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A review on the economic dispatch and risk management of the large-scale plug-in electric vehicles (PHEVs)-penetrated power systems

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ABSTRACT

Nowadays, the deterioration of ecological environment and the ever rising gas price make green transportation our relentless pursuit. Energy-saving, low-emission even zero-emission electric vehicles (EVs) have been considered as one solution to the problem. With the rapid development of plug-in electric vehicle (PHEV) and forceful support and incentives from the government, PHEV and its supporting facilities are being gradually popularized. When randomly being connected to the power grid in large scale, PHEVs will bring new challenges to power grid in operation and management. This paper presents an overall review on historical research on power system integrated with electric vehicles and especially focuses on economic dispatch of PHEV in the electricity market. The paper also discusses the joint scheduling problem considering other renewable energy resources and risk management of PHEV-penetrated power systems.

Contents

1. Introduction

The deterioration of ecological environment and the ever rising gas price make green transportation our relentless pursuit. The goals to lower energy consumption, improve energy efficiency and protect the environment have stimulated people's interest towards electric vehicle (EV). The whole world now regards EVs as a possible alternative mode of transportation for significant factors as low energy cost, high energy efficiency and low emission. The revival and boom of EV can dramatically decrease the dependency on crude oil, reduce air pollution, and alleviate greenhouse effect.

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Nomenclature

i	time interval i
π_f	the price for producing electric energy with fuel
π_g	the price of the grid
π_{gi}	the price of the grid in interval i
E_i	energy exchange in interval i
T_i	the length of interval i
$P_{\max}$,$P_{\min}$	power constraints decided by both the battery and the power grid connection constraints
$E_{\max}$,$E_{\min}$	upper and lower limit of the energy storage capacity of the battery
$E(0)$	energy storage in the battery at the start of the optimization
$P^{DA}(\,)$	the scheduled grid purchase
$P^{DA}(\,)$	the day-ahead electricity price
$d^{DA}(h)$	total demand in time interval h
chg( )	the power charged to PHEV
dchg( )	the power discharged from PHEV
$\mathrm{chg}_{\max}$	batteries capacity
η_{chg},η_{dchg}	charging and discharging efficiencies
$U(h)$	PHEV battery level at the end of time interval h
$P^{RT}(\,)$	real time imported power decisions
$\rho^{RT}(\,)$	the real time price
$\rho^{RTF}(\,)$	price forecast
$d^{RT}(\,)$	the real time load
$d^{RTF}(\,)$	load forecast
$P^{RTF}(\,)$	imported power decisions forecast
NPHEVs	the number of PHEVs
h	time interval h
k	the current time interval

An EV (also referred to as an electric drive vehicle, EDV), different from the internal combustion engine (ICE) vehicle, uses one or more electric motors or traction motors for propulsion [1]. In the USA, hybrid electric vehicles (HEVs) have already been accepted as a mainstream transportation option with close to a million hybrids on the road [2]. In China, the research and development of EV are also proceeding at a tremendous speed. There are now many types of EV existing in the market, pure EV, hybrid electric vehicle (HEV), fuel cell vehicle (FCV) and plug-in hybrid electric vehicle (PHEV). In this paper, the EV that mentioned most is PHEV for its convenient connection to the grid and its larger battery pack than a HEV [3]. According to Ref. [2], a PHEV contains at least: "(1) a battery storage system of 4 kWh or more, used to power the motion of the vehicle; (2) a means of recharging the battery system from an external source of electricity; and (3) an ability to drive at least 10 miles (16.1 km) in all-electric mode consuming no gasoline." Studies show that the wide spread use of PHEVs with an all-electric range sufficient to meet average daily travel needs could reduce per vehicle petroleum consumption by 50% [4].

