Battery Status Sensing Software-Defined Multicast for V2G Regulation in Smart Grid

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***Abstract*— During the bidirectional exchange of electricity between electric vehicles (EVs) and smart grid, plenty of sensors have been deployed to sense the EVs' battery status and monitor the electricity regulation requirements. When electricity consumption at power grid demand-side sharply increases/decreases, charging points (CPs) access these sensors by multicast technology to aggregate the EVs' battery status, publish electricity regulation requests and assign the state of charge (SOC) transition instructs in vehicle-to-grid (V2G). However, intermittent connections arising from distributed and mobile energy storage bring many challenging problems on multicast scheduling. First, in smart grid, peak shaving and load shifting require V2G to sense and regulate the EVs' SOC according to their battery status precisely, while the traditional multicast only considers their mutable network locations (e.g., WLAN, IP, and MAC). Second, as the number of EVs that participate into V2G increases, V2G needs to schedule the massive multicast traffic with priority to satisfy the dynamic and real-time regulation requirements. To address these problems, in this paper, we first aim to demonstrate that the appreciable battery status is more adaptive than network location to act as a multicast primitive in V2G. We propose a battery status sensing software-defined multicast (BSS-SDM) scheme to reduce the latency of V2G regulation services. In the BSS-SDM scheme, the battery status of each EV is identified during SOC transitions and maintained by a centralized controller. Besides, we propose a battery-status-based multicast scheduling algorithm to implement the V2G regulation optimization. Simulation results verify the effectiveness of proposed schemes.**

***Index Terms*— Smart grid, battery status, vehicle-to-grid (V2G), state of charge (SOC), software-defined multicast.**

I. INTRODUCTION

SMART grid has been recently developed to accommodate distributed energy to support the intermittent services [1]. Considering that most of the EVs are parked during average 95% of the time in a day, vehicle-to-grid (V2G) is presented to deliver the distributed energy stored in battery packs back to the smart grid. Key features of V2G include two-way energy flow, general storage re-planning, and active energy distribution [2], [3]. These characteristics are appealing to the future smart grid, with application to smart homes [4], [5], buildings [6] and transportation [7], where various electricity consuming devices are increasingly mobile, intermittently connected and/or in sleep mode. Many works are underway to deploy smart sensors to sense the battery status of distributed EVs [8] and the electricity regulation requirements [9].

In V2G, efficient communication among these sensors also plays a critical role especially in the state of charge (SOC) regulation. The IEC 61850 standard is originally formulated to improve the efficiency of interoperability between various intelligent electric devices (IEDs) in substation networks [10] and it decouples service models from the underlying communication infrastructures. By abstracting the EVs as distributed storage devices, IEC 61850-7-420 has been extended to accommodate V2G technology [11], [12]. In IEC 61850 advanced V2G networks, sensors reporting the sensed battery status, actuators subscribing the SOC regulation instructs and CPs publishing regulation demands are in terms of network location based multicast. The network location based multicast maps electricity aggregation into EVs searching. This mapping complicates the configuration of sensors and presents limitations to cope with the intermittent of V2G.

In an intermittent V2G network, the CPs usually need to run multicast operations to publish the regulation requests to the plugged EVs and then regulate their states of charge (SOC) simultaneously, once the consumers' energy consumption sharply increases/decreases. Considering these CPs' operations concern more about EVs' battery-status, many existing works have shifted to estimate the SOC of each EV [13] and map consumers' power demands into SOC regulation requests [14], respectively. However, an equally important problem to achieve optimal multicast scheduling for regulation requests transmitting under the circumstance of intermittent connections has not yet been studied. Lack of this optimal multicast scheduling will result in many challenges on V2G regulation services.

Fig. 1 shows the process of traditional multicast for power regulation in the IEC 61850 advanced V2G networks. To have a close look at the novel challenging problems of multicast scheduling, we consider a V2G network with n CPs and m_i EVs in i-th CP, where $1 \leq i \leq n$. And also, for a determinate i, there is $1 \leq j \leq m_i$. The $\Phi\ (t)$ is an

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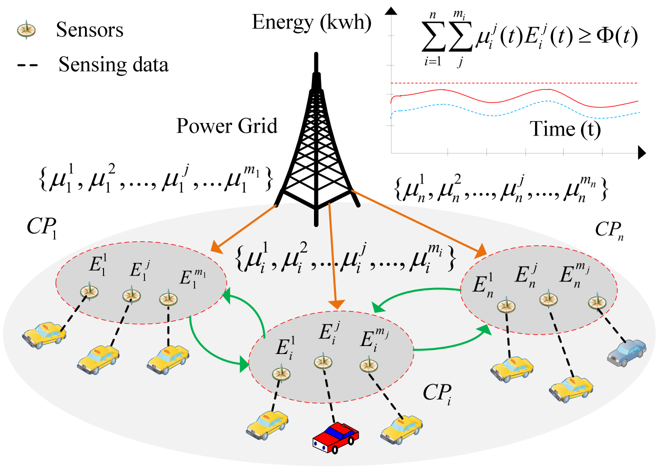

Fig. 1. The process of traditional multicast for power regulation in IEC 61850 based V2G network.

energy demand function and $\sum_{i=1}^{n}\sum_{j=1}^{m_i}\mu_i^j(t)E_i^j(t)$ represents for the real total energy that V2G can supply. $E_i^j(t)$ denotes the available energy in each EV and $\mu_i^j(t)$ represents a discharged percentage of the EV. The V2G regulation is achieved by regulating this $\mu_i^j(t)$. To aggregate electricity and satisfy the requirements of $\Phi(t)$, power grid retrieves the battery status and SOC of each EV by establishing communication links with all EVs, and then binds the identified battery status and SOC with its network location. When the electricity consumption increases/decreases, sensors at power grid demand-side publish electricity requests to the re-planning network locations for retrieving available EVs that can discharge electricity into the power grid. However, trust in location is easily misplaced due to the ephemeral SOC and high mobility of EVs in V2G networks. Moreover, traffic scale of network location based multicast is correlated positively to the EVs number, thus when it needs to aggregate a number of EVs to satisfy the requirements of power grid, congested communication may bring a bad V2G regulation. Besides, if the network location has changed, the whole network will be full of repetitive addressing traffic.

To address these identified challenging problems, we propose a battery status sensing software-defined multicast (BSS-SDM) scheme. The main contributions in this paper are as follows.

1) We identify that the network location based multicast in intermittent V2G network presents low-efficient performances. We demonstrate that the appreciable SOC is more adaptive than location to achieve optimal communication performance in IEC 61850 advanced V2G.
2) We propose a software-defined multicast scheme. A centralized controller is designated to monitor and control the sensors on plugged EVs to support mobility and dynamic configuration.
3) A light-weight V2G regulation scheduling algorithm is presented to improve the average delay time costs of V2G operations. Based on this, simulation experiment is also designated.

The rest of this paper is organized as follows. In Section II, related works are introduced. Section III describes the basic network architecture of state of charge-aware software-defined V2G. Section IV describes the system model, and the stochastic multicast optimization algorithm is presented in Section V. Performances comparisons are demonstrated in Section VI. Finally, Section VII draws a conclusion.

II. RELATED WORKS

Three aspects are analyzed to bring out the meanings and motivations of our works, including promising communication standards for future smart grid, existing efforts on efficient V2G regulation and novel challenges of multicast in V2G.

A series of studies and standards have been presented to improve the capability of interconnection and interoperability between smart grid infrastructures [15]. Towards these issues on interconnection and interoperability, establishing a high-efficient communication network has been perceived as a must. Meanwhile, several communication models have been proposed to satisfy various requirements under different application scenarios, including IEC 61850 for substations, DNP 3.0 for remote monitoring, IEC 61968 for distributions and IEC 62351 for information security, etc [16], [17]. In existing models, multicast technology plays an important role in data retrieval and distribution.

The V2G exploits multicast to aggregate data about surplus energy in EVs and publishes energy demands of smart grid [19]. Many advanced technologies have been applied to V2G networks. Santoshkumar *et al.* [21] proposed a Long Term Evolution (LTE) protocol for EV to EV communication to facilitate the participation of EVs in power transmission. George *et al.* [22] proposed to utilize WiMAX for connecting electric vehicles to the power grid. In [8], an IEC 61850-7-420 based information model for the charge/discharge controller of EV is proposed and it demonstrates that EVs can support better operation of smart grids in terms of reliability and storage. As one of our previous work, software-defined networking based communications and security in vehicle-to-grid is proposed in [23]. Yamei *et al.* [24] presented a comprehensive analysis of the impact of mobility on the end-to-end delay and throughput in V2G communication. Meanwhile, longhua *et al.* [25] proposed a security mechanism for data exchanging between sensors and applications based on IEEE 21451.

The aforementioned studies mainly focus on building communication links between sensors in EVs and CPs. Thereinto, IEC 61850 treats the EVs as distributed storage devices and constructs hierarchical logic devices and logic nodes for the involved battery management functions. IEC 61850 also decouples charging/discharging services from the underlying communication infrastructures. These unique characteristics make IEC 61850 gain increasing popularity in V2G networks [27], [28].

However, there are only few studies that focus on optimizing the V2G multicast models to support the imperative V2G regulation. Recently, as the number of EVs increases sharply, aggregating static EVs into power grid has been perceived to have capability to facilitate the demand response in smart grid because their battery packs, as a form of flexible electricity storage, can be controlled to consume electricity from or feed energy back to the grid depending on user' requirements [17]. To improve the efficiency of energy exchanging control, large accounts of sensors and actuators has been deployed to sense and estimate the battery status of each EV. Paul *et al.* [20] claimed that the intelligent management of connected EVs with ITSs and smart grid requires a more efficient multicast, which can support more efficient data exchange in V2G. Moreover, Daniele *et al.* [18] proposed a procedure to identify the values of the battery parameters in a real-time smart grid management system. Besides, battery status based security protection and privacy preservation during the process of charging/ discharging in V2G networks was also studied in [26].

It can be observed that people increasingly concern more about the battery status and SOC of EVs but less about EV's network location during the charging/discharging process, while establishing communication link still closely relies on the network location based multicast. As a consequence, optimizing costs of multicast to satisfy distinctive V2G regulation requirements given $E_i^j(t)$ and $\Phi\ (t)$ has evolved into a novel challenging problem in V2G. Golla *et al.* [29] focused on the costs reduction of multicast in mobile ad hoc circumstance, improving network lifetime and throughput. Moreover, the security mechanism for multicast in sensor networks were also studied in [30].

It is rather distinct that we propose to directly exploit the battery status to make multicast strategy in this paper. Replacing network location with battery status makes it possible for smart grid to monitor and control the distributed mobile EV energy. The simulation results showed the proposed battery status sensing software-defined multicast (BSS-SDM) scheme can mitigate the demand curve's fluctuation of smart grid and reduce the average delay time cost of V2G operations.

III. Basic Network Architecture

For V2G operators, the EVs are treated as mobile and distributed energy storage devices. To support the intermittent of EVs' connection, the power grid should monitor and control the battery status of each EV in real time. In current vehicle network, the battery status of each EV is only maintained by controller area network (CAN) of the on-board battery management system. The SNMP is an important protocol for various CAN applications (e.g. drive recorder, vehicle network states monitoring and remote wake-up). SNMP also can be exploited to aggregate battery status in real time. In each vehicle, it may have a MIB to cache the battery status a client to upload these energy data. In power grid, it will be deployed a centralized SNMP server. For each client, it will be configured a network location. When power grid requires to schedule the EV's charging, the SNMP server aggregates battery status from distributed clients. It can be found that battery status-awareness in SNMP occurs during the conversation between client and server. In this paper, we focus on the interaction among the EVs, power grid and users but not only intra-CAN. With proposed software-defined multicast scheme, battery status-awareness occurs before the conversation between client and server starts.

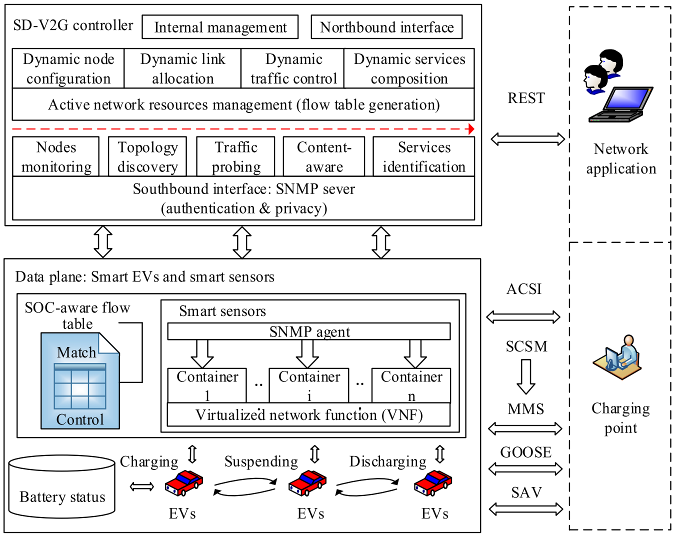

Fig. 2. The battery status sensing software-defined V2G architecture.

The basic network architecture of BSS-SDM scheme, which includes three main entries: smart EVs, SD-V2G controller and network application, is illustrated as shown in Fig. 2. A smart EV with many smart sensors/actuators (such as breakers, dynamometers and voltage/current transformers) is treated as distributed storage device and configured by IEC 61850. It is rather distinct that network functions of smart sensors/ actuators are virtualized and the smart EV will maintain a special SOC-aware flow table. The SD-V2G controller is authorized by CP operators to monitor and control the distributed sensors in data plane. Network application as a critical component of station center belongs to an independent institution.

In this architecture, the EVs access to power grid for charging and the power grid retrieves EVs for discharging, dominated by the SD-V2G controller. During the energy delivery, SD-V2G controller directly communicates with data plane devices. In data plane, distributed devices includes smart sensors, smart EVs, smart meters, RSUs, routers, etc. The communication between SD-V2G controller and data plane devices is driven by southbound interface. It is noteworthy that the southbound interface is not limited to a specific communication model. It can use traditional network management protocols.

In this paper, we specify the simple network management protocol (SNMP) as southbound interface, which is originally deployed in almost all network elements. Additionally, the SNMP v3 considers the security issue of data transmission, supporting role based access control (RBAC), secure sockets layer (SSL) based authentication and privacy. Towards the interface between network application and SD-V2G controller, representational state transfer (REST) principle inherited from software-defined networking (SDN) is utilized. The SDN is a critical networking infrastructure for integration electric vehicles into smart grid [31]. And also, one of our previous work improved the SDN capability to support application-awareness, which can be utilized to recognize the SOC from multicast traffic [32]. On the basis of this, the main components of proposed scheme in this paper are described in detail as follows.

A. SOC-Aware Flow Table

The SOC-aware flow table is generated by SD-V2G controller and executed in data plane devices. Structure of SOC-aware flow table mainly consists of 1) ***SOC matching*** domain and 2) ***multicast control*** domain. The appreciable SOC is considered to encapsulate all data packets, replacing network location. Thus, when a data packet arrives data plane device, the data plane device matches packet header with the ***SOC matching*** domain. If matched, it will be forwarded according to the corresponding policy defined in ***multicast control*** domain. Otherwise, it will be sent into the SD-V2G controller.

B. Virtualized SOC Monitoring

The data plane devices are advocated to deploy virtualized network functions to monitor and control the battery states and state transitions. Each virtualized state monitoring container is assigned for one battery state or state transition. Additionally, all containers need to support SNMP services. Different from traditional SNMP usage, SD-V2G controller treats the SNMP as a southbound interface for communicating with heterogeneous data plane devices. Meanwhile, the processing of SOC-aware flow table is also in these virtualized containers.

C. SD-V2G Controller

The SD-V2G controller has five basic functions: 1) node monitoring, 2) topology discover, 3) traffic probing 4) content-aware and 5) services identification. Correspondingly, there are five promising network services can be provided for operators: 1) dynamic node configuration, 2) dynamic link allocation, 3) dynamic traffic control, 4) dynamic services composition and 5) internal management. SD-V2G controller has ability to gain the whole energy distribution view of the V2G networks based on SOC-aware battery status identification.

IV. SOC TRANSITIONS AND BATTERY STATUS SENSING

Due to the large-scale deployment of EVs, the requirements for centralized battery data collection, storage, analysis and utilization make EVs closely cooperative with power grid and users. During the interaction among EVs, power grid and users, the mobility of EVs makes the power distribution dynamic and the changes of users' travel plans are closely constrained by the SOC. In such dynamic circumstance, network traffic increases and the network performance goes down sharply. The design goal of proposed multicast scheme is to simplify the process of handshake connection between EV and power grid as well as EV and users.

Usually, a fast V2G regulation response closely relies on the battery status sensing. We construct the battery status based network topology, replacing the location based network topology. The battery status based network topology is constructed according to the SOC transitions. The process of our constructing the battery status based network topology can be categorized into three SOC transition instructs generated by EV owner, smart EV and power grid, respectively. The SOC transition instructs contain charging, discharging and suspending as introduced in advance.

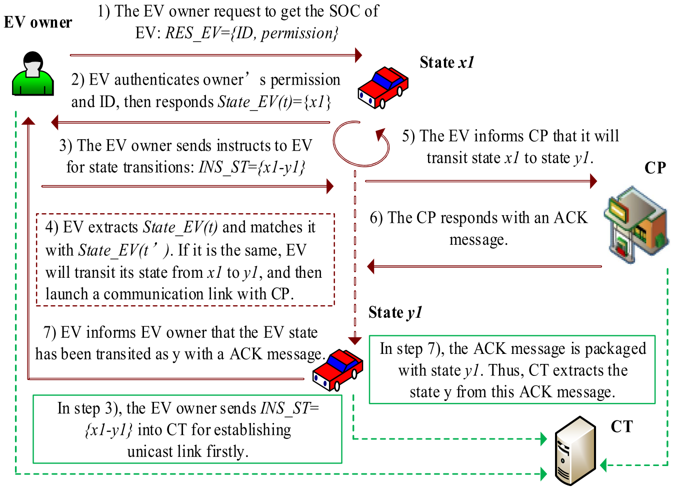

Fig. 3. The battery status sensing during SOC transition launched by EV owner.

A. Sensing Battery Status

We use the notation INS_ST to denote SOC transition instructs generated by EV owner and $State\_EV(t)$ to denote the battery status at t. $\{x1, y1\}$ are a pair of variants to note the battery status and $\{x1 - y1\}$ represents the SOC transition from $x1$ to $y1$.

Fig. 3 shows the whole process of battery status sensing when EV owner launches the SOC transition actively in IEC 61850 based V2G network. The process battery status sensing mainly contains the following main steps. 1) The EV owner requests to get the battery status of EVs by publishing $RES\_EV = \{ID, permission\}$. 2) When the EV receives the requests, they begin to authenticate the permission and decide if it should be responded. 3) If the EV owner obtains the reply, it will send SOC transition instructs to EV for state transitions. 4) When EVs receive the instructs, these instructs are matched with EV's battery status, and the EVs decide if their SOC should be transited. When $INS\_ST = \{x1 - y1\}$ and ACK messages enter into the network for the first time, they will be sent into CT for achieving optimal unicast policy because there is no corresponding SOC-aware flow table at EV. By monitoring this two steps of the communication conversation between EV owner and EV, CT can extract $x1$ and $y1$ from INS_ST and verify that they are valid. With these extracted SOC, a battery status based topology can be reconstructed by the CT partially.

B. Smart EV's Auto-Transitions

When smart EV is full-charged or discharged lower than the minimum threshold capacity, the SOC will be transited

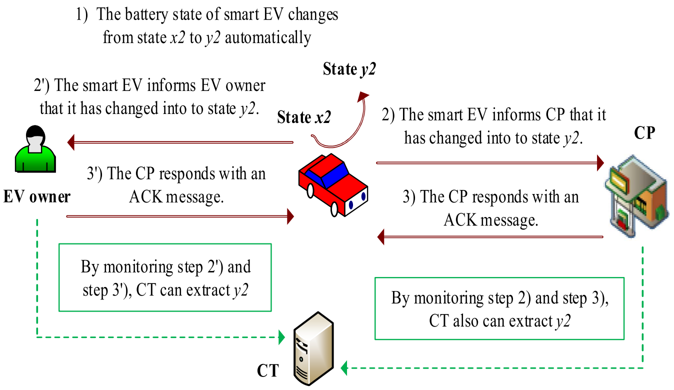

Fig. 4. The battery status sensing during SOC transition launched by smart EV.

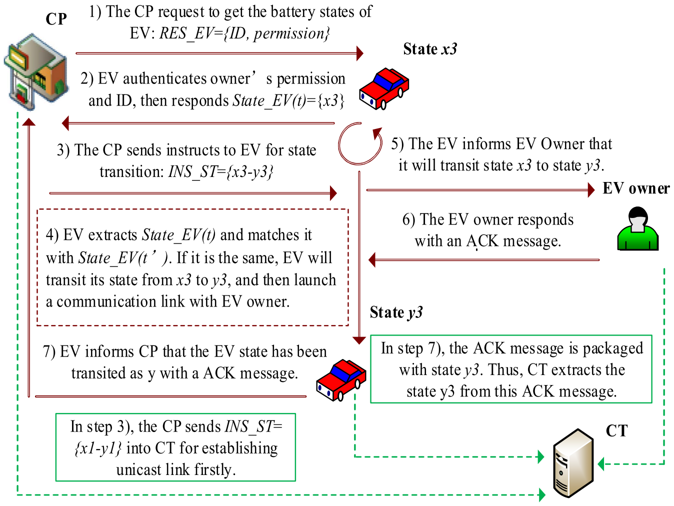

Fig. 5. The battery status sensing during SOC transition launched by power grid.

automatically. By monitoring the communication conversation of this auto-transition, the CT also can gain the SOC of involved EVs in real time. Fig. 4 shows the process of battery status sensing when smart EVs launch SOC transaction in IEC 61850 advanced V2G networks automatically.

The $\{x2, y2\}$ is a pair of variants to denote the two kinds of battery status. Both EV owner and CP should be informed the change of battery status. When $y2$ and ACK message enter into the network for the first time, they will be sent into CT for achieving optimal unicast policy because there is no corresponding SOC-aware flow table at smart EV. By monitoring this two steps of the conversation between EV owner and EV as well as EV and CP. CT can extract $y2$ and verify that it are valid. With these extracted $y2$, another partial topology can be reconstructed by the CT in real time.

C. Power Grid to EV

Fig. 5 shows the process of battery status sensing when power grid launches SOC transaction in IEC 61850 advanced V2G networks. The CP is treated as a minimum unit on behalf of the power grid. We use the notation INS_ST to denote SOC transition instructs generated by power grid and $State\_EV(t)$ to denote the battery status at t. When the difference between energy supplying and energy demands in power grid appears, CPs publish INS_ST for energy control. $\{x3, y3\}$ are a pair of variants to note the battery status and $\{x3 - y3\}$ represents the SOC transition from $x3$ to $y3$. The SOC transition process mainly contains the following seven steps shown as illustrated in Fig. 5. When $INS\_ST = \{x3 - y3\}$ and ACK message enter into the network for the first time, they will be sent into CT for achieving optimal multicast policy because there is no corresponding SOC-aware flow table at smart EV. By monitoring this two steps of the communication conversation between CP and EV, CT can extract $x3$ and $y3$ from INS_ST and verify that they are valid. With these extracted SOC, CT also can construct the other portion of battery status based network topology.

During the above process of SOC transitions and battery status sensing, the multicast technology is rather important and it is responsible for collecting source data from sensors and distributing all instructs into sensors and/or actuators. The use of sensors and actuators data makes power grid reconstruct a battery status based mobile energy network topology.

In this paper, the battery status based mobile energy network topology are maintained by the centralized controller of CT. With the given battery status based mobile energy network topology, we present a battery status sensing software-defined multicast (BSS-SDM) scheme to improve the V2G regulation performance.

V. PROPOSED BSS-SDM SCHEME

We consider a BSS-SDM scheme with **charging** domain, **suspending** domain and **discharging** domain. Communication for V2G regulation is categorized into state transitions. At first, we will give an overview about the difference between proposed BSS-SDM and traditional location based multicast scheme in V2G. And then, we bring out the benefits of proposed scheme by mapping the V2G regulation problem into multicast scheduling. Finally, we propose a light-weight V2G regulation algorithm to achieve optimal policy.

A. System Model

As illustrated in Fig. 6, let $(x - y, U_x)$ denote the structure of INS_ST, where $x, y \in \{C, D, S\}$.

