Nested Control of Plug-in Electric Vehicles for Renewable Power Tracking

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***Abstract*—A robust strategy is proposed in this paper to simultaneously control the source and aggregate charging power of plug-in electric vehicles (PEVs). The charging flexibility of PEVs provides the power grid with control authority to cope with load fluctuations caused by the variation of grid-connected PEVs population and their instantaneous power demand. In this paper, a nested-loop control system consisting of an inner- and outer-loop is developed for aggregate charging power of PEVs. The inner-loop is used to control the charge rate of a fleet of grid-connected PEVs using sliding mode control theory. The outer-loop controller is then developed to adjust the renewable power source to avoid the inner-loop control saturation and the resulted drastic reference tracking error therein. The adjusted power is injected into a battery storage device and dispatched to the grid whenever the power demand is high. The closed-loop performance of the presented approach is demonstrated using real data from renewable sources.**

***Index Terms*—Aggregate model, charge control, plug-in electrical vehicle, sliding mode control**

I. Introduction

The charging flexibility of plug-in electric vehicles (PEVs) provides the power grid with some degree of control authority over load variation of grid-connected PEVs population. However, the uncertainties associated with the available renewable power and the number of PEVs connected to the grid complicate the process of distributing the renewable power among the grid-connected PEVs. In this paper, we propose a nested-loop control strategy for adapting the PEVs power to the available renewable power.

There have been several studies to address both negative and positive impacts of PEVs on the power grid (see e.g., [1], [2], [3]). The negative aspect has been mainly discussing the effect of the additional load by PEVs on the grid and overstretching it for large population of PEVs connected to the grid. On the other hand, the PEVs charging flexibility is deemed beneficial, because it enables the grid to reduce the strain and accommodates the renewable power to a greater extent [4], [5], [6].

From the controls point of view, the interplay between PEVs and the power grid has been considered generally as the grid power distribution properly among the grid-connected PEVs. Hence, most of the control design approaches have been devoted generally to the demand-side load control of PEVs [4], [7], [8], [9]. On the other hand, excessive renewable power can lead to the control saturation which in turn results in a drastic tracking error. To avoid this problem and to take advantage of the extra available renewable power, in this paper, we will propose a nested-loop control design strategy that can provide the grid with adjusted renewable power and adapts the PEVs power demand upon such an adjustment. The proposed approach in fact employs an outer control-loop which captures a portion of the available renewable power, thus eliminating the saturation problem. The captured power is stored in a storage device and the grid can make use of the inherent storage capacity as needed. The utilized storage device can be also used to mitigate the intermittency of the renewable power.

In this paper, we adopt sliding mode control theory to design a robust feedback control system for the PEVs power demand control [10]. It is presumed that the grid provides the control system with real-time supply/demand error signal. Furthermore, it is assumed that the exact number of grid-connected PEVs is not measurable at a given time, but a lower bound on its value is available.

Section II formulates PEVs charge rate problem. In Section III, we present a nested-loop control architecture for PEVs charge rate consisting of an inner-loop and an outer-loop controller along with an integrated storage device. Simulation results are discussed in Section IV and concluding remarks are provided in Section V.

II. Problem Formulation

The aim of this work is to develop a nested control system that can simultaneously adjust the power source and the charge rate of PEVs. To this purpose, an inner-loop is first considered to adapt the grid power demand to the generated power trajectory by renewable power sources. We consider a normalized control input as described in [1] with $0 \leq u_1(t) \leq 1$, which is transmitted unidirectionally by the network operator (see Fig. 1).

Consider the instantaneous power demand from grid as

$$P_{demand}(t) = \sum_{i=1}^{N(t)} P_{PEV,i}^{Max} u_1(t) \quad (1)$$

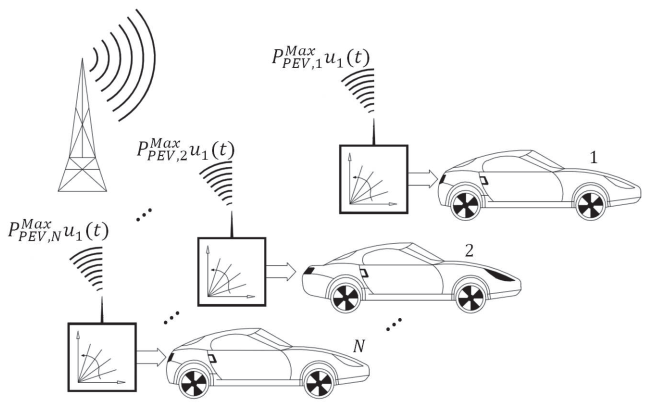

Fig. 1. Schematic of PEV load control

where $P_{PEV,i}^{Max}$ is the maximum power of the i^{th} PEV and $N(t)$ is the number of grid-connected PEVs. By assuming a large number of PEVs connected to the grid, Eq. (1) can be expressed as