PHEVs are being promoted all over world simulated by the growing awareness of environment protection and the support from governments. In order to efficiently integrate PHEVs into power systems, existing organizational structures need to be considered. Potential changes and challenges in the actors' long and short term planning activities should be discussed [5]. And to promote the PHEV market size, legislation of tightened air pollution regulation, establishment of infrastructures for PHEVs and standardization of PHEVs as well as their ancillaries are indispensable. Moreover, identifying potential customers' requirements is also necessary for EV manufacturers [6]. The development of EV has great potential, especially in developing countries. For instance, China is expected to become a testing ground for the promotion of PHEV for in big cities like Beijing and Shanghai in China, people are suffering traffic jams and severe air pollution brought by the booming of ICE vehicles. And at present, 72% of the vehicle purchasers in China are buying vehicle for the first time. Thus, the Chinese government intends to take this opportunity to allow people quickly adapt to EV. According to the "Twelfth Five Year Plan", by 2015 there will be more than 100 thousand of PHEV in Beijing and 150 million all over China. And by then China will have become a major supplier of EV in the world. Germen electric car company Mileworks also set its sights on China and first batch of electric taxis will be put to use in 2013 in Shanghai and other big cities in China. Of course, in China, the rapid development of electric vehicles is facing many problems. For instance, the high prices of EV block its promotion and the repeatedly charging or replacing batteries bring inconvenience to the users. In addition, the lack of infrastructure is also a big problem. At present, China lacks a large number of electric vehicles battery charging/replacement stations and professional maintenance enterprises, which are problems needing to be solved in the future [7,8].

With the rapid development of EV as well as forceful support and incentives from government, EV and its supporting facilities are being gradually popularized. When randomly being connected to the power grid in large-scale, PHEV are bringing new challenges to the operation and management of grid. As an important part of the Smart Grid, the development and increasing penetration of PHEV has profound significance to the construction of Smart Grid, to energy saving and to emission reduction. Taking the randomness of PHEV's charging and discharging behaviors into consideration, significant uncertainty will be brought to the grid by the large penetration of PHEVs, which may greatly influence the operation and control of the power system. Therefore, realizing the communication between vehicle and grid as well as implementing effective load forecasting and scheduling of PHEVs will become the core businesses of generalized dispatch in the future Smart Grid.

This paper is organized as follows. Section 2 presents an overview of the load characteristics of PHEVs and their impacts on the power systems to reflect the necessity for economic dispatch. The emphasis is laid in Section 3 which discusses the economic dispatch of PHEVs in details. Joint scheduling of PHEV with other renewable energy is briefly introduced in Section 4. And Section 5 shows the risk management of PHEV-penetrated power system. At last, Section 6 is the conclusion and an outlook for the future work.

2. The characteristics of PHEV and its impact on the power systems

Considering the random charging behaviors of PHEV, widespread adoption of PHEV will bring significant uncertainty to the operation and control of power systems. And there are both negative and positive impacts on the power grid. The authors of Refs. [4,9] considered that the introduction of PHEVs could impact demand peaks, reduce reserve margins, and increase prices. If no measures are taken, the uncontrolled charging behaviors of PHEVs may lead to negative consequences on voltage control, power quality (harmonics and subharmonics), supply and demand balance, relay protection. In addition, there are also some positive impacts may be brought by PHEV technology. For power companies, the rapid development and wide application of PHEV means huge increase in sales of electricity, which can promote the development of power industry. From the perspective of system operation, the PHEV is equivalent to a kind of distributed energy storage devices. Through V2G technology and smart grid technology, a PHEV has the potential to provide peak power during high demand periods, which can probably improve the sustainability and resilience of the electric power infrastructures and contribute to load leveling

[4,10]. Further, PHEVs can be used as storage devices to absorb excess renewable energy during off-peak hours and inject power back to the grid.

2.1. Load characteristics and load forecasting of PHEV

2.1.1. Load characteristics

PHEV is a kind of special load that when charging its batteries, and has the same behave as the usual load to obtain power form the grid. However, unlike the usual load, in some cases, it can discharge to the grid as a storage device, as a backup power source. When being randomly connected to the grid in large scale, the stochastic nature of vehicle use [11] will bring significant uncertainty to the grid. Different from the traditional load, PHEV load is uncertain at different time and in different space. Thus, it is necessary to study the load characteristics of PHEV.