Thereinto, C is charging, D is discharging and S is suspending) and $U_x \in \{U_c, U_d, U_s\}$ (U represents for the energy percentage that may participate into two-way V2G interaction). Let $\{m_c, m_d, m_s\}$ denote the number of EVs at different battery states.

This novel model is rather distinct with IEC 61850 based V2G. Firstly, it is a more fine-grained model because it classifies all EVs at a CP into three domains according to the battery status, comparing to the model illustrated in Fig. 1. Secondly, this model supports battery status based multicast scheduling. All power regulation requirements can be formulated as SOC transition instructs. Thirdly, the energy supplying curve can be

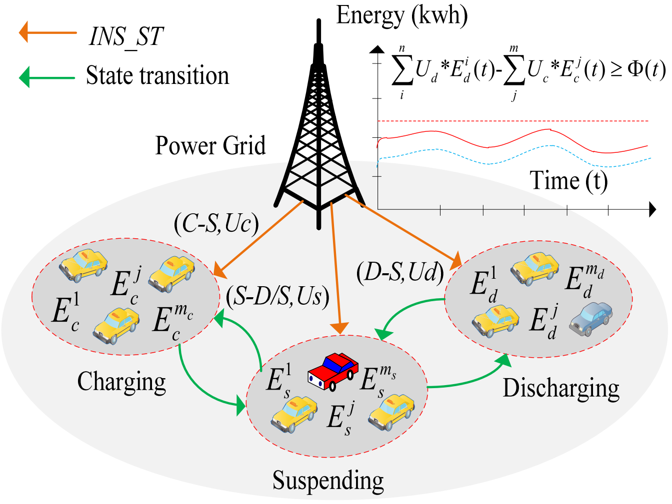

Fig. 6. The proposed BSS-SDM scheme in a V2G network.

formulated as:

$$\sum_i^{m_d} U_d * E_d^i(t) - \sum_j^{m_c} U_c * E_c^j(t) \tag{1}$$

It is not hard to find that EV in suspending state has no relation to the energy supplying curve. Thus, V2G regulation capability assessment is simplified significantly.

In this paper, as we focus on the issue of V2G regulation. Battery status based = multicast scheduling will be introduced in following section.

B. Mapping V2G Regulation Into SOC Control

In the process of power grid's retrieving EVs at a CP, the EVs' battery packs may be in one of the following states: **suspending**, **charging**, and **discharging**. Consequently, there are four SOC transitions: 1) **suspending-to-discharging**, 2) **suspending-to-charging**, 3) **charging-to-suspending**, and 4) **discharging-to-suspending**. We use CT to denote the SD-V2G controller. In a battery status, $\{EV, CP, CT\}$ performs the following operations.

- **In the suspending state:** We use $\{EV_s, CP_s, CT_s\}$ to denote the operations of $\{EV, CP, CT\}$ in the suspending state. When EV_s is in sleep mode or full-charged, it still needs to listen to the wake-up signals from EV_s and its owner. If it is the EV owner that wakes it up, the battery status may be transformed into charging; If it is the power grid that wakes it up, the battery state may be transformed into charging or discharging.
- **In the charging state:** We use $\{EV_c, CP_c, CT_c\}$ to denote the operations of $\{EV, CP, CT\}$ in the charging state. When EV_c arrives at CP_c, it attempts to access CP_c for charging. If the EV_c has been full-charged, the battery state may be transformed into suspending. If the EV_c that is in charging receives a request for discharging, the battery state keep in the same state until it is full-charged.

TABLE I

RELATIONSHIP BETWEEN OBJECTIVES AND SCHEDULING STRATEGIES

Scheduling strategies	Objectives of V2G regulation	
	Peak shaving time	Load shifting time
Saving sources	(C-S, Uc)	(D-S, Ud)
Opening channels	(S-D, Us)	(S-C, Us)
Consolidating body	(D, T)	(C, T)

- **In the discharging state:** We use $\{EV_d, CP_d, CT_d\}$ to denote the operations of $\{EV, CP, CT\}$ in the discharging state. When energy demand increases in power grid, CP_d will publish requests for discharging. If the EV_d that is in suspending receives a request for discharging, it will make a response. If the EV_d that is in discharging receives another request for discharging, this request will discarded.

During communications between EVs and CPs, the battery status of all participating EVs are identified and the EV aggregation is monitored by CT_d. During the SOC transitions, there are different V2G regulation requirements.

- **Suspending-to-discharging:** Initially, the CP_s has no information about the SOC of EV_s. If there is no a center to manage the SOC of EV_s, the CP_s must broadcast discharging requests to all EVs.
- **Suspending-to-charging:** It is common to see that many EV_s have the same SOC. For the owner to wake his vehicle up, unique identity should bind with EV' SOC and unicast mode should be supported. Moreover, when the supplying energy in power grid is excessive, power grid should selectively publish charging requests intoEV_s so that broadcast mode also should be supported.
- **Discharging-to-suspending:** As V2G must provide energy guarantee for EVs' travel plans and smart charging/discharging allows EVs to reserve partial energy resources, the owner requires to have mandatory control ability to stop discharging anytime. Meanwhile, publishing suspending requests as a "buffer" between charging and discharging is significantly beneficial to power grid regulation reliability and EV battery pack's lifetime.
- **Charging-to-suspending:** When EV_c arrives at CP_c, it attempts to establish communication withCP_c for charging/discharging. Thus, the SOC of EV_c is explicit for power grid when charging state will be transmitted into suspending state. Explicit SOC will be beneficial to V2G regulation in IEC 61850 based V2G networks.

C. Battery Status Based Multicast Scheduling

We consider there are two different objectives when power grid retrieves EVs: 1) peak shaving and 2) load shifting. Correspondingly, we consider the battery status multicast scheduling in V2G network based on these two objectives. On the specific strategies, we consolidate control, ease, and absorb liquidity from saving sources, opening channels and consolidating body as listed in TABLE I.

During peak shaving time, power grid retrieves EVs that are in suspending state to incent them to supply energy, retrieves EVs that are in charging state to transit into suspending state and retrieves EVs that are in discharging state to extend discharging time. During load shifting time, power grid retrieves EVs that are in suspending state to incent them to charge, retrieves EVs that are in discharging state to transit into suspending state and retrieves EVs that are in charging state to extend discharging time.