$$P_{demand}(t) = \bar{P}_{PEV}^{Max} N(t) u_1(t) \tag{2}$$

where $\bar{P}_{PEV}^{Max}$ is the average value for the PEVs maximum charging power. Equation (2) is a simplified model for the *aggregate* power demand depending on the number of grid-connected PEVs, $N(t)$. It is assumed that $N(t)$ is a continuous-time signal with a bounded derivative.

III. NESTED CONTROL OF PEVS FOR RENEWABLE POWER TRACKING

In this section, we develop a nested control strategy consisting of an inner-loop for the power tracking and an outer-loop to adjust the reference trajectory to avoid the control saturation. The adjusted reference power is further used to charge a resource battery when the available power exceeds the maximum power demand. Dispatching the stored power in the battery helps to expedite the charging process with higher control authority.

A. Robust Demand-side PEV Load Control (Inner-loop Control)

The control design objective is to force the overall power demand $P_{demand}(t)$ to track the power supply trajectory $P_{supply}(t)$. To this purpose, we follow the approach proposed in [4]. Let us consider the measurable tracking error signal for the demand-side control as

$$e(t) = P_{supply}(t) - \bar{P}_{PEV}^{Max} N(t) u_1(t). \tag{3}$$

For P_{supply}, we will use renewable power source $P_{Rnew}(t)$ consisting of wind and photovoltaic power generation units. The aim of the demand-side controller is to track the available renewable power, i.e., $P_{Rnew}(t)$, in the presence of uncertainties in $P_{Rnew}(t)$ and in the number of grid-connected PEVs.

By adopting sliding mode control as a robust control approach and assigning $e(t)$ as the sliding manifold, one can define a positive-definite Lyapunov function

$$V_1(t) = \frac{1}{2} e^2(t) \tag{4}$$

whose time-derivative

$$\dot{V}_1(t) = e(t)[\dot{P}_{Rnew}(t) - \bar{P}_{PEV}^{Max} \dot{N}(t) u_1(t) - \bar{P}_{PEV}^{Max} N(t) \dot{u}_1(t)] \tag{5}$$

should be made negative-definite. We note that $\dot{V}_1(t) < 0$ results in

$$e(t)[D_1(t) - \nu(t)] < 0 \tag{6}$$

where

$$D_1(t) = \frac{\dot{P}_{Rnew}(t) - \bar{P}_{PEV}^{Max} \dot{N}(t) u_1(t)}{\bar{P}_{PEV}^{Max} N(t)} \tag{7}$$

with the new control input

$$\nu(t) = \dot{u}_1(t). \tag{8}$$

Choosing the control input $\nu(t) = \rho.\text{sgn}[e(t)]$ (sgn denotes the signum function) with $\rho > 0$ and replacing it in Eq. (6) yields

$$e(t)\{D_1(t) - \rho.\text{sgn}[e(t)]\} < 0. \tag{9}$$

The negative definiteness of Eq. (9) can be ensured by choosing $\rho > |D_1(t)|$. Hence, the control input $u_1(t)$ can be obtained by integrating $\nu(t)$ as

$$u_1(t) = u_1(0) + \rho \int_0^t \text{sgn}[e(\tau)] d\tau. \tag{10}$$

The sliding mode control (10) operates upon signum-function or namely switching on the sliding manifold $e(t)$. This characteristic of the sliding mode control, though results in a robust performance of the closed-loop system may excite the high-frequency dynamics of the system particularly for broader uncertainty bounds. Such a high-frequency switching is generally referred to as chattering and has been treated via several approaches like boundary layers and sigmoid-like function instead of the signum function. In this paper, we use the saturation function $sat[e(t)/\epsilon] = e(t)/\epsilon$ for $-\epsilon \leq e(t) \leq \epsilon$, $sat[e(t)/\epsilon] = 1$ and -1 for $e(t) > \epsilon$ and $e(t) < -\epsilon$, respectively.

B. Robust Resource Power Control (Outer-loop Control)

In this section, we develop an outer loop to control the renewable power. The aim of the outer loop is to adjust the renewable power level by storing the excessive renewable power in a battery storage device and dispatching it to the grid to charge the grid-connected PEVs as needed. Block diagram of the system with the outer loop and the augmented control input $u_2(t)$ has been presented in Fig. 2, where the available renewable power resource is now $P_{Rnew}(t) - u_2(t)$. To design the control input $u_2(t)$, we consider the renewable power tracking error as

$$\bar{e}(t) = P_{Rnew}(t) - u_2(t) - \bar{P}_{PEV}^{Max} N(t) u_1(t). \tag{11}$$

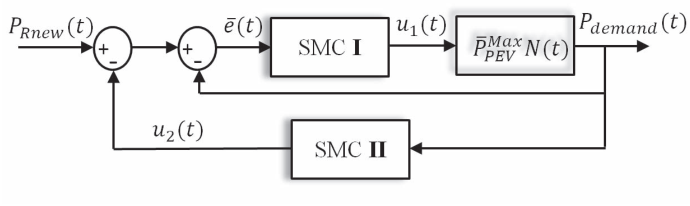

Fig. 2. Closed-loop representation of the Nested Loop Control

By incorporating sliding mode control theory and considering $\bar{e}(t)$ as the sliding manifold, a positive-definite Lyapunov candidate can be defined as

$$V_2(t) = \frac{1}{2}\bar{e}^2(t) \tag{12}$$

whose time-derivative

$$\dot{V}_2(t) = \bar{e}(t)[\dot{P}_{Rnew}(t) - \dot{u}_2(t) - \bar{P}_{PEV}^{Max}\dot{N}(t)u_1(t) - \bar{P}_{PEV}^{Max}N(t)\dot{u}_1(t)] \tag{13}$$

should be made negative-definite. Let Eq. (13) be expressed in the following form

$$\bar{e}(t)[D_2(t) - \chi(t)] < 0 \tag{14}$$

where

$$D_2(t) = \dot{P}_{Rnew}(t) - \bar{P}_{PEV}^{Max}\dot{N}(t)u_1(t) - \bar{P}_{PEV}^{Max}N(t)\dot{u}_1(t) \tag{15}$$

and the new control input is

$$\chi(t) = \dot{u}_2(t). \tag{16}$$

Choosing the control input $\chi(t) = \mu.\text{sgn}[\bar{e}(t)]$ with $\mu > 0$ and replacing it into Eq. (14) yields

$$\bar{e}(t)\{D_2(t) - \mu.\text{sgn}[\bar{e}(t)]\} < 0. \tag{17}$$

The negative definiteness of Eq. (17) can be ensured by choosing $\mu > |D_2(t)|$. Hence, the control input $u_2(t)$ can be obtained by integrating $\chi(t)$ over time interval $0 \le \tau \le t$ as

$$u_2(t) = u_2(0) + \mu \int_0^t \text{sgn}[\bar{e}(\tau)]d\tau. \tag{18}$$

The control input $u_2(t)$ contributes to the reduction of the reference renewable power. Hence, the inner-loop control $u_1(t)$ should make the inner closed-loop system to track the adjusted reference renewable power $P_{Rnew}(t) - u_2(t)$. The amount of reduction is $u_2(t)$, which is dependent on the sliding mode control gain $\mu > |D_2(t)|$. Physically, this means that a portion of the renewable energy is captured to lower the available power. To cope with the power captured from the renewable sources, we will utilize a storage device that is integrated to the grid and stores the excessive power and dispatches it into the grid whenever needed.

Let the mathematical model of a battery storage device that captures the dominant characteristics of a battery be expressed as [11]

$$S\dot{O}C(t) = [P_{Rnew}^{Max}(t) - P_{Rnew}(t)]\eta - u^{dch}(t)(1/\eta) \tag{19}$$

where $SOC(t)$ is the state-of-charge of the battery at time instant t, $P_{Rnew}^{Max}(t) - P_{Rnew}(t)$ is the charging power of the battery that represents the undispatched portion of the power that should be stored, u^{dch} is the discharged power that is injected to the grid, and η is the round-trip efficiency of the battery. For the case in hand, the term $P_{Rnew}(t)$ in Eq. (19) should be then replaced with $P_{Rnew}(t) - u_2(t)$ where the power by the outer-loop is positive. This means that the deducted power by the outer-loop from the grid, i.e., $u_2(t)$, can be used to increase the charging power of the battery as $P_{Rnew}^{Max}(t) - P_{Rnew}(t) + u_2(t)$. It is assumed that the battery is in either charging or discharging state and cannot be obviously charged and discharged simultaneously. Hence, $u^{dch}(t) = 0$ when the battery is in charging mode. On contrary, when the outer-loop control output $u_2(t)$ is negative, it is an indication of further power demand by the grid. Hence, the charged power in the battery can be dispatched to the grid based on Eq. (19) with $u^{dch} = u_2(t)$. Since the battery is in discharge mode, the charging power of the battery will be zero. We will assume that the battery capacity is limited by

$$SOC^{Min} \le SOC(t) \le SOC^{Max} \tag{20}$$

where SOC^{Min} and SOC^{Max} are battery's minimum and maximum capacity, respectively.

The next section will present the simulation results to validate the proposed control design approach.

IV. Results and Discussion

In this paper, we have used the total renewable power consisting of wind and photovoltaic units generation based on California ISO data from November 1st, 2011 [12]. For simulation purpose, we have used MATLAB/Simulink® with Runge–Kutta ODE4 for numerical integration. The program has been run for a population of 1500 PEVs with a variation of $500sin(0.01t)$ in number. We have considered $\bar{P}_{PEV}^{Max} = 2kW$ as the average value for the PEVs maximum charging power. Fig. 3 illustrates the closed-loop response of the system for power charging of PEVs where the inner-loop controller, $u_1(t)$, with $u_1(0) = 0$ and $\rho = 2.5$ makes the closed-loop system track the reference renewable power trajectory. However, for the initial hours of the charging process the control input exceeds saturation limit of $u_1(t) = 1$ (see Fig. 4). This indicates that the available power is larger than the grid-connected PEVs power demand. The saturation problem, in turn, results in an integral windup by the integrator in the control input. Though there has been various anti-windup techniques like projection operator to solve the integral windup problem, we will employ our proposed outer-loop control system that stores the excessive power and dispatches it to the grid when the demand power by the grid is higher than the available renewable power.

The results of applying $u_2(t)$ from Eq. (18) with $u_2(0) = 0$ and $\mu = 90$ have been presented for the closed-loop system in Fig. 5. The dashed-line represents the renewable reference power. The dotted-line depicts the adjusted reference renewable command and the solid-line shows the PEVs tracking