Ref. [12] analyzes a variety of factors related to the power demand of PHEV and establishes a statistical model of PHEV power demand. The authors adopt Monte Carlo simulation method to obtain expectation and standard deviation of power demand power of a single PHEV and further calculate the overall power demand of large-scale PHEVs. In Ref. [13], the authors establish a mathematical model of capacity needs for charging stations and the charging mechanism of public bus fleet which provides a theoretical basis for determining the actual charging mechanism of public buses and the capacity needs of charging station. However, the above two researches are limited to charging power demand without considering V2G mode. The authors of [14] propose a model of grid-connected PHEVs and simulate the 24-h random charging and discharging load curve of PHEV, taking into account the features of different types of PHEV. But there is no systematic analysis of the impact of charging and discharging behavior of a large number of PHEVs on the power system. In addition, the paper also uses a strong assumption that the charging start time is uniformly distributed. Paper [15] studies the probability distribution of charging and discharging power of PHEVs by using stochastic simulation method. The simulation results clearly show that: both the levels of the total charging load and the total output power V2G approximate the normal distribution. However, the simulation results are still based on many assumptions, such as each type of EVs charge or discharge only in their specific charge/discharge period and during charge/discharge period, the specific charge/discharge start time is still uniformly distributed.

2.1.2. Load forecasting

According to Pike Research, from 2010 to 2015, the global EV sales will be over 3.1 million and more than 5.1 million PEVs (plug-in electric vehicles) will be sold globally by 2017. It also predicts that over 80 different models of PEVs will be found on roadways across the globe by 2013 [16]. Asia-Pacific region will be the world's largest market of EV and its charging facilities. China, Japan and South Korea's governments all have committed to invest in construction of EV charging infrastructure and formulate policies to promote the consumption of EVs. Thus, with ever increasing penetration of PHEV, forecasting PHEV load is indispensable for avoiding overload and developing reasonable dispatch plans.

2.2. The impacts brought by the charging behavior of PHEV

Many studies have evaluated the impacts that PHEVs will bring to the grid due to their charging behavior. Some scholars study this topic from load balance while domestic researches in China mainly aim at harmonic pollution and power reduction caused by the charging stations. There are many researches concerning whether existing or planned power generation/supply capacity is able to meet the load growth caused by electric vehicle charging [9,17,18]. Ref. [9] studies the potential impacts of PHEVs on electricity demand, supply, price, generation structure, and emissions levels in 2020 and 2030 in the 13 U.S. reliability regions defined by the North American Electric Reliability Council (NERC) and the U.S. Department of Energy's (DOE's) Energy Information Administration (EIA). This research uses the Oak Ridge Competitive Electricity Dispatch (ORCED) model developed by the Oak Ridge National Laboratory of U.S. Department of Energy to analyze each region in 2020 and 2030 under seven different scenarios. The authors conclude that additional capacity or demand response program is needed in each region to respond to the power demand of PHEV. In Ref. [17], Wynne et al. conduct a scenario-based analysis of the California electricity market and find that under high and low growth scenarios of PHEV, the power load will increase by 2% and 8%, respectively. In paper [18], Letendre uses a bottom-up approach without considering specific charging facilities while only considering fully meeting the natural growth of PHEV. The author studies the PHEV's effects on power load under three scenarios, the optimal charging mode, night charging mode and twice a day charging mode, in the U.S. state of Vermont. Studies have shown that the power grid of Vermont could support 10 million electric cars' charging at night while the peak-hour charging will cause great problems on the power supply.

2.3. The impacts and significance of the discharging behavior (V2G) of PHEV

V2G, short for vehicle to grid, describes a system in which plug-in electric vehicles communicate with the power grid to sell demand response services by either delivering electricity into the grid or by throttling their charging rate [19]. For PHEVs, when they participate in V2G, their rechargeable battery capacity is used to provide power to the grid in response to peak load demands, spinning reserve or regulation requests. Then these vehicles can be recharged during off-peak hours at cheaper rates, helping to absorb excess night time generation as a distributed battery storage system to buffer power [19,20]. The concept of V2G was first raised by Kempton and Letendre [21]. Kempton et al. conducted some following researches concerning the feasibility and potential benefits of PHEV as a kind of energy storage devices [20,22–24], and calculate and evaluate the revenue and costs for PHEVs to supply electricity to three electric markets (peak power, spinning reserves, and regulation) which combining the benefit for both PHEV users and the whole electric system. Also, PHEVs provide ancillary service to the grid by means of V2G connection to increase stability and reliability of the electric grid, lower electric system costs and meanwhile obtain financial return for the service [20].

Furthermore, V2G technology, important part of the smart grid, enables the bi-directional interaction between grid and vehicles, which greatly affect the future commercialization of EVs operation mode. And using PHEV as a power resource for the grid by means of V2G technology can bring considerable economic and environment benefits. Analysis of the UK domestic car use data shows that private cars are occupied by driving on the road only for 5.2% of the time, theoretically 94.8% of the remaining time providing opportunity for load shifting or secondary function. With wide application of V2G and smart grid technology, PHEV's charging and discharging will be deployed with unified procedures according to the established charging and discharging strategy. PHEV users, power companies and automobile companies will realize win-win. (1) For PHEV users, they can recharge their PHEV at low price (during off-peak hours) and sell electricity back to the grid when the price is high (during peak hours) to obtain subsidies from power company, which will bring a cost reduction in PHEV usage. (2) For power grid companies, the rapid development of V2G and Smart Grid will help alleviate the power utility pressure brought by PHEV's large penetration. Moreover, they use PHEVs as energy storage devices for the load regulation and improving operation efficiency and reliability. (3) For automobile companies, high cost is one of the most important factors that impede the popularization of PHEV nowadays. V2G technology effectively reduces the usage cost of PHEVs for consumers, which in turn is bound to promote vigorous development of PHEVs. Thus, these companies will benefit a lot from the boom of PHEV sales.

As to the aspects of renewable energy, V2G technology enables the integration with large-scale wind power, solar power and other new energy sources. New energy sources as wind power is greatly affected by the weather, geography, and time, whose unpredictability, volatility and intermittence made it impossible to be directly connected to the grid in case of affecting the grid stability. Currently, more than 60% of the total power from wind energy power plants is not stable enough to connect to the grid. Therefore, through V2G technology, EVs can be used to store wind and solar power, and then send the power back into the grid stably.

2.4. Summary of the impacts

Impacts of PHEVs on the power systems involve the generation, transmission and distribution networks and the effect area and degree should be determined based on different situations. Although we can use some unified mathematical models and methods to analyze these impacts, but the actual situation must be considered, such as the extent and range of PHEV penetration.

PHEV load changes over time and space. Thus, in space we need to consider the vehicle owners' driving habits and in time we need to consider the users' charging habits. It is not realistic to carefully simulate the behaviors of each PHEV especially after the wide application of PHEV but to study many PHEVs as a whole in a network. Current studies focus on the energy supply mode (charging battery mode or replacing battery mode), economic dispatch and other related issues of PHEV. As to V2G technology, though there are already some theoretical studies, researches into this area are still very preliminary. To really develop and implement V2G technology, a matched electricity market mechanism is necessary.

3. The economic dispatch strategy of PHEV

3.1. Research frame

Current studies have shown that PHEVs have a complex impact on the power systems. It is widely known by the academic communities that, the most effective dispatch and control method is to reduce the negative impact of PHEVs and make use of their function as energy storages. Determining and formulating the charging and discharging strategy of PHEVs in a relative long period (for example, in the next 24 h) are the main task of the dispatch of PHEV. The main purpose is to lower the total charging cost, reduce network loss, shift peak load, stabilize the intermittent renewable energy and achieve other system operational objectives.

Usually, we study the PHEV dispatching from the following aspects, dispatching mode, modeling and algorithm.

3.2. Current studies on the economic dispatch of PHEV

3.2.1. Dispatch mode

The general idea of dispatching the PHEV's charging and discharging mainly contains two steps: (1) regional dispatching center formulates scheduling plan by combining the actual situation of the power plants and power load after predicting available battery capacity of PHEV in one area; (2) charging station will reasonably arrange PHEV's charging and discharging behaviors as well as the corresponding charging and discharging power after receiving the scheduling plan information from the dispatch center.

Most of the existing literature on PHEV dispatch problem is about centralized dispatch mode of transmission system operator. However, with the rapid growth of PHEV in the future power system, centralized scheduling mode may lead to curse of dimensionality in the corresponding optimization problem. Moreover, high requirement of communication channel which is used to collect status information and send dispatch instructions between operator and each PHEV greatly challenge the reliability and bandwidth of communication network. From this we will see that though centralized dispatch mode will help obtain the global optimal solution of dispatch problems in theory, this approach will still face great difficulties when be implemented in large-scale power system under current technology condition. A more realistic solution is to take hierarchical scheme for dispatching PHEV [25]. The core idea of hierarchical scheme is to divide the power system into two or more layers based on the voltage level and continue further divide the layer of distribution system into several regions. For each region, the distribution system operator or an aggregation agent [26] is responsible for the dispatch of the PHEV within this region.

Distribution system operator or the aggregation agent works as a single entity involved in the dispatch process of the transmission system and the transmission system operator no longer needs to care about specific charging and discharging strategy of each of PHEV. By adopting this dispatch scheme, PHEV dispatch problem can be decomposed into a transmission system dispatch problem and some regional dispatch problems. Thus, we can solve the traditional transmission dispatch problem by applying existing methods and focus on the distribution system optimal dispatch of PHEV within different regions.

3.2.2. Dispatch of PHEV under different charging modes

According to Ref. [27], there are four charging mode of PHEV, namely uncontrolled charging, delayed charging, off-peak charging and continuous charging.

1. uncontrolled charging

Vehicle owners charge their vehicles exclusively at home in an uncontrolled manner. The PHEV begins charging as soon as it is plugged in, and stops when the battery is fully charged.

2. delayed charging

All charging occurs at home. However, it attempts to better optimize the utilization of low-cost off-peak energy by delaying initiation of household charging until 10 p.m.

3. off-peak charging

Also assumes that all charging occurs at home in the overnight hours. However, it attempts to provide the most optimal, low-cost charging electricity by assuming that vehicle charging can be controlled directly or indirectly by the local utility.

4. continuous charging

The vehicle is continuously charged whenever it is not in motion, using facilities charging both at home and in public charging stations.

Here, we review current researches concerning the dispatch of PHEVs by classifying them into two kinds based on whether the charging behavior is controlled.

3.2.2.1. Uncontrolled charging mode. Under this charging mode, scholars mainly study the load forecasting [28,29] of PHEV and the impact of uncontrolled charging mode on the power systems.

We can consider both case 1 and case 4 in [27] are uncontrolled charging mode and in both cases the vehicle owners charge their PHEVs based on their habits and needs. The authors present the hourly charging profile for a fleet of vehicles from which we find that under uncontrolled charging mode. The profile shows that charging is concentrated in peak hours especially under the continuous charging mode which has less off-peak charging. The authors of Ref. [30] use two figures to illustrate the impacts of evening charging of 1, 5, and 10 million PHEVs on total California Independent System Operator system load, including one figure that shows load curves with uncontrolled PHEV charging superimposed and the other shows the controlled scenario. From the comparison, we found that uncontrolled charging will result in a significant increase in electricity demand at peak hours, and the larger penetration, the higher peak power demand increase will be. Upgrades to the bulk electric system may help handle high penetrations of PHEVs. However, that will also bring a capacity surplus under normal operating conditions. The optimal charging time is between the evening and early morning when system load reaches the lowest. When the charging behavior is well controlled and limited during off-peak hours, the load curves will became more smooth, and the use of existing equipment will be optimized.

Under uncontrolled charging mode, the discharge behavior of PHEV can also be considered as optimization variables. Ref. [31] establishes a unit commitment model to minimize the combination of the operating cost as well as CO_2 emission amount of generators with 24 h a day considering the charging and discharging of PHEV. The authors introduce the variables representing the charging and discharging power of PHEV into constraints like load balance, spinning reserve, charging and discharging power constraints and capacity constraints. The authors solve the optimization problem under each charging mode mentioned in Section 3.2.2, respectively, and compare those results of different cases. The model considers the discharging power as constants (obtained by fitting the charging load curve) and optimizes the discharging power in different period under uncontrolled charging mode. Results show that under uncontrolled charging mode, the corresponding unit output increases, resulting in the increase of unit operating costs and CO_2 emissions and a great impact on the peak load. Under this charging mode, the charging demand of PHEVs is very high, thus excessive number of PHEVs may result in no solution to the optimization problem.