As introduced in advanced, the SOC of each EV is identified during the state transaction. Combining with the known energy demand curve, power grid can estimate energy supplying curve:

$$ES(t) = \sum_{i}^{n} U_d^{'} * E_d^i(t) - \sum_{j}^{m} U_c^{'} * E_c^j(t) \tag{2}$$

where $U_d^{'}$ and $U_c^{'}$ are the prediction values.

Power grid publishes the instructs of $(C - S, U_c^{'})$ into charging domain, $(S-D, U_s^d)$ and $(S-C, U_s^c)$ into suspending domain and $(D - S, U_d^{'})$ to discharging domain, respectively.

We discuss a scenario during which all EVs are plugged at CP. Moreover, we assume that the SOC of each EV is not impacted by EV owner. In other words, only the power grid can change the battery state of each connected EV. Besides, we assume that all EVs are standardized to have the same maximum storage capability MAX_ES. For sake of presentation and calculation, we use E_x^j to denote the available energy at EV which is in x domain and μ_x^j to denote the available energy at EV for participating V2G. If the EV is in charging domain, it can be noted with a notation "–" for sake of presentation. Thus, power grid publishes a minimum $U_d^{'}$ denoted as $U_{d\min}^{'}$ to all EVs that satisfy $\mu_d^j \geq U_{d\min}^{'}$. Let N_d denote the number of EVs, satisfying the above conditions.

$$N_d = Num\{(\mu_d^1, \mu_d^2, \ldots, \mu_d^{m_d}) \geq U_{d\min}^{'}\} \tag{3}$$

Meanwhile, power grid publishes a minimum $U_c^{'}$ denoted as $U_{c\min}^{'}$ to all EVs that satisfy $-\mu_c^j \geq -U_{d\min}^{'}$. Let N_d denote the number of EVs, satisfying the above conditions.

$$N_c = Num\{(-\mu_c^1, -\mu_c^2, \ldots, -\mu_c^{m_d}) \geq -U_{c\min}^{'}\} \tag{4}$$

Besides, power grid publishes $U_s^{'}$ to EVs that are in suspending states and make then change state. The constraints can be formulated as following equation.

$$N_{s-d} = Num\{(\mu_{s-d}^1, \mu_{s-d}^2, \ldots, \mu_{s-d}^{m_d}) \geq U_{s-d\min}^{'}\} \tag{5}$$

$$N_{s-c} = Num\{(-\mu_{s-c}^1, -\mu_{s-c}^2, \ldots, -\mu_{s-c}^{m_d}) \geq -U_{s-c\min}^{'}\} \tag{6}$$

We also use weighted undirected graph $G = (V, E)$ to describe the network. Thereinto, V represents for communication nodes and E represents for SOC-aware links. For each link, $(\tau, \upsilon) \in E$, we define a real function $d(\tau, \upsilon)$ to represent for the total delay from sending to receiving. Let $S = \{s_1, s_2, \ldots, s_k\}$ denote a set of source nodes and $M = \{m_1, m_2, \ldots, m_l\}$ denote a set of multicast nodes, where $S \subseteq V$, $M \subseteq V$, $k > 1$, $l > 1$. Let $C_{\min} = \{c_1, c_2, \ldots, c_j\} \subseteq V$ as a set of center agents to manage its multicast sharing tree $T(c)$. $T(c)$ is a minimum delay tree, which treat the c as root and cover S and $M_c \subseteq M$. Each $T(c)$ will cover some multicast nodes and the union set of all multicast nodes construct the multicast group, $\bigcup_{c \in C_{\min}} M_c = M$. It is easy to find that the S denotes charging points in V2G and M denotes smart EV.

The maximum V2G regulation delay can be defined as:

$$Delay(T(c)) = \max_{s_i}(\max_{m_j}(\sum_{e \in P_{T(c)}(s_i, m_j)} d(e))) \tag{7}$$

Where $P_{T(c)}(s_i, m_j)$ is the selected path from s_i to s_j.

Usually, when the demand curve at power grid demand-side changes, CPs are required to aggregate electricity from EVs with time constraints. Thus, the V2G regulation problem can be treated as a delay constrained multiple shared multicast tree (DCMSMT), which has been demonstrated as a NP-complete problem.

However, different traditional complicated DCMSMT problem, the number of source node (charging point) can be set as 1 in our proposed battery status sensing SD-V2G network Therefore, the problem can be simplified. The equation (7) can be reconstructed as:

$$Delay(T(c)) = \max_{m_j}(\sum_{e \in P_{T(c)}(s_1, m_j)} d(e)) \tag{8}$$

Let Δ denote the time constraint, the optimization objective function can be formulated as following equation:

$$Delay(T(c)) \leq \Delta \tag{9}$$

Moreover, in proposed architecture, as the SOC of each EV is maintained by the SD-V2G controller, the multicast node can be identified. Therefore, the selection of management center c can be identified dynamically. We propose a light-weight V2G regulation scheduling algorithm to resolve the simplified NP complete problem based V2G regulation.

D. Light-Weight V2G Regulation Scheduling Algorithm

The light-weight V2G regulation scheduling algorithm contains 1) selecting management center, 2) selecting multicast group 3) selecting forwarding path. Fig. 7 shows the decision-tree in proposed algorithm.

Management center selection is based on the services priority. The services priority is equal to the ratio of E_x^j and μ_x^j. We define $\rho = \frac{\mu_x^j}{E_x^j}$ to quantize the service priority. The node with a maximum ρ will be selected as management center υ, $\upsilon \in V$.

Multicast group selection is based on the explicit SOC in V2G network. As introduced in Section III, all SOC are identified during state transition. We use M_υ to represent for a set of objective nodes that a shared tree centered on υ passes by and N_υ denote the node number in M_υ.

