VEHICLE-TO-GRID AUTOMATIC LOAD SHARING WITH DRIVER PREFERENCE IN MICRO-GRIDS

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***Abstract*— Integration of Electrical Vehicles (EVs) with power grid not only brings new challenges for load management, but also opportunities for distributed storage and generation. This paper comprehensively models and analyzes distributed Vehicle-to-Grid (V2G) for automatic load sharing with driver preference. In a micro-grid with limited communications, V2G EVs need to decide load sharing based on their own power and voltage profile. A droop based controller taking into account driver preference is proposed in this paper to address the distributed control of EVs. Simulations are designed for three fundamental V2G automatic load sharing scenarios that include all system dynamics of such applications. Simulation results demonstrate that active power sharing is achieved proportionally among V2G EVs with consideration of driver preference. In additional, the results also verify the system stability and reactive power sharing analysis in system modelling, which sheds light on large scale V2G automatic load sharing in more complicated cases.**

***Index Terms*—Automatic load sharing; micro-grid; V2G.**

I. INTRODUCTION

According to Energy Information Agency 2014 report, transportation sector consisted of over 28% of the global oil consumption in 2012 [1]. On the other hand, traditional gasoline vehicles are widely recognized as the primary reason for air pollution and global warming [2]. With arising energy crisis and environmental problems caused by gasoline vehicle, it provides enough incentives for a switch from gasoline vehicles to Electrical Vehicles (EVs).

With the increasing penetration of EV on the market, EVs are considered major loads when drivers charge EVs. Researchers have extensively studied the field of smart charging, charging safety and multiplexing of EVSE over the last decades [3][4]. Many of these studies focused on better manage the EV as distributed load in the power network and extend the maximum potential of the power grid to quickly and safely charge EVs. As power flows from power grid to EV, these studies are named Grid-to-Vehicle (G2V).

Apart from G2V, the integration of EV to power grid demands the power flow in two directions. The G2V's counterpart Vehicle-to-Grid (V2G) allows the power flows from EV to power grid, making EV not only a distributed load but also distributed storage and generation. In addition, V2G has received tremendous attention recently in power system stability by using V2G to supply load in power system [5]-[10]. Kempton et al. has long standing interest on V2G for ancillary services which consists of peak shaving, frequency and voltage regulation. It is shown that the market size of ancillary services is projected to be 12 billion per year in U.S [5]. Wang et al. focused on peak shaving and valley filling with V2G. The authors proximate desired load curve by convex optimizations, taking into account practical constrains of available EVs, State of Charge (SoC) of each EV and etc. [6]. Apart from peak shaving, Wu et al. showed frequency deviation and voltage drops caused by active and reactive power imbalance can be regulated by benefiting the relative fast response of V2G [7]. Han et al. estimated the Available Power Capacity (APC) of V2G for frequency regulation with normal approximation. Aggregator has to acquire mean and covariance of all EVs with statistics data [8]. Similarly, Lam et al. addressed the voltage regulation capacity of V2G using queuing theory. The pattern of EV owner is assumed to be known [9]. Given the fact that EV owners are highly self-interested and have distinct preference, it is of primary importance to create appropriate incentives for them to provide load support. Yao et al. solved this problem by finding the optimal incentives using prior knowledge of statistical distribution of EVs' preference [10].

As discussed above, there exists literature discussing research work to enable V2G for load support from top level control and algorithms. However, all of the high level algorithms, including the ones that use stochastic modeling or convex optimizations, inevitably require centralized controls or global information about the EVs in the network. It is hard for aggregators to build realistic models to accommodate the highly distributed and randomized EV driving pattern. More importantly this easily gives rise to privacy concerns from the

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EV owners [11]. Therefore, for V2G supporting the load, a decentralized approaches is more practical than centralized manners.

