 5 is estimated using an unscented Kalman filter[13].

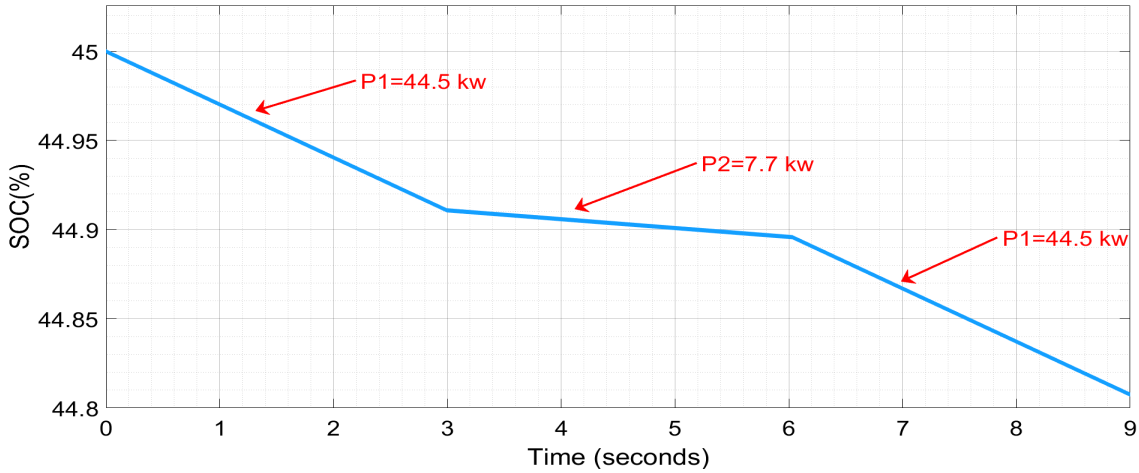


Fig 5. *Variation of the EV's SOC*

Conclusions

Maintaining a stable DC-bus voltage while injecting power into the grid is crucial for a successful implementation of the V2G technology. In this regard, this paper investigated the performance of a double integral sliding mode controller in controlling the isolated bidirectional dual active bridge of the DC-DC charger. The obtained results demonstrated the effectiveness of the adopted control strategy in maintaining a stable DC-bus voltage even under fluctuating power demand. As a result, the authors strongly recommend the use of the DISMC controller as well as the IBDAB converter in V2G charging stations. Prospective studies will investigate the performance of the DISMC when integrated with a backstepping inverter controller and a fuzzy logic–based power management strategy. The objective of this research is to develop a complete control scheme for the V2G-CS.

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