3.2.2.2. Fully controlled charging mode. Charging and discharging behaviors of PHEV can be controlled directly or indirectly [31]. One of the direct guide methods is introducing an aggregator to control the charging and discharging of PHEV within a certain period and regulate the behavior of the vehicle owners based on the operation condition [32]. Indirect guide methods include guiding or influencing the PHEV owners' behavior by using the price mechanism in the power market (for example, peak price and off-peak price) and the government incentive policies.

Qin and Zhang [33] conducted a theoretical study on charging scheduling to minimize waiting time for EV charging in a large-scale road network by calculating the theoretical lower bound of charging waiting time. This study is only concerned with the charging scheduling without considering the V2G technology. If both the charging and discharging of PHEV can be fully controlled and optimized, we will have a fully optimized mode which is an ideal operating state.

Paper [31] also contains the optimization under this fully controlled charging mode. It turns out that the load curve under fully controlled charging mode is very similar to that of the delay charging mode (mentioned in Section 3.2.2) and the optimal value of objective function of this mode is the lowest among the four charging mode (Section 3.2.2).

The models above do not mention the influence of electricity price, while there are also some other dispatch models with electricity price, considering benefits from different perspectives.

From the perspective of individual vehicle owners, optimized charging and discharging of PHEV will bring benefits to them. An on-line energy management (EM) strategy is proposed in Ref. [34] by Kessels et al. This on-line optimization algorithm aims at minimizing the costs for taking energy from each power source (the grid and the battery) and also considers dynamic energy prices that change over time. The calculation model is:

$$\max_{E_i} \sum_{i=1}^{n} E_i \times (\pi_f - \pi_{gi}) \tag{1}$$

Constraints:

$$P_{\min} T_i \le Ei \le P_{\max} T_i \quad i = 1, n \tag{2}$$

$$E_{\min} \le E(0) + \sum_{j=1}^{i} E_j \le E_{\max} \quad i = 1, n \tag{3}$$

Ref. [34] also points out that the plug-in situation is decided by the comparison of the two prices (π_f, π_{gi}) in every time interval to yield maximum profits. When π_{gi} is lower, PHEV charge from the grid to the battery. On the contrary, if π_f is higher, PHEV can retrieve energy from the battery and deliver it to the grid. Further, if taken efficiency coefficient into account, the optimization model will be more complex and one more plug-in situation—neither charge nor discharge will be added. In this strategy, the larger the differences between the two prices, the larger profits. However, the above strategy just focuses on the PHEV users' benefit without considering the economic benefit for the whole power grid.

Considering the difference in the power market model among countries, in those countries where there are retailers existing in the power market, the charging and discharging strategy of PHEV has a great influence on the retailers' benefit. Doostizadeh et al. [35] proposes an optimization technique to minimize a retailer's cost who controls charging and discharging of PHEVs during a day and considers the impact of time variant tariff schemes on customer behavior. The authors model the behavior of customer by economic demand models and establish two models, a day-ahead dispatch model and a real-time operation model for a retailer in competitive electricity market. The day-ahead model which aims to minimize a retailer's energy cost while meet its demand is:

$$\min \sum_{h=1}^{N} P^{\mathrm{DA}}(h) \times \rho^{\mathrm{DA}}(h) \tag{4}$$

Subject to:

$$P^{\mathrm{DA}}(h) = d^{\mathrm{DA}}(h) + \sum_{v=1}^{\mathrm{NPHEVs}} (\mathrm{chg}(h) - \eta_{\mathrm{dchg}} \times \mathrm{dchg}(h)) \tag{5}$$

$$U(h) = U(h-1) + \eta_{\mathrm{chg}} \times \mathrm{chg}(h) - \mathrm{dchg}(h) \tag{6}$$

$$0 \le \mathrm{chg}(h) \le \mathrm{chg}_{\max} \tag{7}$$

$$0 \le \mathrm{dchg}(h) \le \mathrm{dchg}_{\max} \tag{8}$$

$$U_{\min} \le U(h) \le U_{\max} \tag{9}$$

And the real-time model which helps the retailer adjust the imported power to meet its actual load in the spot electricity market is:

$$\min\left[(P^{\mathrm{RT}}(k)-P^{\mathrm{DA}}(k))\times\rho^{\mathrm{RT}}(h)+\sum_{h=k+1}^{N}P^{\mathrm{RTF}}(k)-P^{\mathrm{DA}}(k))\times\rho^{\mathrm{RTF}}(h)\right] \tag{10}$$