We select the set with maximum N_υ as multicast group.Forwarding path selection is also designed. Dijkstra algorithm is utilized to find the shortest path tree T_υ.

$$M_\upsilon = \{m \in M | Delay(m, s_1)\} \leq \Delta, \quad \forall s_1 \in S \tag{10}$$

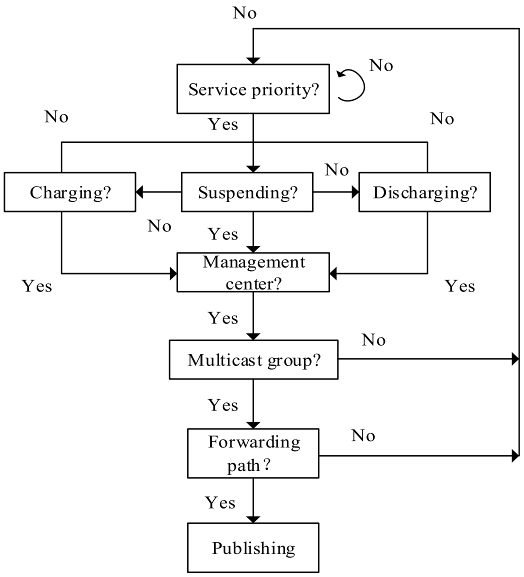

Fig. 7. Process of light-weight V2G regulation algorithm.

Where $Delay(m, s_1)$ represents for the shortest delay from multicast group to charging point.

Comparing to equation (7), the complexity of the algorithm for delay time calculation in software-defined V2G architecture is reduced from $\Theta\ (n^2)$ to $\Theta\ (n)$.

VI. PERFORMANCE ANALYSIS AND DISCUSSIONS

Considering that the mobility of EVs makes the power distribution dynamic and the changes of users' travel plans are closely constrained by the SOC, we do the numerical simulations on the average delay cost at different domains (e.g. charging, discharging and suspending) to validate the feasibility of proposed scheme. In this section, the performance of the proposed optimal solutions is evaluated through numerical examples.

Before the simulations setup, we estimate the network traffic. The scale of message exchanges depends on V2G regulation frequency. Compared to the charging/discharging time of one vehicle (may be 5-15 hours), the V2G regulation frequency from power grid can be set as $0.1 \sim 1$ times per second. Meanwhile, the V2G regulation frequency from users can be ignored for it may be less than 10 times per day. Thus, for one EV, there are 600 thousand data items that need to be processed approximately per day, which is equal to 10G bytes.

The simulation experiment is set up based on the observation of a real airport, the number of EVs is a statistical mean value at different times of a day. The number of CPs is configured as 10:1. E.g., 10 CPs are configured if there are 100 EVs.

In the simulations, we assume that the power grid maintain multiple CPs and each CP has one request instruct U (independently) with possibility P_U, The U consists of state x and state transition from x to y with possibility $P_U(x)$ and $P_U(\mathrm{x}-y)$, respectively. The $P_U(x)$ is equal to the radio between state duration and plugging time, while the $P_U(\mathrm{x}-y)$ is equal to $P_U(1-P_U(x))$. We assume that both $\{P_U\}$ and $\{P_U(x)\}$ follow normalized Zipf distribution. Zipfs law originally states that the probability of a V2G regulation request for the i-th most popular battery status is proportional to 1/i. The popular battery status is a threshold value published by CPs in smart grid.

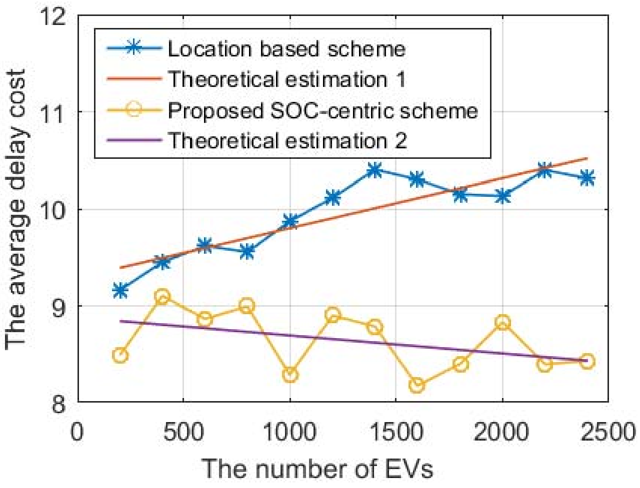

Fig. 8. The average delay time cost during EV aggregation in discharging domains.

For simplicity, we assume that each EV has the same maximum energy capacity and each CP has the same number of EVs that are plugged.

The CP schedules EVs' charging, suspending, and discharging with multicasting probability:

$$P_U^{\mathrm{x}} = P_U(x)|P_U, x \in \{D, C, S\} \tag{11}$$

As the coverage areas of the CPs are assumed to be disjoint, we adopted a commonly used energy demand curve, i.e., each CP aggregates V2G energy during peak time and stores V2G energy during load shifting time.

We take EV aggregation as an example to bring out the benefits of proposed scheme. We compare the average delay time costs of proposed scheme with traditional location based V2G regulation policy. Fig. 8, Fig. 9 and Fig. 10 illustrate the average delay cost at different V2G regulation objectives.

We monitored the process of EV aggregation from energy request to charging response. We use the average delay cost as the indicator, which is equal to the sum of transmission delay cost, queuing delay cost and computational delay cost. For visualization, we implemented simulation experiments for location based scheme and proposed scheme, respectively. Moreover, the trend estimation for each scheme is also demonstrated. The simulation results showed that the proposed scheme had a lower average delay cost.

Fig. 8 shows the average delay time cost during EV aggregation in discharging domain. It is easy to find that the average time cost consumed in location based multicast scheme increases with the number increase of EVs due to the complicated configuration and location mapping. Our proposed scheme makes the average delay time cost reduce with the number increase of EVs. We analyze that achieving

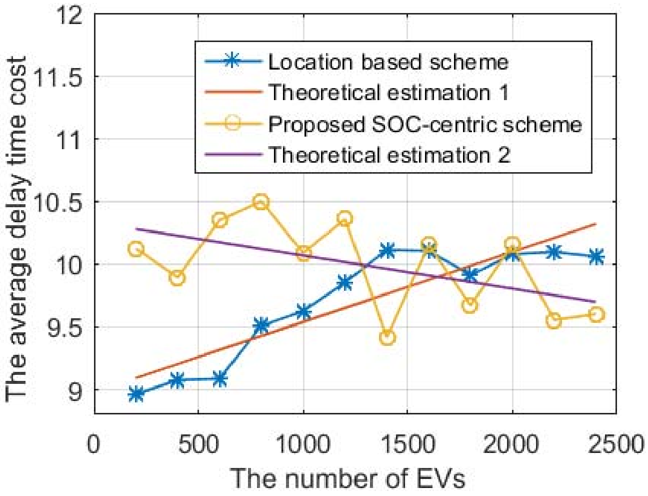

Fig. 9. The average delay time cost during EV aggregation in charging domain.

