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Power system operation risk analysis considering charging load self-management of plug-in hybrid electric vehicles

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HIGHLIGHTS

- The interactive mechanism between system and PHEVs is presented.
- The charging load self-management without sacrificing user requirements is proposed.
- The charging load self-management is coupled to system operation risk analysis.
- The charging load self-management can reduce the extra risk brought by PHEVs.
- The charging load self-management can shift charging power to the time with low risk.

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ABSTRACT

Many jurisdictions around the world are supporting the adoption of electric vehicles through incentives and the deployment of a charging infrastructure to reduce greenhouse gas emissions. Plug-in hybrid electric vehicles (PHEVs), with offer mature technology and stable performance, are expected to gain an increasingly larger share of the consumer market. The aggregated effect on power grid due to large-scale penetration of PHEVs needs to be analyzed. Nighttime-charging which typically characterizes PHEVs is helpful in filling the nocturnal load valley, but random charging of large PHEV fleets at night may result in new load peaks and valleys. Active response strategy is a potentially effective solution to mitigate the additional risks brought by the integration of PHEVs. This paper proposes a power system operation risk analysis framework in which charging load self-management is used to control system operation risk. We describe an interactive mechanism between the system and PHEVs in conjunction with a smart charging model is to simulate the time series power consumption of PHEVs. The charging load is managed with adjusting the state transition boundaries and without violating the users' desired charging constraints. The load curtailment caused by voltage or power flow violation after outages is determined by controlling charging power. At the same time, the system risk is maintained under an acceptable level through charging load self-management. The proposed method is implemented using the Roy Billinton Test System (RBTS) and several PHEV penetration levels are examined. The results show that charging load self-management can effectively balance the extra risk introduced by integration of PHEVs during the charging horizon.

1. Introduction

Road transportation is a major source of pollution source and accounts for about 18% of global CO_2 emissions from fossil fuel combustion. CO_2 emissions from transportation are also growing at a faster rate than total CO_2 emissions in most countries [1]. In order to mitigate deteriorating air-quality and CO_2 emissions, many countries and local jurisdictions have introduced policies that encourage the adoption of electric vehicles (EVs). According to a recent survey of the International Energy Agency (IEA), EV sales are projected to reach 20–30% of the new vehicle market share in China by 2030, and 15% of the market in Canada by 2018 [2,3]. Plug-in hybrid electric vehicles (PHEVs), which combine the advantages of EVs and internal combustion engine vehicles, will likely be more widely adopted because of their mature technology and stable performance, and lower drivers "range anxiety" compared to all-electric vehicles. The growth of

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PHEVs penetration is expected to bring significant social and environmental benefits, yet at the same time it will introduce new challenges in the management of power systems. Regardless of the uncertainties regarding eventual levels of PHEVs penetration, electric utilities should be prepared to accept PHEV charging loads and explore synergies to make improve power system operation. For example, PHEVs can be coordinated to minimize power loss and improve load voltage profile [4–8] examined the impact of charging power on power quality and electricity demand. Another potentially important role of PHEVs is the supply of ancillary services. A charging power control method based on Nash Certainty Equivalence Principle (NCEP) in [9,10] was proposed to reshape smoother load curve.

There is already a rich literature on PHEV's control methods. Ref. [11] proposed a price driven control model based on congestion of internet traffic. A direct control method based on users choice was also proposed in [12] to investigate higher peak demand at the distribution level due to PHEVs and in particular their impact on residential distribution circuits. The analysis introduced several comfort indices to assess the impact of demand response (DR) on consumers' lifestyle [12]. A control model satisfying customer comfort constraints was developed for thermostatically controlled loads (TCLs) in [13], and subsequently expanded to manage energy-constrained electric loads, such as PHEVs and electrolyzers [14–16]. This control model was also used for controlled dispatching of distributed heat pumps to maintain online voltage stability of power system [17]. A conceptual smart charging model was proposed in [18] in which the driver demand has the highest priority, and the remaining spare charging time is optimally utilized to provide as many ancillary services as possible.

