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Bi-level Control Scheme for Vehicle-to-Grid Regulation Services

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Abstract

This paper presents a control scheme of vehicle-to-grid (V2G) operation for the distribution power grid which integrates renewable generation units. An optimal control algorithm is developed to minimize the total operating cost. The potential for providing frequency regulation when the vehicles are idle is also analyzed. The power output of plug-in hybrid electric vehicles (PHEVs) is regulated to redistribute the PHEV charging energy and meanwhile provide the grid services. The regulation of PHEV charging load can consume the excessive power from wind generation units during the off-peak time. And with the frequency regulation, the power fluctuation of wind generator can be compensated and therefore stabilize the voltage and frequency. Finally, simulation results verify that the optimal control of V2G power can reduce total operating cost and enhance the voltage stability. Furthermore, the regulation capacity of V2G used for frequency regulation can improve the power quality and facilitate the integration of wind power generators.

Keywords: V2G, Renewable generation, electric vehicles, operating cost minimization, frequency regulation.

1 Introduction

To cope with global energy crisis and environmental pollution, renewable generation especially wind power is becoming desirable to integrate into the existing power grid [1], while electric vehicles (EVs) especially the plug-in hybrid EVs (PHEVs) are becoming attractive for green transportation [2]. Because of the intermittent nature of wind power, it is a challenge to maintain both transient and steady-state balances of the power grid. Vehicle-to-grid operation can help to address the challenges by acting as a energy storage devices [3].

Currently, the V2G power is utilized in various power grid services to produce the economic and environmental benefits [4]. However, the V2G power is merely used as a dispatchable generation resource from the power system point of view. The characteristics of charging or discharging PHEVs to compose the V2G power are not sufficiently considered in the economically optimal control model. In reality, the battery charging and discharging introduce several important limitations of the V2G power. The V2G power can not be simply regarded as the normal dispatchable generation unit and deployed as the conventional peaking power plant in the unit commitment model. In this paper, the power capacity of PHEV aggregation is reformed by considering the properties of on-board battery pack and the cost for utilizing V2G power is included in the optimal control scheme. In order to form the V2G power in a test power system, the driving pattern and typical battery pack in the PHEVs are used to estimate the energy requirement of charging PHEVs and the charging time period. Moreover, the uncertainty of connecting the PHEVs with a certain place in the power network is taken into account to analyze the availability of V2G power at the certain bus.

2 Power Grid with New Components Integration

2.1 New components

Technological development of power electronics devices paves the way for integrating new power generation units or controllable load into the power grid. A typical example is the PHEVs which can be plugged into the grid for V2G operation, acting as controllable load, dispatchable resources or energy storage devices.
The V2G implementation in the power system of the future has to cooperate with other new components, typically the distributed generators. Renewable Portfolio Standard (RPS) has been enacted in U.S. which specifies, through 2025, an annually increasing amount of electricity that must be generated from renewable resources [5]. V2G as an energy storage device can allow a larger scale of intermittent renewable generation installed in the grid [6]. Moreover, V2G power for frequency regulation can effectively compensate the power fluctuation and support the power supply from wind power generators. The conventional grid structure must be improved to accommodate the comprehensive components.

2.2 Multi-level grid structure and hierarchical control network

As shown in Fig. 1, a framework is derived to coordinate the operations of comprehensive system components in the future power grid. The two-way communication network must be built for any control scheme and transfer the signal with the new components consisting of wind power generators, the PHEVs and the aggregator for PHEV fleets. The aggregation of PHEVs in a certain region can contribute to the power regulation in different levels of power grid. A PHEV aggregation of large scale can be regarded as the peaking generation plant to participate in the unit commitment controlled by transmission grid operator. The PHEV aggregation with smaller energy storage has the equivalent property as a common distribution generator in a distribution grid.

Moreover, the V2G power from PHEVs can support the operation of the micro-grid, especially for the islanding operation mode. When the micro-grid is disconnected from the external distribution grid, the PHEV aggregation as the energy storage device can play an important role in power supply and power regulation.

2.3 Updated distribution Grid

The main focus of this paper is at the distribution grid level that directly connects to the micro-grid, small generation units and the electric appliances at the lowest level. The new grid structure and electrical components are introduced into a traditional 33-bus radial test power network [7]. As shown in Fig. 1, the subtransmission line is connected from one bus of the distribution grid. The micro-grid with novel electric devices of smaller rated power is connected to the feeder at the substation. To formulate the PHEV charging load, the power and energy required for fully charging the battery must be calculated. The scale of the PHEV penetration and the characteristics of on-board battery pack are used in calculation and listed in Table I.
Apart from the estimation of power capacity, the V2G power should be restricted within the appropriate range which is to reflect the boundaries of charging rate for each individual PHEV. The maximal charging and discharging rate are mainly determined by the maximal power of battery charging facility. For home charging, the PHEVs are plugged into the grid through the standard household outlet at the rated power of 3kW. The constant voltage and constant current charging methods are commonly adopted in the power interface for PHEVs. Therefore, the PHEV charging power and the increase in the SOC can be derived from the typical charging pattern for Li-ion battery, which is shown in Fig. 2.

Table 1. Simulation parameters for the PHEV fleets

Specification of the PHEVs integrated into the grid	Value	Unit
Average battery capacity	9.4	kWh
Maximum charging rate	3	kW
All-electric range	60	km
Average energy use over drive cycle	59 and 23	Wh/km km/l
CD-mode energy use	0.183	kWh/km
Expected number of PHEV	1000	vehicles

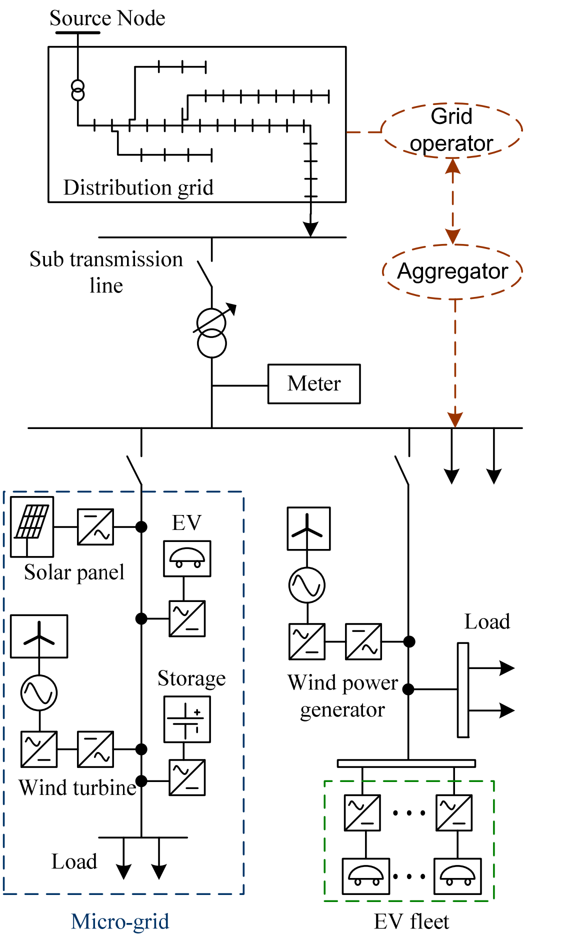


Fig. 1. Multi-level power grid with the integration of new components.

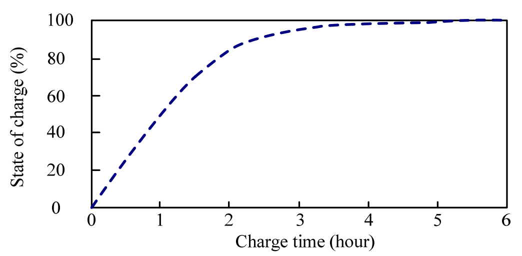


Fig. 2. generic charging pattern of the PHEV battery.

3 Cost Minimization by Using V2G Regulation Power

3.1 Mathematical formulation of the optimal control scheme

The integration of renewable energy with higher degree may introduce new challenges to the power grid. The intermittent characteristics of wind power generator increase the uncertainty of the power generation so more peaking plants installed is necessary to provide sufficient capacity to ensure the system reliability. The operation of peaking plants is expensive so the plant income must be supplemented by incentive from capacity market. This capacity payment can be significant and is the primary means of covering capital costs for peaking plants. The new components in the updated power grid can act as the peaking plants and get revenue in the similar way [8-10]. The power for charging and discharging PHEVs can be controlled to minimize the operating cost of the power grid with a relatively high level of wind power integration.

The operating cost the distribution grid can be formulated as the following equation.

$$TOC = \sum_{t}^{H}\sum_{gi}^{Ng} F_i(P_{gi,t}) + \sum_{t}^{H}\sum_{gi}^{Ng}(STC_{t,i} + SDC_{t,i}) + \sum_{EVi}^{Nev} p_{Evi}\sum_{t}^{H} P_{EVi,t} + \sum_{EVi}^{Nev}\rho_{Evi}(EL_{EVi} - \sum_{t}^{H} P_{EVi,t}) \quad (1)$$

where the notations used are as follows:

TOC total operating cost of the novel power grid.

Fi(Pgi,t) fuel cost function of the ith generation unit with generation output Pgi,t at the time indext t.

$$F_i(P_{gi,t}) = a_i P_{gi,t}^2 + b_i P_{gi,t} + c_i \quad (2)$$

STC start-up cost of the ith generation unit

SDC shut-down cost of the ith generation unit

p_{EVi} revenue paid for providing regulation through V2G

$P_{EVi,t}$ power output of the ith PHEV aggregation when participating in V2G regulation

p_{EVi} penalty price for unserved electricity required for fully charging PHEV

L_{EEVi} the electricity required for fully charging PHEVs by the end of the charging period

To calculate the revenue paid for PHEVs to participate in the optimal control scheme, both the regulation up and regulation down must be taken into account. Although in many energy market, different prices are claimed for regulation up and regulation down, only one price is practically given for regulation. For this reason, only one section describing the revenues from V2G is required in the total cost equation.

It should be noted that there will be a penalty cost for PHEVs if the amount charged is less than the amount required. Furthermore, in the test distribution grid, there is only one main power supply at the slack bus no. 1 which is connected to the external transmission grid. The load demand of the distribution grid should be fully supplied from a certain number of generation units in the upper power grid. The cost to serve the varying load demand is represented by the fuel cost, start up and shut down cost in the equation. But the analysis of the distribution grid cannot explicitly assess this part, although the cost is practically impacted. Because if the difference between the peak and off-peak demand is serious, the expensive peaking generation unit would run and more generation units should be shut down to remove the surplus generation during the off-peak time. Thus, the parameters for fuel cost will take the average value to reflect the combination of normal generation units and the peaking plants in the upper grid, and the start-up and shut-down costs are replaced. Instead, the penalty for overload or oversupply which is mainly caused by wind generation during the off-peak time is introduced and the equation is revised to:

$$TOC = \sum_{t}^{H} \sum_{gi}^{Ng} F_i(P_{gi,t}) + \sum_{t}^{H} \rho_{ol}(P_{gi} - P_{up}) + \sum_{t}^{H} \rho_{os}(P_{lp} - P_{gi}) + \sum_{EVi}^{Nev} p_{Evi} \sum_{t}^{H} P_{EVi,t} + \sum_{EVi}^{Nev} \rho_{Evi}(EL_{EVi} - \sum_{t}^{H} P_{EVi,t}) \quad (3)$$

where p_{ol} and p_{os} are the penalty price for overload and oversupply; P_{up} and P_{lp} are the upper and lower boundaries of the power demand in the distribution grid.

The objective function of the optimal control scheme is to minimize the total operation cost described in the above equation.

Owing to the operational requirements, the minimization of the objective function *Min(TOC)*, is subjected to the following constraints:

$$P_{g,t} = \sum_{EVi}^{Nev} P_{EVi,t} + \sum_{WGi}^{Nwg} P_{WGi,t} + \sum_{Li}^{Nb} P_{Li,t} + P_{loss,t} \quad (4)$$

Power output limits for the participants in power regulation are expressed by:

$$P_{EV,\min} \le p_{SMi}(t) \le P_{EV,\max} \quad (5)$$

$$0 \le E_{EVi,\text{int}} + \int p_{EVi}(t)dt \le E_{EVi,\max} \quad (6)$$

where P_{EVi} and E_{EVi} represents the power flow and energy of an PHEV aggregation. $P_{EVi,max}$ and $P_{EVi,min}$ are the upper and lower bound for V2G power. The energy stored in the battery will change from the initial state $E_{EVi,int}$, but should not exceed the battery capacity $E_{EVi,max}$ nor become negative value. The boundaries of PHEV charging and discharging power are also included in the constraints.

