SDN-Based Framework for the PEV Integrated Smart Grid

Nan Chen, Miao Wang, Ning Zhang, Xuemin (Sherman) Shen, and Dongmei Zhao

ABSTRACT

In this article, we investigate the plug-in electric vehicle (PEV) integrated smart grid for efficient system operation. Due to the stochastic characteristics of PEVs, the intermittent nature of renewable energy sources, and the heterogeneity of the devices, it is a great challenge to achieve system flexibility, reliability, and interoperability. To address these issues, we propose a two-tier SDN-based framework for the PEV integrated smart grid. The upper tier targets the primary feeder level to have a general view of the system, while the lower tier focuses on the secondary feeder level to achieve granular control of data and power operation. The framework is presented hierarchically, followed by a detailed explanation of the system operation in each tier. In particular, the integration of PEVs, which includes both PEV charging and V2G, is well illustrated in the SDN-based framework. Finally, we provide a case study to validate the emerging need for SDN deployment in the smart grid.

INTRODUCTION

In the past decade, plug-in electric vehicles (PEVs) have received worldwide attention owing to their environmental and technical advantages when compared with the conventional petroleum-consuming vehicles. From the environmental perspective, PEVs have more electricity generation options (e.g. hydro, wind, and solar) rather than fossil fuels. The various electricity generation options help reduce the reliance on fossil fuels in the transportation sector. From the technical perspective, PEVs can achieve a high propulsion conversion efficiency of 90 percent, while conventional petroleum-consuming vehicles have an efficiency of only 45 percent [1]. With both environmental and technical advantages that PEVs bring to the transportation sector, governments have launched a large number of laws and research projects worldwide to accelerate the commercialization of PEVs [2].

As the PEV penetration rate increases in the next decades, the frequent interactions between the smart grid and PEVs require a thorough study to improve the reliability, sustainability, and efficiency of the system [3]. Compared with the traditional power grid, the PEV integrated smart grid has four main features. First, the integration of PEVs remarkably increases the system energy storage capacity through vehicle-to-grid (V2G) technology. Second, the smart grid incorporates a high percentage of renewable energy source-distributed generations (RES-DGs) to enhance system sustainability. Third, the Internet of Things (IoT) technique is adopted to guarantee system connectivity and automation. Finally, the smart grid enables bidirectional power and data communication to improve the reliability and efficiency of the system.

However, by integrating PEVs and RES-DGs into the power grid, the smart grid faces many challenges from both power and communication perspectives. In terms of the power challenges, the stochastic properties of PEVs can severely jeopardize the system reliability [4]. When a large number of PEVs are in charging mode, the simultaneous charging of PEVs in the residential area may severely damage the system components (e.g. transformers) [5]. On the other hand, the random driving patterns of PEVs may cause failures to accomplish V2G service timely, which can decrease the system reliability or even result in blackouts. In addition, the intermittent nature of RES-DGs can cause load imbalance in extreme weather conditions, jeopardizing the system reliability. In terms of communication challenges, as the PEV penetration rate rises, the number of IoT devices is rapidly increasing in the smart grid, which has a significant influence on the system scalability [6, 7]. Moreover, heterogeneous connected devices (e.g. PEVs, RES-DGs, etc.) require significant manual effort for device configuration and maintenance, which is a huge economic cost [6].

To address the above challenges, many coordination schemes have been proposed in previous studies. For example, the authors in [8] implement an advanced version of the ISO 15118 communication protocol to enable the flexible integration of PEVs into the home energy system. The authors in [9] define an information model based on IEC 61850-7-420 to guarantee the control of PEV integration into the smart grid. A similar network implementation is reported in [10] based on IEEE 802.16 for V2G technology. However, the above works have only implemented network functions based on a specific communication protocol, which is not flexible and scalable for the heterogeneous scenarios in the smart grid.

As a promising paradigm, software-defined networks (SDNs) have the potential to improve the flexibility, scalability, and interoperability of the smart grid. SDN refers to a network architecture that separates the control logic from the underlying data forwarding devices [6, 7]. By deploying SDN into the smart grid, the decoupling of the control plane and the data plane not only increases the flexibility, interoperability, and reliability of the system, but also decreases system upgrade costs by simplifying the hardware operation.