This paper proposes and studies an automatic load sharing approach for V2Gs to share the both active and reactive loads among EVs in a distribution network. The above mentioned V2G load support applications need the global information of the power network and EVs. In practice, information of other EVs, such as voltage profile and power, in the same distribution network is not usually available or it is hard to access. Moreover, it is entirely reasonable that the time to collect each EV's information and process Optimal Power Flow (OPF) in a centralized way exceeds the required response time. Thus, it is necessary to have a localized distributed controller that reacts quickly and makes the global load sharing based merely on each EV's information. The contribution of the paper is three-fold: First of all, the load sharing is first time systematically studied for V2Gs. The proposed load sharing takes into account the fact that not only load profile is continuously changing in a distribution network, but also the randomness of the connecting and disconnecting of EVs. Second, the proposed control scheme is analyzed and simulated in a micro-grid for validation. It sheds light on how V2G for automatic load sharing can be done in large scale. It also analyzes the difficulty in controlling reactive power flow in the proposed control algorithm. Third, the proposed controller takes into account driver preference. Drivers are able to adjust maximum V2G power by setting an upper limit.

The remainder of the paper is organized as follows: Section II derives the mathematical model and control strategies. To verify the performance of the control, simulation is carried out and results are analyzed in Section III. Finally, conclusion is drawn and future work is discussed in Section IV.

II. SYSTEM MODELING AND ANALYSIS

In this section, the problem formulation of V2G automatic load sharing in micro-grid is introduced. Then the distributed control algorithm is developed. It is followed by an analysis of system dynamics and active and reactive power sharing. And finally, a load sharing mechanism taking into account driver preference is proposed.

A. V2G Automatic Load Sharing without Control

The study of automatic load sharing with V2G is carried out in a micro-grid with limited communication between vehicles. V2G EVs have only local information and the voltage profiles of other nodes are not known. The target is to achieve load sharing among V2G EVs with limited knowledge of the micro-grid. An analysis of load flow in a micro-grid reveals many of the general principles useful in load sharing for more complicated cases. The studied system is shown in Fig.1. Three V2G EVs are connected to a constant load which has fixed active and reactive power consumption. The EV's DC battery packs are converted to AC with a DC/AC inverter. According to [12], the interface impedance of EV z_i *(i=1,2,3)* is much larger than the line impedance z_{ij} *({(i,j)}= {(1,2),(2,3),(3,4)})*. Therefore, it is reasonable to neglect the line impedance. Each V2G EV is represented as a voltage source with an amplitude V_i, and phase angle θ_i while the load is modeled as a *P+jQ* constant PQ load. The amplitude and phase angle of a V2G EV can be independently adjusted. In this paper we assume the V2G EVs response fast and there are no stator transients [13].

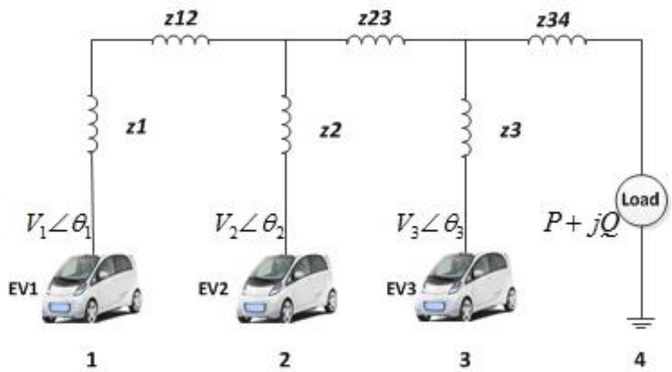

Figure 1. Studied V2G automatic load sharing system

Without any additional control, the load cannot be shared proportionally among V2G EVs. In this study, at first the load is *-3-j1.6 pu*, which is shared evenly among the three EVs. However in reality, the load is not constant. A change in load profile, for example the load is changed to *-4-j2 pu*, the additional load will not be shared proportionally among three EVs if these EVs maintain the same voltage profile. Given the fact that each EV has its own maximum allowable V2G power, it is entirely possible that due to the additional load one of the EVs exceeds its maximum allowable V2G power and causing battery damage and safety hazard. Therefore, it needs a closed loop control algorithm to accommodate the load change as well as generation change in the network.