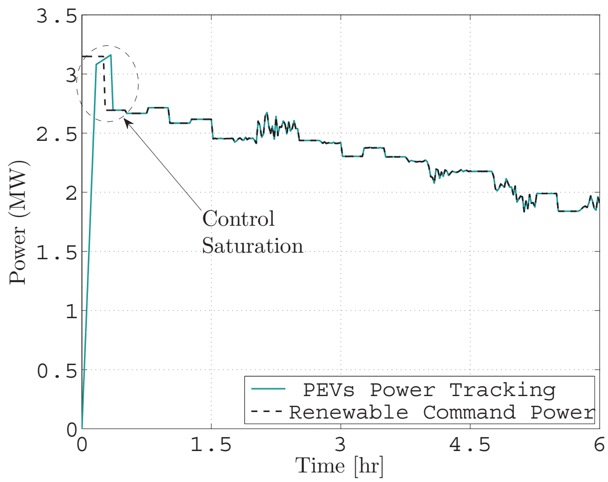

Fig. 3. PEVs power tracking with the inner-loop control

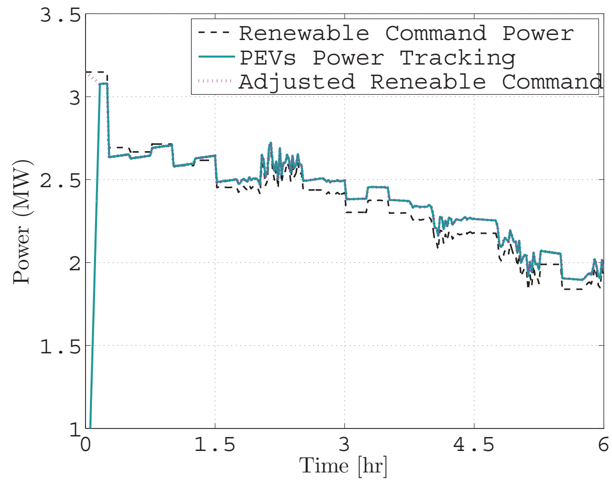

Fig. 5. PEVs power tracking with the nested inner- and outer-loop control

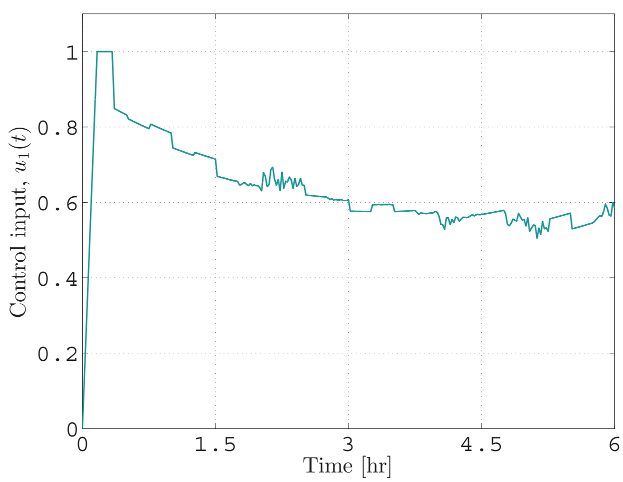

Fig. 4. The control input $u_1(t)$ without the outer loop

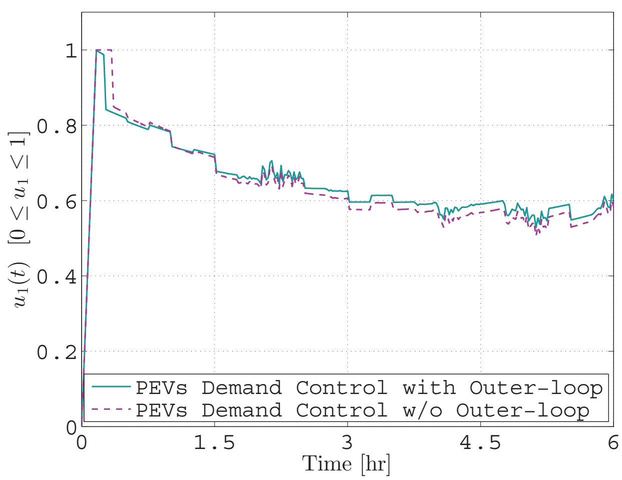

Fig. 6. The control input $u_1(t)$ with and without the outer-loop control

profile. It is shown that during the first hour, the reference power shifts down to reduce the amount of excessive available power. For the rest of the simulation, the adjusted reference power represents an augmented reference power by the outer-loop control output $u_2(t)$, which has been tracked by the inner-loop control strategy. The corresponding control inputs with and without the outer loop have been demonstrated in Fig. 6. It is shown that the reduced reference power (see Fig. 5) leads to a reduction in the control input $u_1(t)$, thus resolving the control saturation problem. However, the term $\bar{P}_{PEV}^{Max}N(t)$ dominates $u_2(t)$ in Eq. (11) and reduces it such that it crosses the zero power (see Fig. 7). Further reduction of $u_2(t)$ results in an increase in $u_1(t)$, thus demanding more power. The increased control input $u_1(t)$ helps to expedite the charging process of PEVs. Physically, this implies that the grid should be maintained with further power to meet the demand.