In this article, we propose a two-tier SDN based framework for the PEV integrated smart grid to

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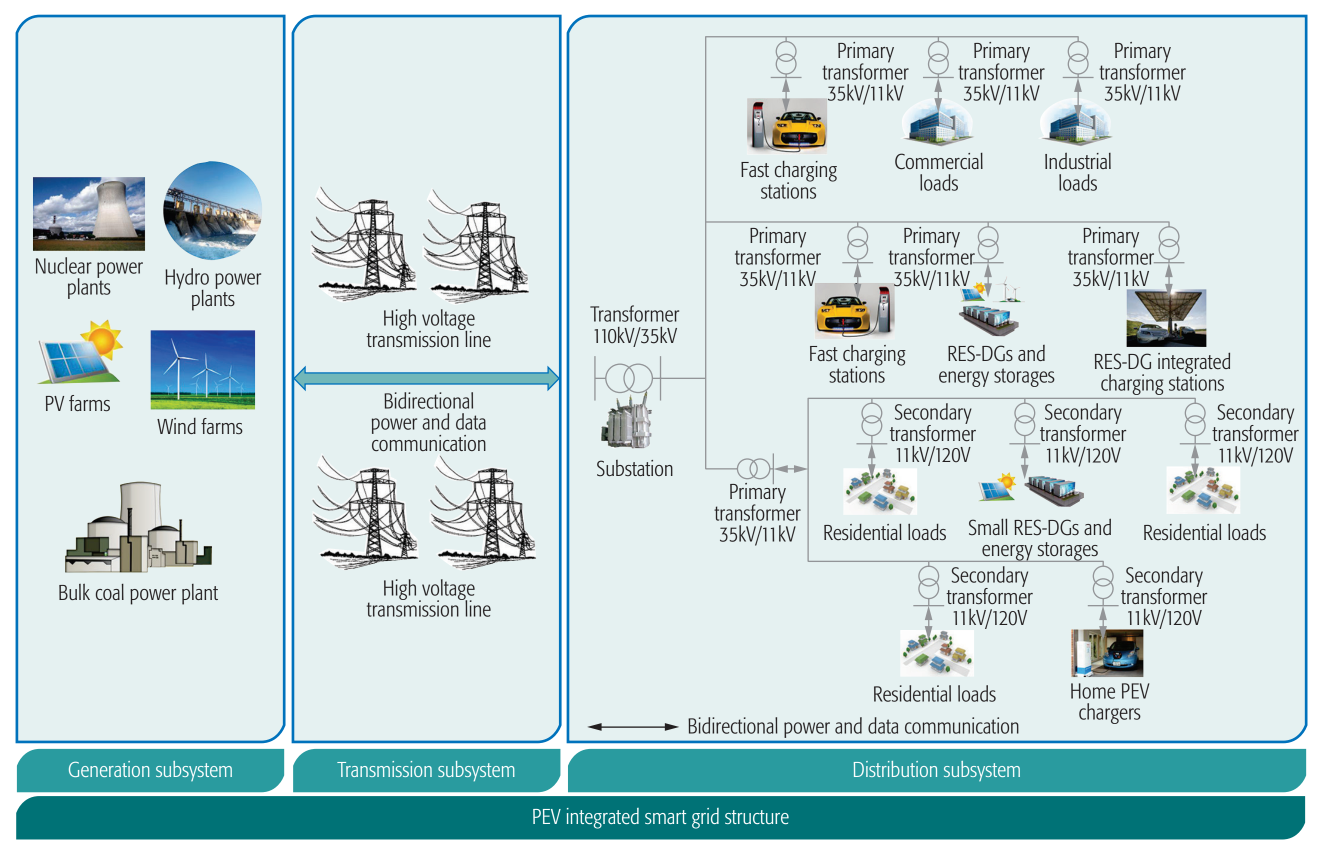

FIGURE 1. The Structure of PEV Integrated Smart Grid

enable flexible and scalable system operation. The framework is presented hierarchically to explain the detailed system operation process. Furthermore, a case study is provided to validate the urgent need for SDN deployment in the smart grid.

The remainder of this article is organized as follows. The following section introduces the PEV integrated smart grid and discusses related challenges. In order to overcome the challenges, the SDN based framework is proposed with the detailed operation processes, followed by a case study. Then we discuss open research issues related to the SDN based framework. Finally, conclusions are given.

The PEV Integrated Smart Grid

PEVs have two main features: the plug-in feature, which enables the battery to recycle, and the electricity-to-propulsion capability, which reduces environmental pollution. When PEVs run out of electricity, they can be connected to power outlets to be recharged. In terms of the charging standards of power outlets, the outlet deployments in the grid vary. When PEVs provide V2G services, the requirements of PEV connection points also vary in terms of diverse service tasks and utility contracts. In the context of smart grid, in this section we present the PEV integration process and discuss the corresponding challenges.

The Structure of PEV Integrated Smart Grid

The structure of PEV integrated smart grid is shown in Fig. 1, where the smart grid consists of the generation subsystem, the transmission subsystem, and the distribution subsystem.

The generation subsystem is composed of bulk-size generations (e.g. coal power plants, wind farms, PV farms, etc.) which are responsible for providing daily power consumption. As the generation subsystems are deployed remotely from the electric loads, high voltage transmission subsystems are utilized to transmit the power to the distribution subsystem. By utilizing the step-up transformers, the transmission subsystem transmits the power at an extremely high voltage level (above 110 kV) to minimize the power transmission loss.

When the power arrives at the distribution subsystem, the power voltage is decreased through transformers according to the load voltage requirements. The voltage is generally transformed into two levels: 11 kV–22 kV at the primary feeder and 110 V–220 V at the secondary feeder. Based on the PEV requirements, different PEV integration facilities are deployed correspondingly. For example, since fast charging stations require high voltage levels (up to 600 VDC) with large power outputs (up to 240 kW), they are normally connected to the primary feeder, along with large industrial and commercial loads. Medium-size RES-DGs and energy storage devices are also deployed at the primary feeders to provide local green energy for the large loads. On the other hand, regular in-home and parking charging facilities are deployed at the secondary feeders, as they require a relatively small voltage level and power output. Secondary feeders mostly provide power service for residential loads, along with small-size RES-DGs deployed to facilitate local green energy utilization.

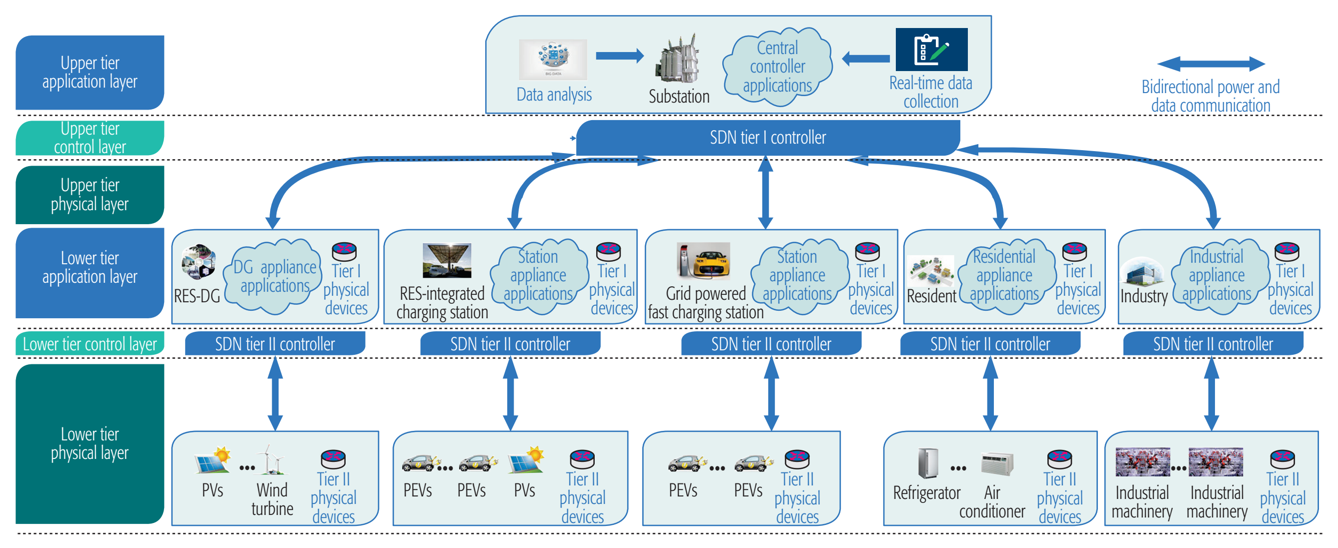

FIGURE 2. The SDN Framework for the Distribution System in the PEV Integrated Smart Grid.

Based on the geographic subsystem deployment, different types of communication networks are deployed among subsystems to meet the system operation requirements. Wide area networks (WANs) are deployed from the bulk generation subsystems to the substations in the distribution subsystems, which require long-distance communication technologies. Neighborhood area networks (NANs) cover communication between the substations and the loads to help achieve load balance efficiently. Within the buildings or the home areas, home area networks (HANs) facilitate communication among the appliances in the area.

CHALLENGES

By integrating PEVs and RES-DGs into the smart grid, many challenges are encountered in both power and communication aspects.

From the power point of view, the stochastic characteristics of PEVs causes load unbalance during uncoordinated integration processes. In addition, the intermittent nature of RES-DGs increases the risk of jeopardizing system reliability. For example, when the local RES-DGs are integrated in the PEV charging station, the variant power supplies of DGs and the stochastic driving patterns of PEVs may incur load unbalance issues. The deployment of RES-DGs and PEVs results in the dynamic, time-variant energy generation and consumption process, which requires fast and automated system operation.

From the communication point of view, the smart grid cannot guarantee the reliability of communication, which can significantly influence power operation, especially for time-sensitive power services. Moreover, the adoption of IoT and the integration of PEVs into the smart grid pose great pressures on system scalability, which requires a huge economic cost. Finally, the heterogeneity in the connected devices requires device configuration and maintenance to enable system interoperability, which requires significant manual efforts [11].

Facing the above challenges, the conventional smart grid is not flexible and reliable enough to overcome the issues.

SDN BASED FRAMEWORK FOR THE PEV INTEGRATED SMART GRID

As an emerging network paradigm, SDN has the potential to address the above challenges. SDN refers to a network architecture where the forwarding control in the data plane is managed by a remotely controlled plane decoupled from the former [6]. By decoupling the planes, the network switches become simple forwarding devices while the control planes implement the logically centralized controllers to instruct the underlying physical devices. Moreover, the programmability provided by the open interfaces allows dynamic coordination algorithms which can enhance system agility.

A general SDN architecture consists of three layers: the application layer, the control layer, and the physical layer. The application layer implements system operation managements, which are interpreted to the control layer through the northbound interface. The northbound interface refers to the application program interface (API) that provides the application developer with particular communication between the control layer and the application layer. Then, the control layer works as a network operating system to assign instructions to the physical layer through the southbound interface. By defining the communication protocol between the forwarding devices and control plane, the southbound interface can efficiently interact between the two layers. Then, the devices in the physical layer perform instructions from the upper layer to accomplish data transfer.

The novelty of this SDN framework can be illustrated from both power and network perspectives. From the power perspective, although the SDN based system is centrally controlled as the conventional power system, the SDN open interfaces between each layer enable the programmability of system operation, which facilitates the flexibility and efficiency of the system. Moreover, the SDN framework normalizes devices on the physical layer, which simplifies system maintenance and configuration to improve the system cost-efficiency. From the network perspective, the communication between the control layer and

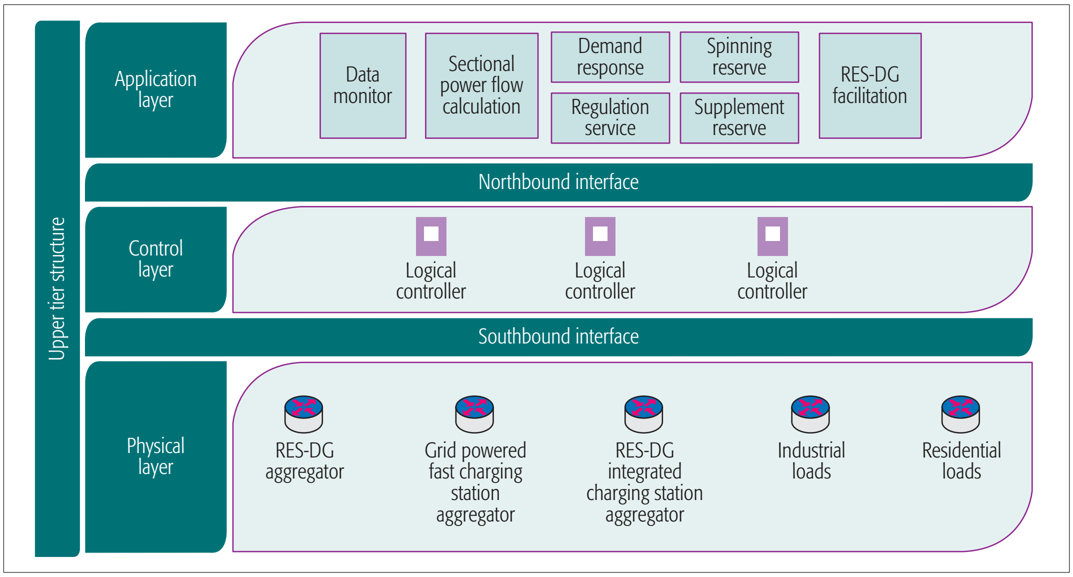

FIGURE 3. The Operation Structure of Upper Tier SDN Framework.

the physical layer not only focuses on the data flow as in the network case, but also adds power command communication according to the system regulation. The tiered power command communications facilitate the hierarchical operation to further optimize the system.

As a large number of PEVs and RES-DGs with stochastic characteristics are deployed in the distribution subsystem, the load balance and data communication are essential. To this end, the proposed framework is deployed within the range of the distribution system.

THE STRUCTURE OF THE SDN FRAMEWORK IN THE DISTRIBUTION SYSTEM

As a large number of PEVs and RES-DGs with stochastic characteristics are deployed in the distribution subsystem, load balance and data communication are essential. To this end, the proposed framework is deployed within the range of the distribution system, as shown in Fig. 2. Moreover, the power flow of the distribution system has two tiers. First, the power flows from substations to primary feeders to provide power for large-size commercial and industrial loads. Then, the power flows from primary feeders to secondary feeders to supply the small-size resident loads. Corresponding to the power structure, the proposed SDN framework also has two tiers. The upper-tier controller is deployed in the substation to have an overall view of the system, while the lower-tier control is managed by each aggregator in primary feeders to perform fine-grained power and data operations.

To dynamically operate the system, SDN controllers on each tier collect the date regularly. The collected data are analyzed on the application layer to achieve optimal operations within their service ranges. The application results are then translated into instructions and sent to appropriate physical devices to update their command sets and execute the commands accordingly.

OPERATION OF THE UPPER-TIER SDN FRAMEWORK

As shown in Fig. 3, the tier I applications include data monitoring, sectional power flow calculation, demand response, ancillary services for smart grid (e.g. regulation service, spinning reserve, and supplement reserve), and RES-DG facilitation. In terms of diverse properties of aggregators, the collected data vary. For instance, the RES-DG aggregator sends out the power output and predicted output data. The grid powered fast charging station and the RES-DG integrated charging station send the PEV charging load demand to the controller while the industrial and residential loads transmit power data (e.g. voltage, frequency, etc.).

By regularly performing the data monitoring function, the collected data are utilized for the sectional power flow calculation to obtain the timely system operation status. To balance power generation and demand, demand response is performed to shift or shave the load. Whenever the voltage or the frequency needs regulation, the regulation service function can be performed. Since the response speed of the regulation service is within one minute, the controller delivers the regulation requests only to currently connected RES-DGs or PEVs. Compared with regulation services, the spinning reserve and supplement reserve services have a loose response speed requirement of less than 10 minutes. In this case, the controller can deliver service requests not only to the connected devices, but also to the moving PEVs on the road. Apart from utilizing the V2G technology for power ancillary services, PEVs can also be assigned to compensate the power difference between the load demand and RES-DGs when RES-DGs are interrupted due to weather conditions.

When performing services on the application layer, the corresponding results are interpreted through the northbound interface to the controller to further instruct each aggregator. The controller sends out the information including the electricity price for the load demand aggregator, the ancillary service assignment (e.g. required power, rated voltage, rated frequency, and service time) of each available PEV connected aggregators and RES-DGs aggregators. Meanwhile, the

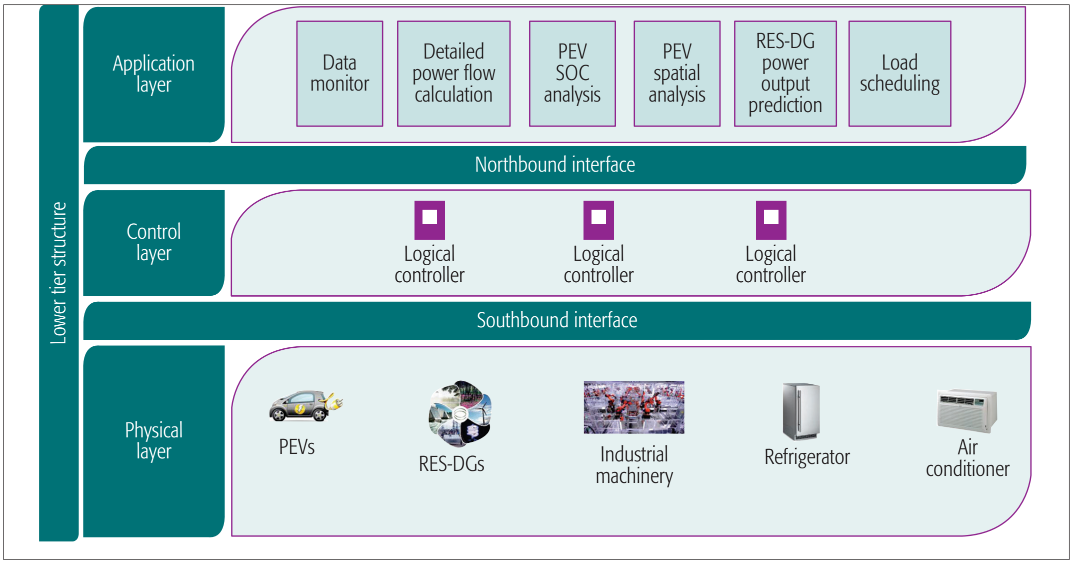

FIGURE 4. The Operation Structure of Lower Tier SDN Framework.

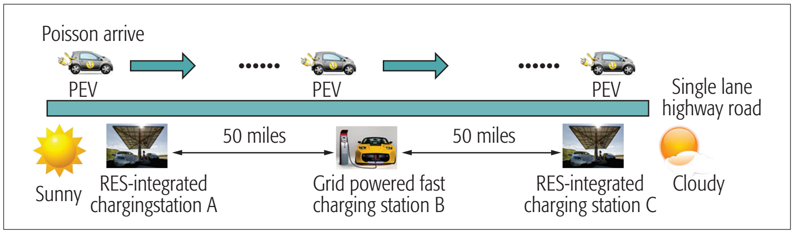

FIGURE 5. The Layout of Fast Charging Stations along the Highway.

SDN controller also sends the ancillary service purchase price to each available source connected aggregator as participant incentives.

Operation of the Lower-Tier SDN Framework

As shown in Fig. 4, network applications on the tier II application layer are data monitoring, detailed power flow analysis, PEV state-of-charge (SOC) analysis, PEV spatial analysis, RES-DG power output prediction, and load scheduling.

In the tier II SDN system, logical controllers are the aggregators at primary feeders that overlap with the physical devices in the tier I system. As the connection points, aggregators receive the operation commands from the upper tier controller. The commands can be further analyzed on the tier II application layer to implement the physical devices at the secondary feeders (e.g. PEVs, RES-DGs, industrial machineries, and other electrical loads). On the other hand, when physical devices send requests to the logical controllers, the controllers first analyze requests through applications, and then decide to operate locally or forward the requests to the upper tier.

The stationary PEVs (no movement for a relatively long time, e.g., more than half an hour) regularly send out information including their current SOCs, expected departure SOCs, expected departure time, and their contracts with the power company. The moving PEVs regularly send their locations, SOCs, and power contracts to the nearby aggregators. When aggregators receive the PEV information, they can perform the PEV SOC analysis to determine the starting time and time period of the V2G process for each PEV based on their SOC information. Then, ancillary service requests can be assigned to each PEV accordingly. When stationary PEVs cannot fulfill ancillary service requests, the aggregators assign service requests to their nearby moving PEVs through PEV spatial analysis [12–14] or forward the requests to the upper tier. Normally, the moving PEVs have signed ancillary service contracts with local power companies. Hence, the number of service requests to fulfill annually for each PEV is regulated.

The local RES-DGs regularly send out their electrical data while the RES-DG integrated charging station sends out the number of current arriving PEVs to the aggregator in case of any emerging power demand request. Through RES-DG power output prediction, the controller can detect potential power interruption cases, and then assign PEVs to the RES-DG areas to balance the local load.

The electrical appliances in the residential and industrial community regularly send out their load demand, load priority degrees, and expected payment threshold to the aggregators. Then, the aggregators perform load scheduling applications to schedule the operation period for each appliance while guaranteeing that the electricity bills are within the owners' budgets [15].

Benefits of the SDN Based Operation

By utilizing the SDN framework, the operation command implementation is simplified at the device ends (tier II physical layer). On one hand, through the open southbound interface, the interoperability of heterogeneous sensor devices can be better supported. Instead of implementing most of the functions on the physical devices, the two-tier SDN platform implements most of the operation commands on the controller level, and delivers the simplest rules to the physical devices. For example, if PEVs are instructed to provide ancillary services to the smart grid, PEVs only need to change the integration mode as instructed by the aggregator. The battery management system embedded in the PEV does not need to consider the SOC management or the battery life cycle during the service, as the SDN applications on the SDN tier II control layer are in charge of them. On the other hand, the open northbound interface simplifies the modification and upgrade of the system operation by dynamically arranging the system coordination and optimization functions on the SDN application layer. Since now the upgrade and modification are implemented on the software rather than on proprietary hardware, the cost can be reduced dramatically.

CASE STUDY

In this section, we present a case study that is closely related with PEVs and RES-DGs to show the necessity of applying SDN into the smart grid.

As the main PEV connection points in the smart grid, fast charging stations are responsible for charging PEVs as well as providing ancillary services through V2G technology. Therefore, we consider a multiple charging station coordination case where all the charging stations have ancillary service requests to fulfill. Three fast charging stations are deployed along the highway, as shown in Fig. 5. Both charging stations A and C are PV integrated fast charging stations where the electricity is generated by solar. Station B is a grid powered fast charging station where all electricity comes from the main grid. The distance between each charging station is 50 miles, and PEVs arrive at each charging station following a Poisson process with hourly variant arrival rates [2].

In the case study, all fast charging stations send V2G requests to the passing PEVs for additional power supplement. The case considers a PEV penetration rate of 15 percent and PEVs enter the station following a uniform distribution. Stations A and C have the same PV capacities that can charge two PEVs simultaneously, and all the charging stations have five PEV connection points. The case study considers that the weather at station A is sunny while the weather at station C is cloudy, and that three stations receive the same power ancillary service requests.

The service performance of each station and the performance comparison are shown in Fig. 6. The performance of the uniform PEV arrival rate at each station is shown in Fig. 6(a) as the base-line case. It can be seen that as the PEV arrival rate increases, PV integrated stations have more PEVs arriving in the stations, while the grid powered station does not incorporate any PEVs into the V2G service, because the grid powered station has a stable and consistent source for V2G service. As for the PV integrated station, the cloudy station requires more PEVs to perform V2G services than the sunny station as the cloudy station cannot provide enough power for the local grid through its own PV power output. However, with the uniform PEV arrival rate at each station, most PEV resources are wasted.

By running the SDN lower-tier operation in this case, passing PEVs can be fully utilized to help stations complete their V2G tasks. When the fast charging station aggregators at the upper tier receive the V2G requests, they perform the PEV analysis functions on the application layers, and then send the V2G requests to nearby PEVs. The SDN coordinated performance is shown in Fig. 6(b) to illustrate the performance improvement. It can be seen that as the PEV arrival rate increases, the cloudy PV integrated station requires far more PEVs than other stations. Since the SDN based system analyzes the service requests based on the weather conditions, it can direct more PEVs to the most needed station to facilitate the V2G services. Moreover, from the total PEV participation comparison as shown in Fig. 6(c), it can be seen that as the PEV arrival rate increases, the PEV participation percentage of the SDN coordination case increases dramatically compared with the non-coordinated case.

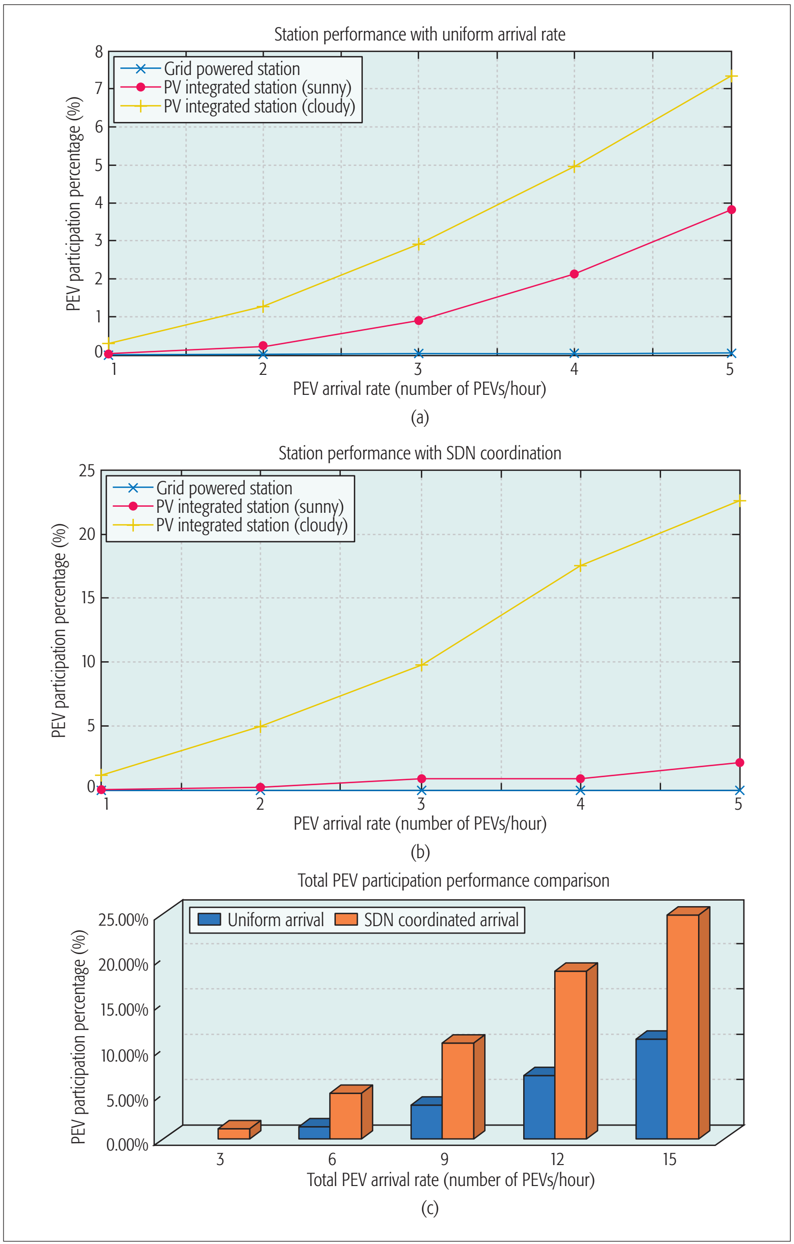

FIGURE 6. The Station Ancillary Service Performance.

In this case study, the V2G tasks are only coordinated through the PEVs in the lower tier of the SDN framework. If the number of PEVs on the road is predicted to be small, the task requests can be forward back to the upper tier for reassignments. Hence, by coordinating the system on the application layer dynamically, the SDN framework guarantees a cost-efficient, scalable, and reliable system.

To pave the road toward SDN based PEV integrated smart grid, there are still challenges ahead such as the realization of the open interfaces between each layer, the hierarchical algorithm designs in the application layer, and the development of control algorithms with low complexity.

OPEN ISSUES

As an emerging technology, the deployment of the SDN framework in the smart grid requires inter-disciplinary research collaboration in the power, communication, and information areas. In this section, we highlight open research issues that can facilitate the deployment of SDN in the smart grid.

REQUEST BALANCE BETWEEN TIERS

As the joint point of the two-tier framework, the aggregators at primary feeders not only need to receive and implement the instructions coming from the upper tier, but also receive the requests coming from the lower-tier physical devices and provide appropriate responses. However, the unsynchronized data transfer of instructions from the upper tier and the requests from the lower tier may cause a lack of consistency at the lower-tier controllers. For example, the upper tier instructs the aggregator to provide ancillary services based on the received data while the lower tier has an emerging power breakdown. Under this circumstance, the analysis process at the lower-tier controller encounters contrary operation conditions, which confuses the controller. Hence, the command balance and evaluation between the upper-tier instructions and lower-tier requests is an essential problem that needs to be thoroughly studied.

COMMUNICATION PROTOCOL IMPLEMENTATION

As a large-scale system, the smart grid requires diverse communication technologies with heterogeneous features. For example, with respect to communication coverage, WANs require long-distance-enabled technologies while HANs only need short-range communication within the home or building area. Moreover, in terms of different system operations, the requirements for exchanging information are varied as well. To simplify the operation on the physical layer, all the communication protocols are interpreted through the southbound interface to the physical devices. In this case, the interpretation of the southbound interface is very challenging. With heterogeneous communication protocols, the flow tables embedded in the switches require a large amount of efficient command settings. Moreover, the overall upgrade of switches and hardware enhancements are very challenging due to the large communication requests, and they need to be thoroughly studied.

CLOUD COMPUTING EMPOWERMENT

As a logically centralized control system, the SDN controller needs to be able to collect and analyze data without compromising the system response speed. However, the number of sensor devices is expected to increase dramatically due to the utilization of IoT. Therefore, the overhead of the data flow processing becomes a critical issue in the SDN framework for the smart grid. In this case, the empowerment of cloud computing technology in the SDN based smart grid has the potential to solve this issue. By utilizing cloud computing technology, data management in the SDN controller can be simplified and optimized. Meanwhile, cloud computing facilitates inter-data center communication to provide more valuable information (e.g. mobile PEV location, upcoming weather conditions) for the system operation. Furthermore, by utilizing the large computing capacity of cloud computing, the overhead of data processing can be decreased significantly. Hence, the empowerment of cloud computing including service deployment and service access can be an interesting research area.

CONCLUSION

In this article, an SDN based framework for the PEV integrated smart grid has been proposed. With the SDN framework, automated and flexible operations are enabled in each control level. Moreover, the upgrade and configuration of the smart grid become much easier due to the decoupling of the control plane and the data plane. In addition, the open SDN based framework can accelerate service innovation for the PEV integrated smart grid. To pave the road toward the SDN based PEV integrated smart grid, there are still challenges ahead such as the realization of the open interfaces between each layer, the hierarchical algorithm designs in the application layer, and the development of control algorithms with low complexity.

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