B. V2G Automatic Load Sharing with Droop Controller

A droop controller for V2G automatic sharing is presented for proportionally sharing the load within one micro-grid. Several droop control algorithms for distributed generation are studied in [13]-[15]. In this paper, a conventional droop controller will be considered first and later a revised algorithm better suit to V2G applications will be presented. The droop controller used in this paper is presented as follows, for active power control:

$$\dot{\delta}_i = -kp_i(P_{mi} - P_i^0) \tag{1}$$

and reactive power control

$$\Delta V_i = -kq_i(Q_{mi} - Q_i^0) \tag{2}$$

for *i = 1,2,3*, where δ_i denotes the phase angle of i^{th} V2G EV, ΔV_i is the voltage difference between the instant voltage and the initial voltage. Control parameters kp_i and kq_i are active and reactive power droop coefficients for the i^{th} EV, respectively. P_i^0 and Q_i^0 represent the reference active power and reactive power. P_{mi} and Q_{mi} are the measured active and reactive power. The controller works like a droop, i.e., when the measured active power is larger than the reference value; it decreases its phase angle.

The sensors for measuring the active and reactive power can be modelled as first order systems; the time-constant of the system models the sensing delay:

$$\frac{P_{mi}(s)}{P_i(s)} = -\frac{\omega_f}{s+\omega_f} \tag{3}$$

and

$$\frac{Q_{mi}(s)}{Q_i(s)} = -\frac{\omega_f}{s+\omega_f} \tag{4}$$

where $P_i(s)$ and $Q_i(s)$ represents the instant active and reactive power of i^{th} V2G EV and ω_f is the time constant.

C. System Dynamicsof the Micro-grid

The power flow of each bus shown in Fig.1 can be expressed as follows:

$$P_i = \sum_{j=1}^{4} V_i V_j (G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}) \tag{5}$$

$$Q_i = \sum_{j=1}^{4} V_i V_j (G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) \tag{6}$$

for $i=1,2,3,4$, where $\delta_{ij} = \delta_i - \delta_j$, and G_{ij} and B_{ij} can be extracted from admittance matrix.

Following controller described in (1) and (2) and the sensor dynamics in (3) and (4), the dynamics of the system is described as follows:

$$\dot{\delta}_i = -kp_i \Delta P_{mi} \tag{7}$$

$$\Delta \dot{P}_{mi} = -\omega_f (\Delta P_{mi} - \Delta P_i) \tag{8}$$

$$\Delta \dot{Q}_{mi} = -\omega_f (\Delta Q_{mi} - \Delta Q_i) \tag{9}$$

$i = 1,2,3$, where

$$\Delta P_i = \sum_{j=1}^{4} \Delta P^0_{i\delta_j} \Delta\delta_j \tag{10}$$

$$\Delta Q_i = \sum_{j=1}^{4} \Delta Q^0_{i\delta_j} \Delta\delta_j \tag{11}$$

and $\Delta P_{mi} = P_{mi} - P_i^0$, $\Delta Q_{mi} = Q_{mi} - Q_i^0$, $\Delta P^0_{i\delta_j}$ and $\Delta Q^0_{i\delta_j}$ can be obtained from (5) and (6) with partial differentials around equilibrium points:

$$\Delta P^0_{i\delta_j} = \left.\frac{\partial P_i}{\partial \delta_j}\right|_{P_i^0} \text{ and } \Delta Q^0_{i\delta_j} = \left.\frac{\partial Q_i}{\partial \delta_j}\right|_{Q_i^0} \tag{12}$$

Expressions for (12) can be obtained from (5) and (6). The dynamics of the system is linearized with (12) and can be modeled with the above differential equations.