Although PHEVs can utilize excess power at night for their regular charging cycles, the random power demand of large PHEV fleets would impose significant stress on power system operation. Conversely, uncertain power outages would affect the charging of PHEVs. Probabilistic risk assessment can effectively handle random factors in power system security analysis and has been used to analyze power system integrating with renewable energy generation. In this approach, the fluctuation of wind and photovoltaic generation is modeled by a discrete method and the resulting multi-states of renewable energy generation are used to calculate system risk [19–21]. Besides intermittency due to renewable power generation, the impact of PHEV penetration on power system reliability was also investigated in [22]. A Monte-Carlo model considering the miles driven, and departure and arrival time of PHEVs was used to calculate composite power system reliability in [23]. Most studies that have to date analyzed the impact of demand response management (DSM) on power system risk focused on peak clipping and valley filling, and risk analyzed based on the reshaped load profile [24,25]. Ref. [26] presents a probabilistic reliability assessment methodology for DSM. Effective operate reserve rates rather than real market rates were used to control demand response, and preliminary results were presented for a system incorporating wind turbines illustrating how customers might be able to observe power system reliability information using a web-based monitoring system.

In this paper, we develop a smart charging model to simulate the time series power consumption of PHEVs. The model allows the state transition boundaries to be adjusted to achieve self-management of charging power without sacrificing end-use performance. The maximum control capability is predicted simultaneously based on an aggregator model. Load curtailment is determined by the traditional dispatching of generators and loads under different outage scenarios, and charging power control is used to reduce actual load curtailment. Finally, the operation risk for a whole day is calculated using the enumeration method. To maintain risk under an acceptable level, the charging power of each bus is controlled based on its proportional contribution to total risk. The main contribution of this work is to present an improved operation risk analysis method considering the detailed PHEV model, including the charging power aggregation and self-management model. The proposed method can reduce the conservation of previous risk analysis methods ignoring the influences of charging power control and further explain the interrelationship between the charging power and system risk.

The remaining part of this paper is organized as follows. Section 2 reviews the interactive mechanism between power system and PHEVs. Section 3 presents a brief introduction on the charging load self-management, including the smart charging model and aggregator simulation model. Section 4 describes the proposed operation risk analysis method considering charging load self-management. Case studies are discussed in Section 5. Conclusions are drawn in Section 6.

2. Interactive mechanism between system and PHEVs

Two approaches are broadly used to integrate PHEVs into power systems: the centralized charging mode, which is utilized in commercial charging stations and large-scale parking lots; and the distributed charging mode, in which users typically have charging panels in their residential garages or apartment complexes [27]. Regardless of the mode chosen by users, each individual vehicle represents only "noise" to the power system, hence the need to aggregate vehicles into large fleets, whose combined impacts are tangible for the grid, which is similar to the behavior of e.g. air conditioners. In traditional power system management, the operators reserve adequate generation capacity for these uncertain loads. Under high penetration rate of PHEVs, this approach is obviously not economical, especially at times when a small number of vehicles are connected to the system. Charging load is greatly affected by variability and limited predictability, but active control can be used to respond to system reserve capacity shortage signals and reduce the risk. Such an interactive mechanism between power system and PHEVs is illustrated in Fig. 1.

Three levels are required to represent this interactive mechanism. The first level is component level, where a smart charging model is used to calculate and control the charging trajectory of each individual vehicle. At this level, it is important to determine the switching status of PHEVs. The second level is aggregator level to mimic the function of real-time data acquisition, analysis and charging power control agency. We focus on the physical properties of aggregators in this mechanism. On the one hand, the aggregator gathers charging state of vehicles and converts them into aggregated load signal, which can be used by operators to analyze power system operation state. The aggregated load signal contains the aggregated charging power (P_E) and the maximum aggregated control capability (P_E^{min} P_E^{max}). On the other hand, the aggregator can optimally allocate the raw control signal to each individual PHEV. Finally, we conduct system optimization at the top (third) level using the enumeration method to calculate the system operation risk. The charging load control quantity, which is the raw control signal at this level, is decomposed into independent control command u_k to steer the charging load and maintain the risk under an acceptable level.

3. Charging load self-management model

3.1. Smart charging model

The charging trajectory of PHEVs is simulated following a recent smart charging model developed for TCLs [13–16]. The vehicle charging state can be determined as: