

Combined Controls for Variable EV Charging and Reactive Power Support with Device Emulation and Power-HIL Implementation

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Abstract—Growing electric vehicle (EV) adoption is expected to increase peak load and introduce voltage regulation challenges in distribution grids. At the same time, bidirectional EV chargers present an opportunity to provide grid support services such as demand response (DR) and reactive power support (RPS). This paper presents a novel decentralized RPS controller that continuously adapts its volt/var droop setpoints using local voltage measurements. The proposed controller was evaluated on the IEEE 13-node test feeder, where it reduced the number of voltage violations caused by high EV charging demand by 98.3%. To experimentally demonstrate the variable charging control required to provide reactive power headroom during battery charging, a fully integrated microgrid power hardware-in-the-loop (PHIL) test bench was developed in which analog programming was used to regulate the charging current. A custom EV emulator circuit is also presented to facilitate laboratory testing of EV supply equipment (EVSE) without requiring a physical vehicle or commercial EVSE test equipment.

Index Terms—Power hardware-in-the-loop (PHIL), reactive power support (RPS), electric vehicle (EV), SAE-J1772

I. INTRODUCTION

A significant amount of distributed energy resource (DER) infrastructure has already been deployed in the United States (US) including solar photovoltaic (PV) generation and electric vehicle (EV) chargers [1]–[3]. This equipment may be used for grid control and management functions such as demand response (DR) and reactive power support (RPS) [4]. Standard SAE-J1772 EV supply equipment (EVSE) has the capability to communicate desired charging status and power level to the vehicle battery management system (BMS) [5]. This signaling protocol may be leveraged to decrease the active power charging rate, making it possible to provide RPS even while the vehicle battery is charging [6].

Since EV charger operation is constrained by the apparent power rating, active and reactive power must share the available converter capacity. Consequently, the charging power

must be reduced to provide sufficient headroom for RPS during battery charging [7]. At the rated charging power, there would be no remaining capacity for RPS. This limitation only applies while the battery is charging; when the vehicle is connected but not charging, the full apparent power capacity is available. Since the aggregated impact of EV charging can contribute to voltage sag on the distribution system, battery charging may be the period during which RPS provides the greatest benefit from the perspective of the utility [8].

One approach for public charging stations proposed in the literature is to oversize EV charger converters beyond the maximum charging power, providing additional apparent power capacity for RPS without reducing the charging rate [9]. A previous study by our group evaluated co-located battery energy storage for voltage regulation in distribution grids with EV charging stations [10]. These methods, while very effective, may not be practical for residential installations due to the increased hardware cost.

Many existing studies of RPS from bidirectional EV chargers formulated centralized optimization problems that determined battery charging power and reactive power subject to the apparent power constraint to improve power factor or regulate voltage [11]–[13]. In contrast, this paper proposes a decentralized volt/var controller that adjusts the battery charging rate to provide reactive power headroom while adapting the droop characteristic to local operating conditions.

Previous studies implemented laboratory testing of SAE-J1772 communication protocol with physical vehicles [14], [15]. Others introduced charging emulation test beds that operate without a physical vehicle. These include a power hardware-in-the-loop (PHIL) laboratory setup developed to evaluate a smart charging algorithm and a PHIL-based battery and grid emulator deployed to test EV charger operation within a low voltage grid [16], [17]. Existing studies relied on off-the-

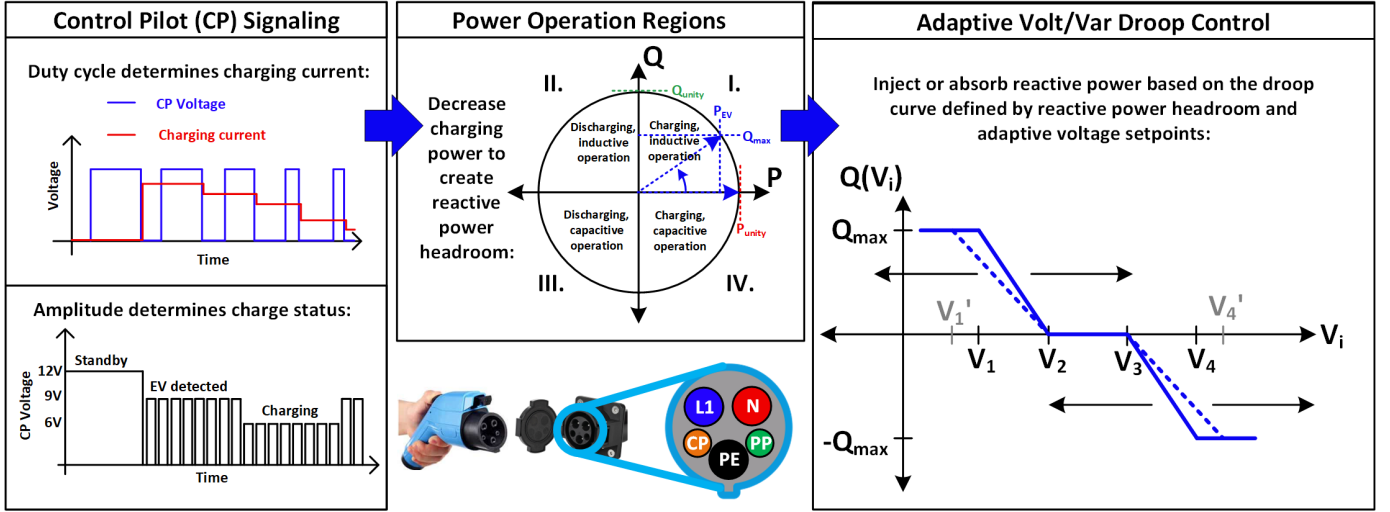


Fig. 1. For an SAE-J1772 standard EV charger, the control pilot (CP) is used to facilitate communication between the EVSE and vehicle. The vehicle communicates the charging state to the EVSE by changing the voltage amplitude between CP and protective earth (PE). The EVSE communicates the desired charging level to the vehicle battery management system (BMS) through pulse width modulation (PWM) of the CP-PE voltage signal. This method may be used to adjust (lower) the charging active power level to create apparent power headroom for the proposed reactive power support (RPS) method.

shelf EV supply equipment (EVSE) testers or physical onboard chargers to satisfy vehicle detection protocol. The testbench developed in this study enables EVSE testing without the need for a physical EV or dedicated products. The main contributions include:

- Development and evaluation of a novel decentralized, locally adaptive reactive power support (RPS) controller for bidirectional EV chargers that continuously adjusts the voltage setpoints of its volt/var droop curve based on the estimated steady-state error (SSE).
- Design of a laboratory test bench to emulate EV charging without a physical vehicle or dedicated product.
- Power hardware-in-the-loop (PHIL) validation of variable EV charging level control, demonstrating a practical method for dynamically increasing reactive power headroom during battery charging.

II. REACTIVE POWER SUPPORT FROM BIDIRECTIONAL EV CHARGERS

A. Background

The IEEE 1547 standard provides technical specifications for the integration of distributed energy resources (DERs) in distribution grids [18]. For reactive power support (RPS) of bidirectional EV chargers, we propose an adaptive form of the volt/var droop curve defined in this standard. For conventional droop control, the following piecewise function determines the amount of reactive power that needs to be injected or absorbed by each DER:

$$Q_i(V_i) = \begin{cases} Q_{max}, & V_i \leq V_1 \\ \frac{Q_{max}}{V_2 - V_1}(-V_i + V_2), & V_1 < V_i \leq V_2 \\ 0, & V_2 < V_i \leq V_3 \\ \frac{-Q_{max}}{V_4 - V_3}(V_i - V_2), & V_3 < V_i \leq V_4 \\ -Q_{max}, & V_i > V_4, \end{cases} \quad (1)$$

where Q_{min} , Q_{max} are the minimum and maximum amount of reactive power that can be injected or absorbed respectively; V_i , the voltage measured at the point of common coupling (PCC); and V_1 , V_2 , V_3 , and V_4 , the voltage setpoints.

One major challenge of conventional droop control is defining fixed voltage setpoints that result in convergence while also achieving a low steady state error (SSE) [19]. Selecting voltage setpoints that are too aggressive may result in voltage oscillations or instability, where more conservative setpoints can increase SSE, causing the system voltage to converge farther from the desired operating point. This tradeoff motivates the proposed adaptive RPS method, in which the voltage setpoints are continuously adjusted in response to changing system conditions.

B. Proposed Adaptive RPS Method

The proposed method for RPS is demonstrated in Fig. 1. If the battery is actively charging, the power level is adjusted (decreased) using control pilot (CP) signaling to reserve capacity for reactive power. The EVSE communicates the desired charging level to the vehicle battery management system (BMS) by changing the duty cycle of the CP voltage signal [14].

Since reactive power injection and absorption are limited by the apparent power rating of the EV charger, $S_{ev, rated}$, then the available capacity for RPS, Q_{max} , is dependent on the active power charging rate, P_{ev} , while the battery is charging, as follows:

$$Q_{max} = \sqrt{S_{ev, rated}^2 - P_{ev}^2}. \quad (2)$$

If the EV is plugged-in but not actively charging the battery, the available capacity is simply the rated apparent power of the charger:

$$Q_{max} = S_{ev, rated}. \quad (3)$$

Most drivers in the US have a short commute, so the majority of EV batteries may be charged to a high SOC overnight even while decreasing the active power charging rate to allow capacity for RPS [20]. We propose an adaptive droop controller to continuously shift the reference voltage, V_{ref} , for each controller based on the estimated SSE at the PCC. The reference voltage is the desired operating point and can be defined according to the following expression:

$$V_{ref} = \frac{V_2 + V_3}{2}, \quad (4)$$

where V_2 and V_3 are the voltage setpoints that bound the deadband of the droop curve. The SSE at the current time step, E_t , is estimated as the difference between the measured voltage at the PCC, $V_{i,t}$, and V_{ref} :

$$E_t = V_{i,t} - V_{ref}. \quad (5)$$

Next, we apply the exponential moving average formula to filter out short-term voltage fluctuations due to temporary disturbances at each timestep:

$$E_{t,f} = \alpha \cdot E_t + (1 - \alpha) \cdot E_{t-1,f}, \quad (6)$$

where $E_{t,f}$ is the filtered SSE at the current timestep; E_t , the measured SSE at the current time step; and $E_{t-1,f}$, the filtered SSE from the previous time step. If $E_{t,f}$ is outside the error band, the required voltage setpoint shift at the current time step, $V_{shift,t}$, is updated:

$$V_{shift,t} = \begin{cases} V_{shift,t-1} - E_g \cdot E_{t,f}, & |E_{t,f}| > E_{db} \\ 0, & |E_{t,f}| \leq E_{db}, \end{cases} \quad (7)$$

where E_{db} is the error band; $V_{shift,t-1}$, the required voltage shift from the previous time step; and E_g , the gain applied to prevent overly-aggressive adjustments by scaling down the filtered SSE. Adjustments were limited by a clamp correction as another precaution to avoid overly-aggressive adjustments:

$$V_{shift,t} = \text{clip}[V_{shift,t}, V_{shift,min}, V_{shift,max}], \quad (8)$$

where $V_{shift,min}$ and $V_{shift,max}$ are the minimum and maximum amount the voltage setpoints may be shifted per timestep, respectively. Finally, $V_{shift,t}$ is added to each nominal voltage setpoint. Since the same offset is applied to $V_1 - V_4$, the entire droop curve is translated horizontally while maintaining the original deadband width and slopes:

$$V_{1,t} = V_{1,t-1} + V_{shift,t}, \quad (9)$$

$$V_{2,t} = V_{2,t-1} + V_{shift,t}, \quad (10)$$

$$V_{3,t} = V_{3,t-1} + V_{shift,t}, \quad (11)$$

$$V_{4,t} = V_{4,t-1} + V_{shift,t}, \quad (12)$$

note that $V_{shift,t}$ represents the incremental voltage shift for time step t of one controller. Each EV charger operates its

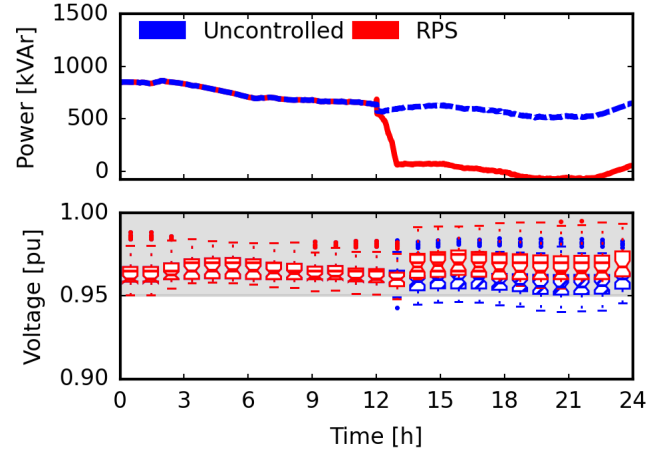


Fig. 2. Total reactive power load (top) and node voltages (bottom) of the system without and with the proposed RPS method with adaptive droop control. Uncontrolled EV charging at unity PF caused node voltages to fall below the acceptable margin of 0.95pu, while implementation of RPS shifted node voltages above the margin while EVs were connected to the grid between hours 12 and 24.

own adaptive controller, allowing the reference voltage to be adjusted independently based on local system conditions. This method ensures that variations in voltage sensitivity and loading throughout the distribution grid are accounted for.

III. TEST CASE: RPS WITH ADAPTIVE DROOP ON A DISTRIBUTION GRID WITH HIGH EV PENETRATION

The proposed reactive power support (RPS) method with adaptive droop control for bidirectional EV chargers presented in section II was simulated on a distribution grid using OpenDSS, a circuit simulation software developed by the Electric Power Research Institute (EPRI) [21]. The IEEE 13-node test feeder was the circuit model used in both test cases [22]. To allow for time series simulation of the system, the active and reactive power of each individual load was scaled by per-unit (pu) field data measured at the substation transformer with one-minute resolution.

Additionally, EV charging profiles were added to the scaled base loads. A total of 60 EV chargers were introduced across the system, and the initial battery state-of-charge (SOC) for each was determined using daily travel distances from the 2022 National Household Travel Survey [23]. Gaussian Kernel Density Estimation was used to sample a smaller set of travel distances (60) from the large dataset while maintaining the original distribution. A detailed explanation of this method was included in a previous publication by our group [20].

A capacity of 100kWh was assumed for each EV battery, and an apparent power capacity of 10kVA was assumed for each charger. Two test cases were simulated: the uncontrolled case, where all EV chargers operate with unity power factor (PF) at their rated capacity; and the RPS case, where the proposed method with adaptive droop control is implemented. In the RPS case, the active power charging level of each EV

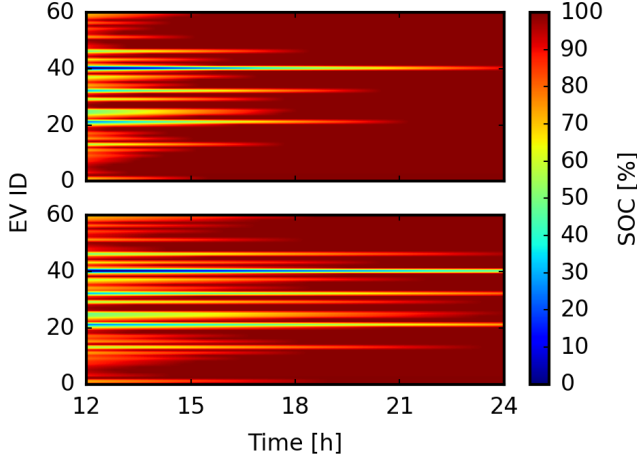


Fig. 3. Battery state-of-charge (SOC) for EVs during the test cases without (top) and with (bottom) the proposed RPS method. Even though the active power charging level was reduced to 50% for RPS, 57 out of 60 EV batteries were charged above 90% SOC within 12 hours.

in the circuit was reduced to 50% of rated apparent power capacity (5kW) to provide reactive power headroom.

The following settings were used for all RPS controllers in the simulation: -0.010 for $V_{shift,min}$, 0.015 for $V_{shift,min}$, 0.003 for E_g , 0.030 for E_α , and 0.001 for E_{db} . The nominal droop curve voltage setpoints were set to 0.940, 0.965, 0.975, and 1.000 for V_1 , V_2 , V_3 , and V_4 , respectively.

All EVs on the system were assumed to start charging simultaneously at hour 12 and the initial battery SOC were calculated assuming that all occupants completed their daily commute for 5 days prior to charging. Although this scenario is not representative of typical charging behavior, it was intentionally selected to provide a conservative stress test to evaluate the proposed RPS control under worst-case operating conditions. The system level results are shown in Fig. 2. In the uncontrolled case without RPS, system voltage fell under the low end of the acceptable margin (0.95pu) due to high EV charging demand in the evening.

The proposed RPS method significantly improved voltage violations by injecting reactive power to increase system voltage. Note that the value plotted in the top subplot is the total system *load* reactive power, so a decrease in this value indicates injection of reactive power by the EV chargers. Implementation of the RPS method decreased the number of system voltage violations from 3,773 to 66.

The SOC of EV batteries in both test cases between hours 12 and 24 are illustrated in the color maps of Fig. 3. Despite only charging at 50% rated power in the RPS case, 57 out of 60 total EV batteries were charged to above 90% SOC by hour 24. This is only a slight reduction from 59 out of 60 in the uncontrolled case. These results indicate that the active power charging level can be reduced to provide headroom for RPS while simultaneously satisfying charging demand.

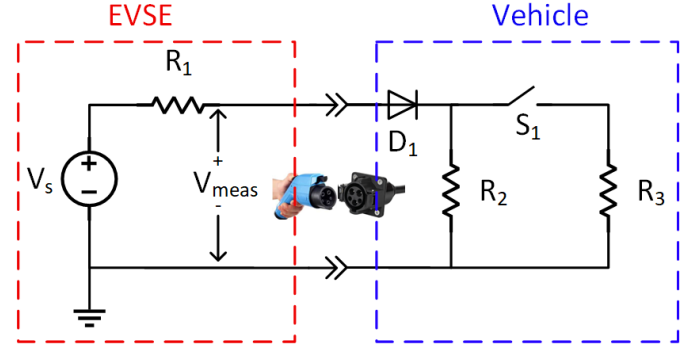


Fig. 4. Schematic of the control pilot (CP) signaling circuit. The measured voltage, V_{meas} , determines the charging state. The section of the circuit within the red box is included in the EVSE while the section within the blue box was constructed to control the charging state without a vehicle or EVSE tester.

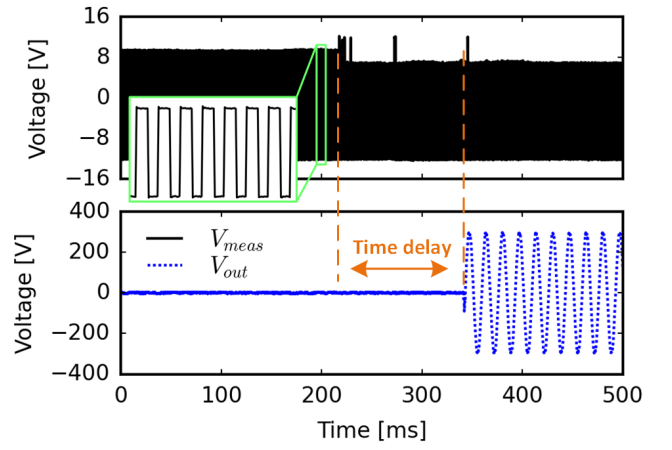


Fig. 5. Experimental measurements of V_{meas} and the AC voltage output of the EVSE (V_{ac}) as it switched from the “vehicle detected” state to the “charging” state. When the vehicle-side circuit was connected with S_1 open, V_{meas} had a positive cycle amplitude of 9V. Once S_1 was closed at 220ms, the amplitude reduced to 6V and the EVSE entered the “charging” state, where the power cables were energized after a delay of approximately 120ms.

IV. SPECIAL EV TESTBENCH WITH VEHICLE EMULATION

It is important to note the difference between an EV charger and EV supply equipment (EVSE). An EV charger is commonly on-board the vehicle and includes the power converter, while an EVSE refers to the device that delivers electricity from the grid to the EV charger and is typically a “box” outside the vehicle.

For SAE-J1772 standard EV charging, vehicles communicate charging status to the EVSE with the voltage amplitude between the control pilot (CP) and protective earth (PE) wires. A circuit diagram showing the CP circuit is included in Fig. 4. The vehicle-side of this circuit, shown inside the blue square, was constructed to communicate charging state to the EVSE without a vehicle or dedicated testing product.

There are three possible charging states: “standby”, “vehicle detected”, and “charging.” The charging state is communicated

to the EVSE by changing the positive cycle magnitude of the measured CP-PE voltage V_{meas} . When the vehicle is unplugged from the EVSE, the CP circuit is open. In this case, V_{meas} is equal to the source voltage, V_s , since there is no voltage drop across R_1 . This signals to the EVSE that a vehicle is not connected, so the EVSE will remain in standby with the power lines de-energized:

$$V_{meas} = V_s. \quad (13)$$

When a vehicle is connected to the EVSE but switch S_1 is open, the diode D_1 and resistors R_1 and R_2 are connected in series with V_s , causing the positive cycle voltage amplitude to change according to the following expressions:

$$V_{meas} = V_{D_1} + V_{R_2}, \quad (14)$$

$$V_{R_2} = (V_s - V_{D_1}) \frac{R_2}{R_1 + R_2}, \quad (15)$$

where V_{D_1} is the voltage across D_1 and V_{R_2} is the voltage drop across R_2 . This signals to the EVSE that a vehicle is detected but not ready to charge, so the power cables of the charging plug remain de-energized.

When a vehicle is connected and ready to charge, the vehicle battery management system (BMS) closes S_1 , adding resistor R_3 in parallel with R_2 , which changes V_{R_2} according to the following expression:

$$V_{R_2} = (V_s - V_{D_1}) \frac{\left(\frac{R_2 R_3}{R_2 + R_3}\right)}{R_1 + \left(\frac{R_2 R_3}{R_2 + R_3}\right)}, \quad (16)$$

where V_{meas} can once again be calculated with (14) using the new value of V_{R_2} . Once S_1 is closed, the change in positive cycle voltage amplitude signals to the EVSE that a vehicle is connected and ready to charge. Only then are the power cables energized, which is precisely why the proposed CP signaling circuit is required for laboratory testing of EVSE without a vehicle or dedicated product. Unlike previous studies, which used on-board vehicle equipment or dedicated EVSE testing products to emulate CP signaling without a physical vehicle, the proposed custom-made CP signaling circuit was used for the experimental demonstration in this study.

According to IEC 61851, the premier international standard for EV charging, the CP-PE positive cycle voltage magnitudes required to signal “standby,” “vehicle detected,” and “charging” to the EVSE are 12V, 9V, and 6V, respectively [24]. To force V_{meas} to equal 9V when S_1 was open and 6V when S_2 was closed, the resistance values chosen for R_2 and R_3 in the custom-made control pilot (CP) signaling circuit were 2.74k Ω and 1.3k Ω , respectively. The value of R_1 within the EVSE was 1k Ω .

The diode, D_1 , was connected in series between R_1 and R_2 to open the circuit during the negative cycle voltage of V_s , which generates a 1kHz square wave of $\pm 12V$ during the “vehicle detected” and “charging” states. The diode is

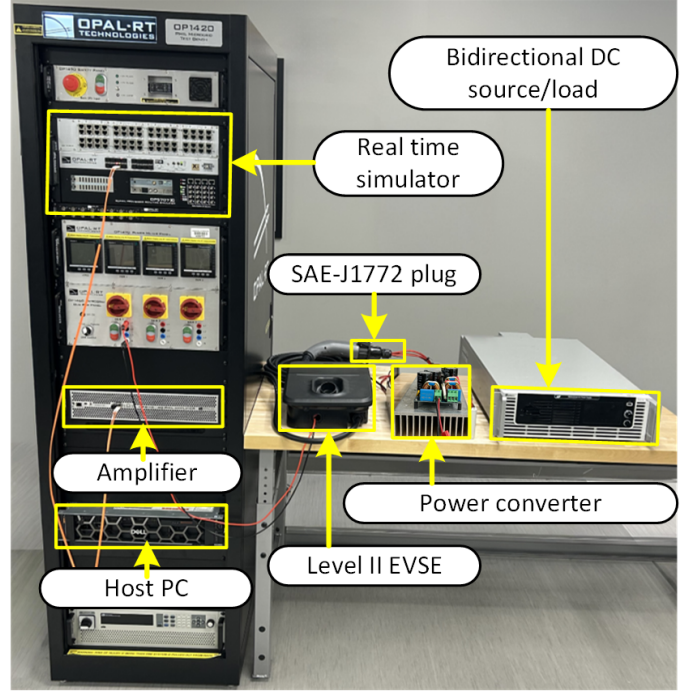


Fig. 6. The laboratory test bench used to complete the hardware experiments presented in this study. Equipment includes a fully-integrated microgrid PHIL test bench, level-II EVSE, 3kW converter with power factor correction (PFC), and a 6kW bidirectional DC source/load.