Although the presented approach reduces the reference

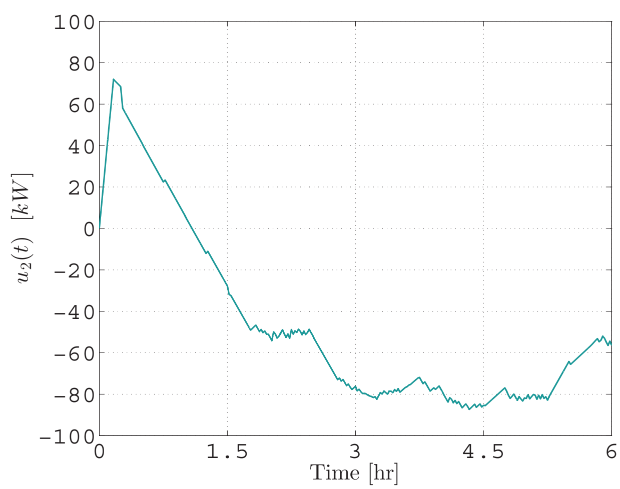

Fig. 7. Outer-loop control $u_2(t)$

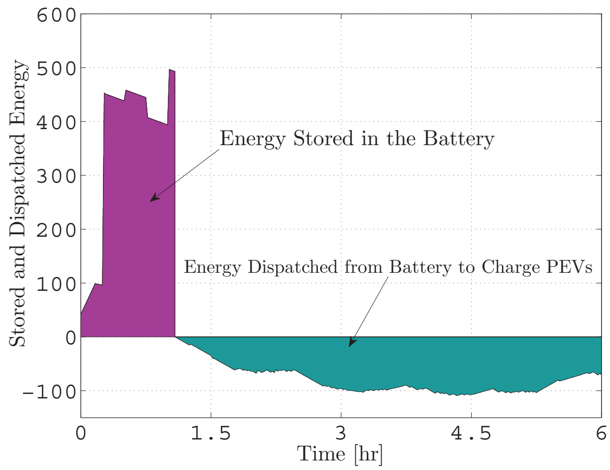

Fig. 8. Stored and dispatched energy from battery for the nested inner- and outer-loop control

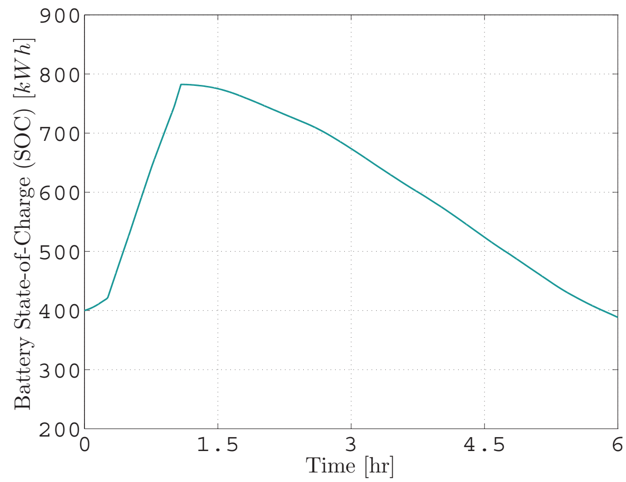

Fig. 9. Battery state-of-charge (SOC) for the nested inner- and outer-loop control

power to avoid the saturation problem, it can provide the grid with further power supply in a way that it stores the deducted power and dispatches it to the grid whenever needed. As outlined in the preceding section, a battery storage device is utilized to capture the excessive power and store it through Eq. (19). Fig. 8 demonstrates the attainable energy to be stored in the battery. During the first hour, the stored energy by the reduction in the reference power through $u_2(t)$ is $390kWh$. For the rest of the process, the stored energy is gradually dispatched to the grid as shown in Fig. 8. Fig. 9 represents the battery state-of-charge for the stored and dispatched power. It has been assumed that the battery has initial energy of $400kWh$ and its capacity varies as $0.3MWh \leq SOC(t) \leq 1MWh$. Furthermore, it has been assumed that the maximum value of the generated power by the renewable energy sources is $P_{Rnew}^{Max}(t) = 3.2MW$. Initially, the battery is charged with the round-trip efficiency of $\eta = 0.8$ and the maximum stored energy in the battery reaches $790kWh$. Then it turns to dispatch the stored energy to the grid when the outer-loop control input becomes negative. It is shown in Fig. 9 that the grid demands $400kWh$ from the battery, which is $10kWh$ higher than the stored energy in the battery within the first hour of operation.

V. Conclusion

A nested feedback control strategy was proposed to provide the grid with adjusted reference power and adapt the aggregate charging power of PEVs. An inner-loop was first considered to address the PEVs power-demand management. The shortcomings of the inner-loop control in dealing with saturation problem was treated by introducing an outer loop, which could reduce the reference power. Such a reduction in the reference input was demonstrated as an efficient method to deal with the saturation problem. The windup drawback, which is an intrinsic characteristics of the designed integral controller due to the zero relative-degree of the system, can lead to a large tracking error when the system sticks to its bounded limits. The proposed approach was shown to be able to track the reference power with no need to anti-windup techniques. Furthermore, it was shown that the reduced power by the outer-loop can be stored in a battery storage device and can be dispatched to the grid whenever needed. The future work involves the use of more sophisticated real-world PEVs charging patterns.

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