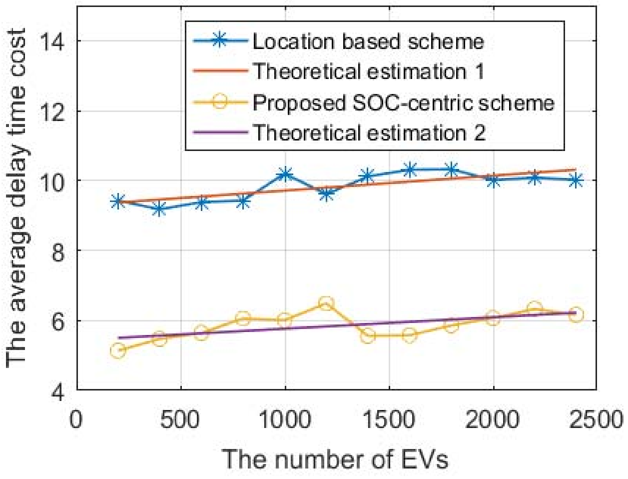

Fig. 10. The average delay time cost during EV aggregation in suspending domain.

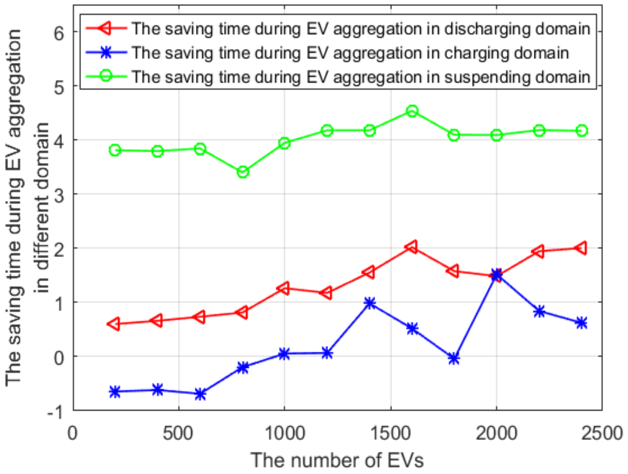

Fig. 11. The time saving during EV aggregation in different domains.

this benefit mainly contains two important factors. 1) The proposed algorithm supports the intermittent of EVs' connections, thus more EVs can receives the SOC transition instructs; 2) The battery status based multicast scheduling reduces the misplace rate of EVs aggregation, EVs that are insufficient can't participate into the power grid.

Fig. 9 shows the average delay time cost during EV aggregation in charging domain. What it should be stressed is that the aim of SOC regulation in charging domain is to transit EV state from charging to suspending. Thus, we retrieve all EV that are approximately full-charged. It is also easy to find that the average time cost consumed in location based multicast scheme increases as the number of EVs increases, while our proposed scheme makes the average delay time cost reduce as the number of EVs increases. Initially, there are a few full-charged EVs. If there are no responses for the instructs, request instructs will be re-transmitted redundantly. Therefore, the advantage of proposed architecture can't be presented. Consequently, the proposed scheme is more adaptive to be applied in a scenario, in which there are a large number of EVs.

Fig. 10 shows the average delay time cost during EV aggregation in suspending domain. In a CP, the percentage of suspending EVs is largest. The wanted EVs may be distributed in multiple network domains in traditional V2G network so that location based SOC regulation should publish multiple different destinations. In proposed scheme, we merely publish SOC into the corresponding state domain. Concurrent retrieval mode makes the average delay time cost be reduced significantly.

It can be observed that the proposed scheme presents a lower average delay time cost in discharging domain, charging domain (if the number of EVs is more than 2000) and suspending domain. Therefore, the proposed scheme will be more adapt to large-scale vehicle network.

The mobility of EVs makes the power distribution dynamic and the changes of users' travel plans are closely constrained by the SOC. In such dynamic circumstance, network traffic increases and the network performance goes down sharply. The design goal of proposed multicast scheme is to simplify the process of handshake connection between EV and power grid as well as EV and users. We construct the battery status based network topology, replacing the location based network topology. Simulation results shows that message exchanges in battery status based network topology can facilitate the V2G regulation to be more efficiency.

To bring out the strengths of proposed scheme, we evaluated the time saving during EV aggregation in different domains. The evaluation results were shown as illustrated in Fig. 11. In suspending domain, we save more time than the other two domains, that means the efficiency of V2G regulation is improved significantly.

VII. CONCLUSION

In this paper, we exploited plenty of sensors to collect the SOC and battery status from EVs. And then, we formulated an important communication problem to improve the efficiency of V2G regulation given the SOC and battery status to satisfy consumers' power demands. A novel communication requirement for efficient V2G regulation between these sensors was identified in detail.

We presented that the appreciable SOC and battery status are more adaptive than network location to achieve optimal V2G regulation delay time costs in IEC 61850 advanced V2G. Moreover, we proposed a battery status sensing software-defined multicast (BSS-SDM) scheme to reduce the average delay time cost of V2G operations. The process of battery status sensing during the SOC transitions was described in detail. Based on this, we also proposed a light-weight V2G regulation scheduling algorithm to reduce the average delay time costs of V2G operations. The simulation was also done and simulation results demonstrated the effectiveness of proposed scheme. For smart grid, the proposed algorithm has enabled V2G regulation to cope with the sharp fluctuation of power grid demand curve.

VIII. FUTURE WORK

Simulations showed that the proposed scheme enables real-time V2G regulation. But this is a partial case to validate the proposed scheme.We consider that the proposed scheme may have a great impact on V2G's dynamic pricing. Therefore, we plan to simulate the impact of the distance between the two cost trends on energy pricing in future work. Lower computational cost is promising to facilitate to reduce the users' expenses.

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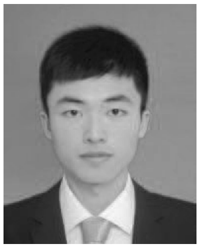

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