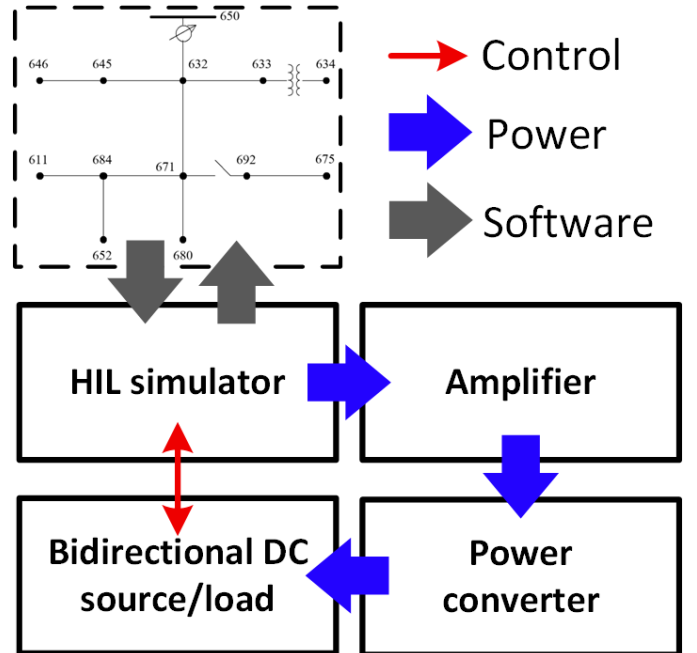


Fig. 7. The test bench configuration for PHIL validation of variable EV charging controls. A bidirectional DC source/load was employed to emulate a vehicle battery and a 3kW PFC converter was used in place of an on-board EV charger. The real-time simulator interfaced with the circuit model while sending a control signal to the DC source/load to regulate the charging current.

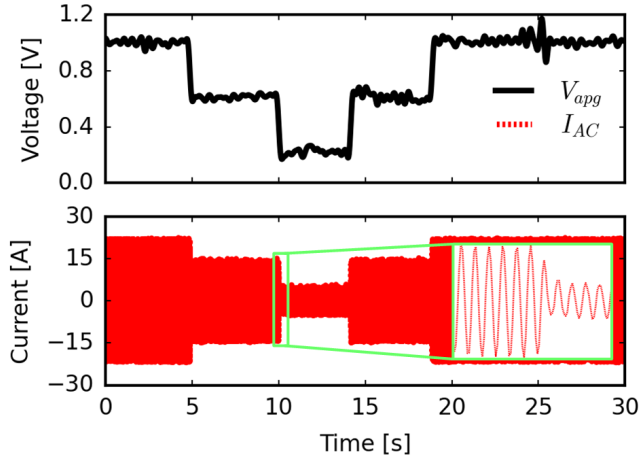


Fig. 8. Experimental results from the PHIL variable charging test including the control voltage signal, V_{apg} , (top) and current measured at the input of the converter (bottom). No significant delay is observed as the DC source/load changed the current almost immediately in response to variation of V_{apg} .

required because the EVSE detects a fault if the negative cycle amplitude of V_{meas} is not equal to 12V.

The signaling circuit was experimentally verified, and all three charging states were achieved. The experimental measurements in Fig. 5 demonstrate the CP signaling circuit toggling the EVSE state from “vehicle detected” to “charging” by closing switch S_1 at 220ms. After a short time delay of approximately 120ms, the EVSE responded to the CP-PE positive cycle voltage magnitude change and closed its smart breaker, energizing the power cables of the charging plug.

It is also possible for the EVSE to communicate the desired charging level through pulse width modulation (PWM) of the CP-PE voltage signal, where the duty cycle and charging current are linearly correlated. For the variable charging experiment in section V, the analog programming interface (APG) of a bidirectional DC source/load was utilized instead due to the limitations of not having a physical vehicle or BMS.