D. Active and Reactive Power Sharing with V2G

For active power, the system will reach a steady state, when the following equations hold:

$$\dot{\delta}_1 = \dot{\delta}_2 = \dot{\delta}_3 \tag{13}$$

The system will falls into steady state when the changing rates of δ_i are the same. In steady state, $P_{mi}=P_i$. Therefore, the active power of the micro-grid is shared proportionally as follows:

$$kp_1(P_1 - P_1^0) = kp_2(P_2 - P_2^0) = kp_3(P_3 - P_3^0) \tag{14}$$

On the other hand, reactive power sharing is a much complicated problem that requires further discussion. In the following analysis, it is assumed that the micro-grid has a low R/X ration and we assume there is no sensor delay in (4). Then (6) can be rewrite as:

$$Q_i = -V_i V_4 B_{i4} cos\delta_{i4} - V_i^2 B_{ii} \tag{15}$$

for $i=1,2,3$, where $B_{i4}=-B_{ii}$. Supposedly there is a change in node 4. For simplicity without losing generality, the relative angles δ_{i4} stay exactly the same in active power steady state. Then (15) can be reformulated as:

$$\Delta Q_i = kq_i \Delta Q_i V_4 B_{i4}\cos\delta_{i4} - V_i \Delta V_4 B_{i4} cos\delta_{i4} - 2kq_i \Delta Q_i V_i B_{i4} \tag{16}$$

Following (16), the reactive power is shared as follows:

$$\frac{\Delta Q_i}{\Delta Q_j} = \frac{V_i kq_j \cos\delta_{i4}(V_4 B_{j4}\cos\delta_{j4} - 2V_j)}{V_j kq_i \cos\delta_{j4}(V_4 B_{i4}\cos\delta_{i4} - 2V_i)} \tag{17}$$

for $i,j = 1,2,3$. It is clearly shown that the reactive power sharing is highly coupled. The proportion depends on a number of parameters besides the reactive power sharing coefficients.

E. V2G Automatic Load Sharing with Driver Preference

From the previous derivation and analysis, it is shown though reactive power cannot be easily shared among V2G EVs, active power is shared proportionally. Inspired by this fact, this paper proposes a droop based active power sharing with driver preference. The driver of each EV is able to choose an upper limit that prevents active power shared beyond the limit. It corresponds to different maximum V2G power allowed for different EV models in practice. The controller is described as follows:

$$\begin{cases} \dot{\delta}_i = -kp_i(P_{mi} - P_i^0) & P_i^l \succ P_{mi} \\ \dot{\delta}_i = -kp_i(1 + P_{mi} - P_i^l)(P_{mi} - P_i^0) & P_i^l \le P_{mi} \end{cases} \tag{18}$$

where P_i^l is the maximum allowable active power sharing for i^{th} EV. The active load sharing works as conventional droop controller when the measured power does not exceed the maximum allowable power. However, when the measured power exceeds the limit, the local droop based controller dynamically adjusts its sharing coefficient based on the feedback of how much power it exceeds the limit. The more V2G power it exceeds its limit, the faster its active power sharing coefficient increases, consequently the lower active power the EV is sharing. It is noted that there is a possibility when the supply of the grid cannot meets its demand, which may result in oscillation of the micro-grid. It will be discussed in the following section.

III. Simulation Results and Analysis

Based on the analysis of the previous section, this section simulates three practical scenarios of using V2G for automatic load sharing, including a case when an EV is connected to the network with constant load, a case when EVs are connected but load changes and a case when load stays the same while an EV is disconnected from the network. All other application scenarios of V2G automatic load sharing in micro-grid level is a combination of these three fundamental scenarios. Thus, it is important to understand these three fundamental application scenarios.