Minimal charging energy limits are expressed by:

$$SOC \ge 50\% \quad (7)$$

The *SOC* in each PHEV should not be lower than 50% at the end of the charging period. That means the net energy gained from the grid should be above the half of the energy required for fully charging PHEVs.

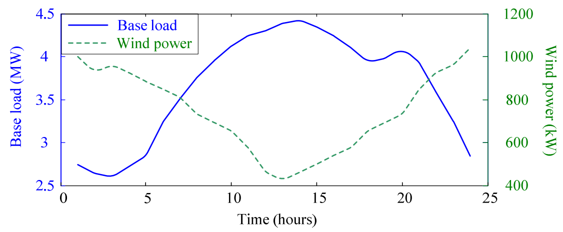
The limit for the SOC of PHEV is equivalent to the following equation describing the energy changes during the whole planning period:

$$\int p_{EVi}(t)dt = E_{EVi,\max} - E_{EVi,\text{int}} \quad (8)$$

where $p_{EVi}(t)$ is the charging or discharging rate of the PHEV aggregation *i*, $E_{EVi,\max}$ and $E_{EVi,\text{int}}$ are respectively the maximum and initial energy storages of the PHEV aggregation *i* at the end and beginning of the charging period.

Table 2. Simulation parameters for the power grid

Grid parameters		System parameters	
$P_{i,\max}$	420 kW	pEVi	0.03$/kWh
$P_{i,\min}$	60 kW	A	2e-9$/kWh2
$Q_{i,\max}$	600 kVar	B	0.03$/kWh
$Q_{i,\min}$	20 kVar	c	670$/h
$R_{l,\max}$	1.068 p.u.	pol	0.04$/kWh
$R_{l,\min}$	0.0575 p.u.	pos	0.04$/kWh
$X_{l,\max}$	0.8457 p.u.	Pup	4 MW
$X_{l,\min}$	0.0393 p.u.	Plp	2 MW



(a)

Fig. 3. Daily profiles of wind power generator and the load demand.

3.2 Simulation results

To develop the appropriate control scheme, the power supply and the consumption in this grid should be estimated. Fig. 3 shows the typical power profile of daily load demand and the wind generation plant. The parameters applied in the algorithm are listed in Table II. The operating cost in optimal control and uncontrolled scenario are listed in Table III. The average values of V2G power per hour are summed up during the regulation period in order to evaluate the participation of PHEVs in the control scheme. Compared to the uncontrolled charging scenario, the operation cost can be significantly reduced The reduced cost is mainly due to the participation of PHEVs into the load regulation which can flatten the demand profile and therefore exempt from the penalty for overload or oversupply. The charging profile of PHEVs in uncontrolled scenario and the V2G power profile in optimal control scheme are depicted in Fig. 4. The PHEV aggregation at bus no. 29 is selected to show the difference in V2G power when the revenue for PHEV participants is lowered. In order to analyze the V2G performance in response to the increment of regulation revenue, the revenue is set higher and the two set of results are compared. The bus voltage is an important factor for the power quality of the grid and should be maintained within a limited range according to the standard [11]. The maximum, minimum and average values of bus voltage during the regulation period are shown in Fig. 5. The voltage deviation can be restricted in a smaller scope which indicates the improved power quality.

The pattern of V2G regulation power under the different parameter setting for V2G revenue and cost fuel are compared in Fig. 6. Among the six PHEV aggregations in the distribution grid, the largest and smallest aggregations are selected to illustrate the change of V2G power pattern. From the simulation results, we can see that the intention to engage the PHEVs into the control scheme declines as the revenue needed to pay for V2G is set to a higher value. It is necessary to choose appropriate revenue for participants so that both sides can have benefits in this control scheme.