V. LABORATORY TESTING ON A PHIL SYSTEM

Variable EV charging control was experimentally demonstrated on the IEEE 13-node test feeder with a fully-integrated microgrid power hardware-in-the-loop (PHIL) test bench, which is shown in Fig. 6. A 3kW converter with power factor correction was deployed in place of an on-board charger and a bidirectional DC source/load was utilized to emulate the EV battery. The real-time simulator implemented the distribution test feeder in a MATLAB/Simulink environment and executed within RT-Lab while sending a control signal to the programmable DC source/load through its analog programming interface (APG), as illustrated in the diagram of Fig. 7.

The APG maps an analog input voltage between 0 and 10V to the load current, allowing the real-time simulator to regulate the charging current drawn by the DC source/load. This control method differs from standard SAE-J1772 protocol, where the duty cycle of the CP-PE PWM signal communicates the

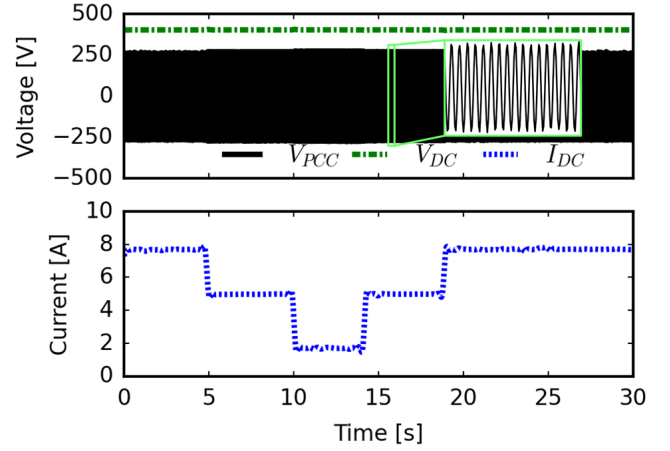


Fig. 9. Voltage measured at the grid-side/input and load-side/output of the converter (top) and the current draw of the DC source/load (bottom). The voltage remained stable as the charging level was varied as there were no significant voltage fluctuations observed.

desired charging current to the battery management system (BMS). The analog interface was adopted to produce the same functional outcome of variable charging control without a physical vehicle or BMS.

The PHIL test bench was used to test variable EV charging control on the IEEE 13-node test feeder, where charging power level was changed four times over a 30-second time interval. In the discussion of results, V_{PCC} and I_{AC} refer to the AC voltage and current measured at the grid-side (input) of the converter, while V_{DC} and I_{DC} refer to the DC voltage and current measured at the load-side (output) of the converter, respectively. Furthermore, V_{apg} represents the APG control signal voltage.

As shown in the experimental measurements of Fig. 8, the initial charging level was 3kW, then decreased below 1kW before being increased back to 3kW. There was no significant delay in response time as the DC source/load changed the charging current almost immediately in response to the step changes in V_{apg} . The measured voltages during the test are plotted in the top subplot of Fig. 9. Note that the output voltage magnitude of the converter is significantly higher than that of the input voltage. This is why I_{AC} and I_{DC} differ in magnitude and is simply due to the design of the converter.

VI. CONCLUSION

A novel decentralized reactive power support (RPS) method employing locally-adaptive droop control for bidirectional EV chargers was proposed and evaluated on a simulated distribution grid. The novel approach continuously adapts voltage setpoints based on the estimated steady-state error (SSE). The proposed controller effectively mitigated voltage violations caused by high EV charging demand, demonstrating the potential for EV chargers to provide localized voltage support. As EV chargers are limited by the apparent power rating of their converter, providing RPS during battery charging requires

sufficient reactive power headroom. Rather than oversizing converters, this work proposed reducing the active power charging rate to reserve converter capacity for RPS while avoiding the additional hardware cost associated with higher converter ratings.

Experimental power hardware-in-the-loop (PHIL) validation demonstrated variable EV charging level control using analog programming as a practical method for dynamically increasing reactive power headroom for the proposed RPS strategy. Additionally, a custom EV emulator circuit was designed to facilitate laboratory testing of EV supply equipment (EVSE) without requiring a physical vehicle or dedicated commercial product. Experimental validation with a level-II EVSE demonstrated successful communication of the three SAE-J1772 charging states through the control pilot (CP), providing a flexible platform for future research on EV charging and grid support functions.

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