A. V2G Load Sharing with Additional EV Be Connected

In the first simulation, a fundamental V2G automatic load sharing scenario is studied. Following the topology described in Fig.1, originally EV1 and EV2 are connected to a constant PQ load and reach a steady state. Then EV3 is connected to the original network while the load stays constant. The target of this simulation is to verify the controller as well as study its dynamic behavior and stability. The system parameters of the micro-grid are specified in Table I. The micro-grid is modelled as a lossy network with a low *R/X* ration.

TABLE I. System Description of The Micro-Grid

Parameter	Value
kp	*[0.1 0.3 0.2]*
kq	*[0.001 0.003 0.002]*
z1 (pu)	*0.01+j0.05*
z2 (pu)	*0.01+j0.10*
z3 (pu)	*0.005+j0.15*
load *(pu)*	*-3-j1.6*
ω_f *(rad/s)*	*10*

Fig.2 shows the automatic load sharing of the described scenario. EV3 is not connected to the micro-grid at first with both active and reactive power at *0pu*. The load is shared by EV1 and EV2. At *t=1s*, EV3 is connected to the original network and additional generation is introduced to the micro-grid. Active and reactive power of the load is shared by EV3. Thus, P1 and P2 drops while P3 increase. It is noted that the reference active power used in this simulation for EV3 is *2pu*. As shown in the figure, $\Delta P_1=1.10pu$, $\Delta P_2=0.37pu$, $\Delta P_3=0.56pu$ and $kp_1\Delta P_1= kp_2\Delta P_2=kp_3\Delta P_3$ within acceptable errors. The errors result from two major reasons: first, the sensing delay of sensors; and second, the micro-grid studied in this simulation is not a non-lossy network. Some shared active power is compensated in the lossy network.

On the other hand, reactive power sharing is much more complicated. It is observed that $\Delta Q_1=0.13pu$, $\Delta Q_2=0.37pu$, $\Delta Q_3=0.02pu$. As shown in the Fig.2, reactive power sharing has oscillations at each EV. This is expected, as shown in (16), $\cos\delta_{i4}$ does not equal to a constant number before it reaches steady state. As presented in (17), the reactive power sharing is related to a number of factors besides the reactive sharing coefficients, not to mention (17) is a simplification for non-lossy networks. To the best of authors' knowledge, compared to active power sharing, the problem of reactive power sharing has not yet reached a universal and decent solution [12]-[16]. More efforts are needed to understand the reactive power flow and resonance in power network.

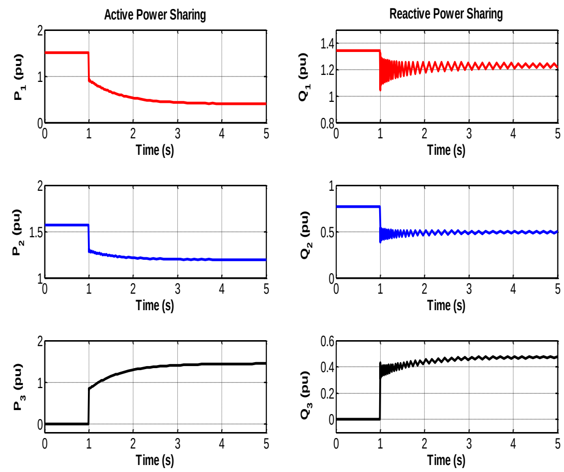

Figure 2. Automatic load sharing with V2G when an EV is connected to the original micro-grid

Fig.3 presents the phase angle and voltage amplitude change over time of the studied scenario. As indicated in the figure starting from 1s, EV3 is connected to the network, which introduces dynamic response to the system. The phase angle differences δ_i-δ_j $(i\neq j,\ i,j=1,2,3)$ stay the same after the changing rates δ_i $(i=1,2,3)$ are synchronized. It is shown in Fig.3 that after *3s*, the three curves of phase angle are almost parallel. It matches Fig.2 which shows a steady state of active power sharing has reached after *3s*. It also verifies the stability analysis in (13) and (14).