Table 3. Operating cost and V2G regulation power

	Uncontrolled scenario	Optimal control scheme
Operating cost	9.1354e3	7.1747e3
Sum of average power per hour at PHEV A1	1133 kW	1133 kW
Sum of average power per hour at PHEV A2	1648 kW	1648 kW
Sum of average power per hour at PHEV A3	1442 kW	1486 kW
Sum of average power per hour at PHEV A4	1339 kW	1419 kW
Sum of average power per hour at PHEV A5	927 kW	1011 kW
Sum of average power per hour at PHEV A6	618 kW	699 kW

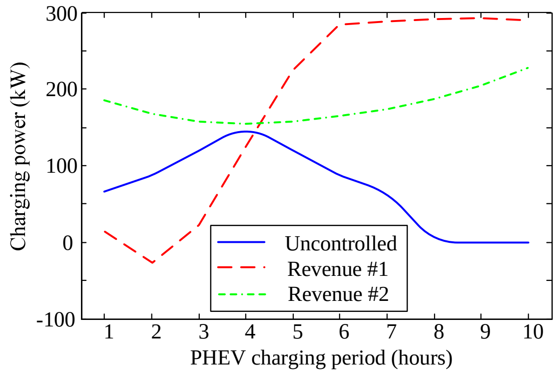


Fig. 4. Charging profile of the PHEV aggregation at bus no. 29 in the uncontrolled scenario and the optimal control scheme with the different revenues for V2G regulation power.

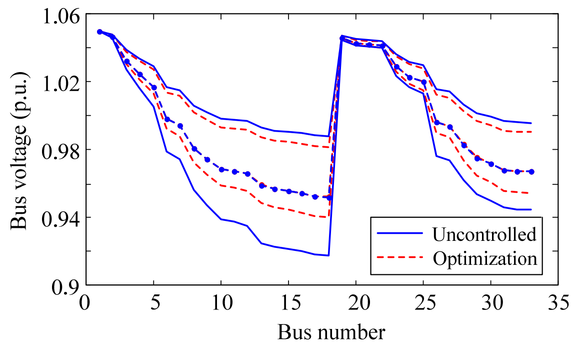


Fig. 5. Bus voltage in the uncontrolled and optimal control scheme: maximum voltage, mean voltage and minimum voltage during the planning period of time.

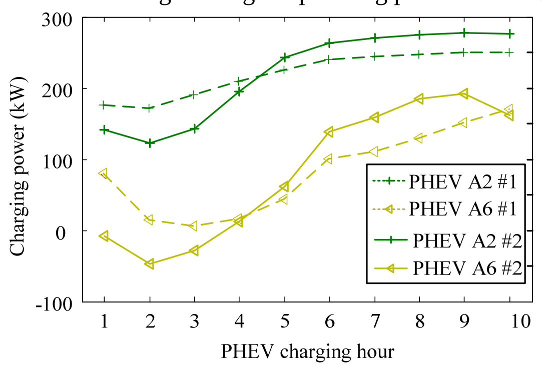


Fig. 6. Comparison of the V2G participation with the high and low revenues.

4 Frequency Regulation in Multifunctional Control Scheme

The V2G power at each hour is computed as the solution of the cost minimization control scheme, the signals are given out to each PHEV aggregation. To implement the hourly V2G power, not all the PHEVs are required to charge at all times. The idle vehicles can be considered to provide the frequency regulation, and get paid for its available power capacity. In this grid structure, the wind power generation keeps change due to the variation of wind speed, the V2G power can continuously compensate the power unbalance caused by the adjacent wind generator. As shown in the framework of the new distribution grid, the PHEV aggregation close to the terminal of the wind plant can be employed to flatten the power output of wind power generator by compensating the power variation during every small time interval.

The connection of wind power generator and PHEVs in the proposed grid is illustrated in Fig. 7. Some PHEV fleets that are close to the terminal of wind generator are able to have instant response to the power fluctuation. The simplified battery model, which is composed of a controlled voltage source and an internal resistance, is expressed by equation (9). The internal resistance is supposed constant during the charge and discharge cycles in spite of the varying current, and the impedance is specified by the battery manufacturer [12-13]. The battery current, output voltage and power transfer with the grid are calculated using:

$$E = E_0 - K\frac{Q}{Q - idt} + A\exp(-Bidt) \quad (9)$$

$$U_{bat} = E - RI_{bat} \quad (10)$$

$$P_{bat} = n_{bp}U_{bat}I_{bat} \quad (11)$$

where E and E_0 represent the open-circuit voltage and battery constant voltage. Q and R denote the battery capacity and internal resistance. U_{bat} and I_{bat} are the output voltage and current. Several battery cells are wired in parallel and series in the on-board battery pack so the power transfer is calculated by multiplying n_{bp}.