Subject to:

$$P^{\mathrm{RT}}(h)=d^{\mathrm{RT}}(h)+\sum_{\nu=1}^{\mathrm{NPEVs}}(\mathrm{chg}(h)-\eta_{\mathrm{dchg}}\times\mathrm{dchg}(h)) \tag{11}$$

$$P^{\mathrm{RRT}}(h)=d^{\mathrm{RTF}}(h)+\sum_{\nu=1}^{\mathrm{NPEVs}}(\mathrm{chg}(h)-\eta_{\mathrm{dchg}}\times\mathrm{dchg}(h)) \tag{12}$$

and (6)–(9).

Their results show that time variant tariffs programs adopted by the retailer effectively flatten the load curve. What is more, discharging of PHEV batteries in peak period and charging in non-peak period will minimize the retailer's cost.

3.2.3. Algorithm

The scheduling problem for the PHEV is characterized by high dimension, nonlinear and non-convex, which makes the widely used algorithms in the traditional power system scheduling optimization such as the interior-point method do not have global convergence. In Ref. [36], Sojoudi and Low consider the scheduling problem for the PHEV charging to be a joint OPF-charging (dynamic) optimization which is a highly non-convex problem. The authors look for the global optimum to the joint OPF-charging optimization by solving its convex dual problem whenever the duality gap is zero for the joint OPF-charging problem after proving that the duality gap is zero for the joint OPF-charging optimization if it is zero for the classical OPF problem.

Usually, we can adopt two kinds of global optimization algorithm according to whether the objective function and constraints are continuously differentiable [25]:

1. When the objective function and constraints are continuously differentiable, we can apply Lagrangian multiplexer method, Gold-Price algorithm [37], etc.
2. When the objective function and constraints are not continuously differentiable, heuristic searching algorithms are usually adopted, such as particle swarm optimization (PSO), genetic algorithm (GA).

4. Joint scheduling of PHEV with other renewable energy

One of the goals of smart grid is to integrate large amounts of renewable energy into the power grid [38]. Except EV, renewable energy resources such as wind power, solar are also playing a major role in meeting the increasing demand for electricity, reducing reliance on gas as well as significantly decreasing greenhouse gas (GHG) emissions [39]. Paper [15] develops a stochastic economic dispatch model which considers the wind generators and uncertain output of PHEV. In Ref. [40], Marano and Rizzoni model a multi-configurable personal eco-system with a PHEV and tend to conduct an energy and economic evaluation of PHEV and their interaction with the power grid and the energy market. The model uses a set of data for the State of Ohio, including cost of energy, potential photovoltaic capacity, wind patterns and government regulations and incentives. The authors find that this integration helps increase the economic viability of renewable sources and strongly reduce CO_2 emissions.

Taking the joint scheduling of PHEV and wind power as an example, PHEVs can be used to absorb excess wind power [38] and to store the power generated by other renewable resources which is not stable enough to connect to the grid. China is expected to have more than 100 million kW of installed wind power capacity by 2020. In the period between 2010 and 2020, the core problem is to increase the ability and efficiency of wind power digestion. The development of smart grid and the construction of charging infrastructure provide the basis for realizing the joint scheduling of wind power and PHEV energy storage. Ref. [41] is an example of joint scheduling of wind power and PHEV in China which studies the feasibility of the coordination of the controlled charging of PHEV and the fluctuation of wind power. Yu et al. propose a wind power–PHEV joint scheduling model with an objective to limit fluctuations of equivalent load in the grid. Through scenario analysis of the North China Power Grid and the Northwest Power Grid, they verify the feasibility of using PHEV–wind power coordination method to digest excessive wind power overnight. With the increasing number of PHEV connecting into the grid, the effects of the PHEV–wind power coordination method on improving load characteristics and absorbing excessive wind power are also increasing correspondingly. Thus, the coordination and complementarity of PHEV and wind power will improve the efficiency of renewable energy connected to the grid.

5. Risk management of PHEV-penetrated power system

The explosive growth of PHEV will bring not only benefits but also risks. Risk dispatch management attempts to obtain the total maximal of revenue or reduce the cost and risk of system [42], aiming to solve the uncertainty of PHEVs' behavior. It is very hard to give an accurate load forecasting of the PHEV, so the penetration will bring about risks for systems and indeterminacy for dispatchers. Usually, load demand forecast error, outages of generators and transmission lines all bring risk to the system. However, large penetration of renewable energy, such as PHEVs, is raising new risks so that the extra operational risks caused by them must be carefully analyzed and investigated.

Though not much work has been done concerning the risk dispatch management of power system integrated with PHEVs. We can borrow the idea and the method of risk management of wind-penetrated system. In Ref. [42], the authors reviewed the risk dispatch management methods of wind power in power market. Li et al. propose an optimal economical dispatch (ED) model and develop a method to estimate risk and manage hybrid power systems for the short-term (24 h) operations in Ref. [43]. They adopted value at risk (VaR) which is a popular method to evaluate financial risks and integrated risk management (IRM) separately to assess the risk, so that an optimal tradeoff between the profit and risk can be made for the system operations.

Stochastic dispatch of PHEV will increase the uncertainty of power load in the grid, thus more spinning reserve or any other power which has quick response are needed to ensure the safe operation of power system. However, high cost of spinning reserve forces the grid operator to find a balance between system security and cost. In this case, dispatch models based on stochastic programming or combining with the financial risk management tools will be effective choices, such as chance-constrained dispatch model and dispatch model combined with conditional value at risk (CVaR), etc. In addition, demand-side management is another effective means to solve the problem of load fluctuation. Since PHEV has the feature of interruptible load and controllable load and is an excellent resource of demand response, grid operators should consider about how to guide the vehicle owners to participate demand response rather than rely on another demand response resource to suppress fluctuations of PHEV demand. Dispatch center should develop several dispatch strategies of different levels of risk. Vehicle owners will also face certain degree of economic risks for their charging or discharging habits are usually based on the forecast of electricity price. The forecast error may increase the cost of the vehicle owners. Participating in real-time demand response is the best choice for the owners to avoid such risks.

Under fully controlled dispatch mode, PHEV plays a vital role in both aspects of power and capacity. And PHEV batteries response fast and have high efficiency of charging and discharging. As a result, large-scale controllable PHEV can improve system quick-response ability, which is the shortage of nowadays power system dominated by thermal power. Therefore, in order to meet the demand of frequency modulation, batteries of PHEV can be used instead of system spinning reserve. In addition, batteries of PHEV have the function of not only charging and discharging, but power storage as well. For example, especially for region with large peak and valley difference ratio, the function of large-capacity power storage can be used in optimizing system load curve, which will decrease the need of startup and shutdown thermal turbines for peak shaving and largely reduce the cost of power grid operation.

6. Conclusions

This paper has mainly presented an overview of the economic dispatch and risk management of PHEV in electricity market. The burning problems of environment and the ever rising gas price rekindle the popularity of EV. Facing the upcoming boom of EV, we must prepare to perfect our electricity market to integrate with PHEVs. First, we should make it clear that how PHEV's large penetration impact the grid, which will help formulate reasonable scheduling plans to avoid the negative consequences and take advantages of the positive ones. Secondly, an effective strategy to control the charging and discharging of PHEVs are indispensable to avoid overloading, flatten the load curve, increase stability and reliability of the electric grid and provide ancillary service through V2G connection. Finally, the joint scheduling of PHEV with other renewable energy is also important for integrating renewable energy with the grid.

There are also some efforts can be made in the future, for example, the combination of the economic dispatch of PHEV and risk management. We not only need to consider the risk brought by PHEV but also hope to use PHEV as a quick-response resource to minimize the risk brought by more dynamic and violate renewable energy. Thus, research on this field will help evaluate the risk, and then minimize, monitor, and control the probability and/or impact of unfortunate events.

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