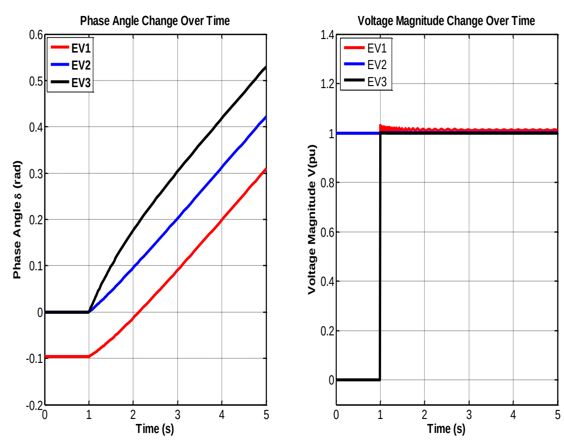

Figure 3. Phase angle and voltage amplitude change over time of automatic load sharing with V2G

B. V2G Load Sharing with Load Change and Driver Preference

Apart from studying how an EV connection introduces dynamics to the micro-grid level V2G load sharing, it is essential to understand how power is shared when there are no EV connections and disconnections dynamics, but rather a load change in micro-grid. A simulation is run with EV1, EV2 and EV3 connected to the micro-grid supporting load through V2G. Load change both in active and reactive then happens and V2G EVs react to this change. This simulation shows how driver preference affects automatic load sharing in micro-grid.

As for preference, it corresponds to the upper limit of V2G active power for each EV, i.e. P_i^l, mentioned in (18). In this simulation, a case which one of the EVs has a lower allowable V2G power is simulated: $P_1^l=1.5pu$, $P_2^l=P_3^l=2.5pu$. This is a reasonable assumption because in practice, different EV models allow different maximum V2G power.

Fig.4 presents the simulation results of load change with driver preference in solid line and without driver preference with dash line for 3 V2G EVs. At first, EV1, EV2 and EV3 are sharing active and reactive power at steady state. At $t=1s$, the load changes from $-3\text{-}j1.6pu$ to $-5\text{-}j2pu$. The additional load will be shared among three V2G capable EVs. As shown in the figure, after the load increases, EV1's active power sharing increases to $2pu$ which exceeds its maximum allowed V2G active power. The controller in (18) detects the overflow, and then dynamically decreases EV1's active power sharing according to the feedback of how much it exceeds the limit. As shown in Fig.4, the active power sharing of EV1 is constrained to $1.5pu$ versus if sharing $2.1pu$ if no driver preference is implemented. The observed delay time before P_1 decreases from $2pu$ is due to sensing delay. An overshoot is observed at $t=1.3s$, which is desired: in practice, power electronics can only sustain overcurrent for a short time. Thus, an under-damped system with overshoot decreases its time working in overcurrent operations.

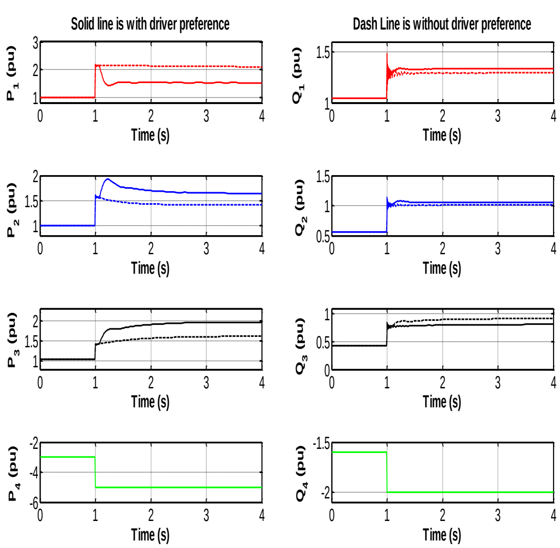

Figure 4. Automatic load sharing with V2G when load changes

It is noted that there is a possibility when the three EVs' maximum allowed V2G active power combined cannot meet the demand of the load. In that case, the droop based driver preference controller can never reach a steady state. However, this is something not expected as automatic load sharing only make sense when generation meets the demand. Fig.4 also presents the reactive power sharing under driver preference. Though the driver preference controller is implemented for active power sharing, it slightly affects relative power sharing. This is expected, because (17) shows reactive power sharing is related to δ_{i4} which is affected by active power sharing.