The variation of wind speed is shown in Fig. 8, and the voltage at wind power bus is varying consequently. As shown in Fig. 9, the terminal voltage can be stabilized by using V2G power installed close to the wind generator. The power regulation of PHEV aggregation in the same timeframe is also given in Fig. 10. It can be seen from the simulation results that the power supply of PHEVs for wind power drop can be roughly offset by the power absorbed during the excessive generation period; thus the net variation of energy is zero. This is a remarkable advantage of frequency regulation over the V2G power regulation, since the approximate mean of long-term energy request is zero and no energy consumption is counted in the cost defined by equation (1).

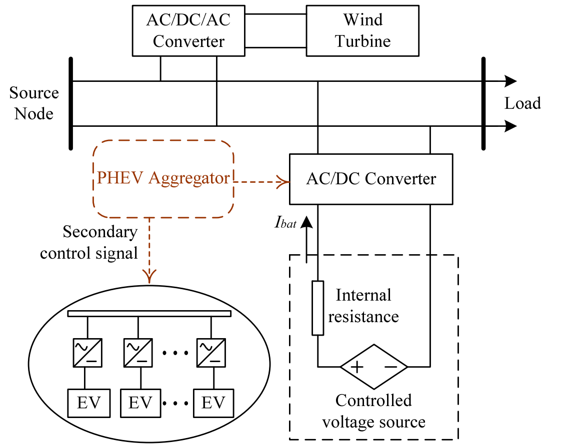


Fig. 7. Power interface for connecting the new components.

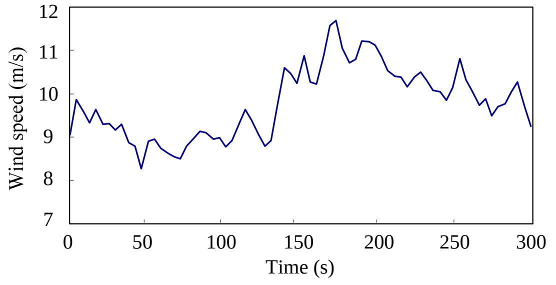


Fig. 8. Wind speed on a smaller time scale.

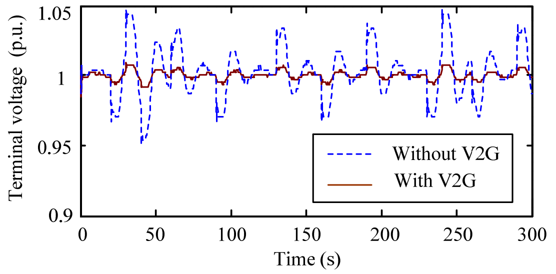


Fig. 9. Voltage profile at the terminal of wind generator with and without the power compensation from V2G.

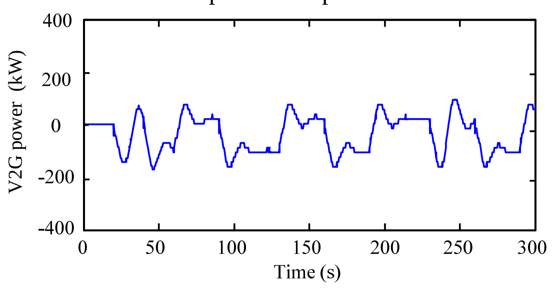


Fig. 10. Regulation power of V2G installed at the terminal of wind generator.

5 Conclusion

In this paper, the wind power generators and PHEVs with the capability of V2G operation are integrated in the distribution grid. A coordinated control method is derived to regulate the charging and discharging of PHEVs. The regulation power of V2G operation can be utilized to flatten the load demand and therefore minimize the cost and improve the power quality. The appropriate regulation revenue should be set to balance the operating cost and the incentive for participating in V2G program. At the meanwhile, the PHEVs in idle state can participate in frequency regulation and compensate the continuous variation of wind power. In both sections, the characteristics of on-board battery are taken into account to form the PHEV model. The simulation results verify that the V2G power can be effectively utilized for multiple functions.

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