C. V2G Load Sharing with EV Be Disconnected

In the end, it is necessary to study how EV's disconnection affects the power sharing of connected EVs while the load stays constant. Combined with the previous two simulations, it accounts for all fundamental V2G automatic load sharing dynamics in a micro-grid.

During this simulation, the load is constant. As shown in Fig.5, at first, three EVs are sharing active and reactive power through V2G at steady state. At $t=1s$, EV3 is disconnected to the micro-grid. It is observed that $\Delta P_1=-0.79pu$, $\Delta P_2=-0.28pu$, which correspond to the active power sharing control $kp_1\Delta P_1= kp_2\Delta P_2$. It is also observed $\Delta Q_1=-0.17pu$, $\Delta Q_2=-0.31pu$. Similar to analysis in the previous section, the reactive power is not shared according to reactive power sharing coefficient. This simulation also shows that even for a simple case when only load is shared between two V2G EVs, reactive power sharing is hard to control. It needs more effort before researchers can proportionally share reactive power as its counterpart.

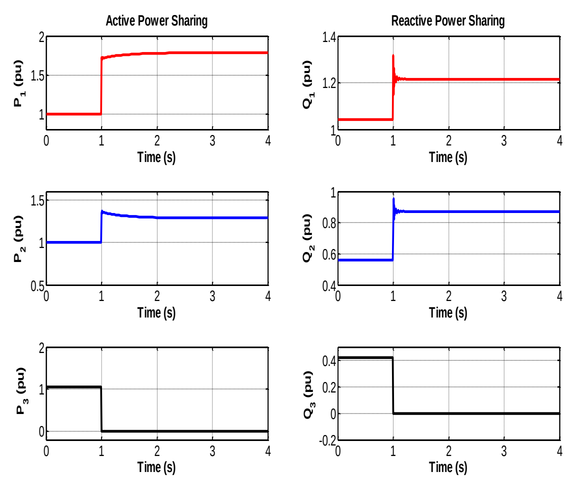

Figure 5. Automatic load sharing with V2G when an EV is disconnected to the network

IV. CONCLUSIONS

This paper presents a droop based automatic load sharing with driver preference using V2G capable EVs in a micro-grid. Unlike conventional centralized control methods, this paper studies a scenario when communication is limited, and V2G EVs have to adjust active and reactive power sharing based on their own information. A micro-grid with connected EVs is modeled as a lossy network with low *R/X* ration without loss of generality. The power flow and load sharing among EVs are carefully analyzed with reasonable simplifications. A droop based controller taking into account driver preference is proposed in this paper. It limits the V2G active power sharing to the driver's preset maximum value, which models the maximum allowable V2G power in practice. Stability of the controller is studied to understand the robustness of the studied system. The analysis of the active and reactive power sharing in a micro-grid level sheds light on large scale V2G load sharing in distribution networks. Three practical application scenarios of V2G load sharing are simulated, which include a case when an EV is connected to the micro-grid with constant load, a case when load changes while EVs are connected and a case when an EV disconnects to the micro-grid with constant load. All other application scenarios of V2G automatic load sharing in micro-grid level is a combination of these three fundamental scenarios. Simulation results show that the proposed controller constrained the active power sharing to the EV driver's preference. Simulation results also demonstrate the stability of the system and proportional active power sharing among V2G EVs. However, reactive power cannot be shared proportionally as active power, due to the fact that it is highly coupled. More efforts on understanding and decoupling the reactive power sharing are needed in the future.

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