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The impact of PHEVs charging and network topology optimization on bulk power system reliability

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ABSTRACT

Exhausting fossil fuels and increasing environmental pollutions call for the wider deployment of plug-in hybrid electric vehicles (PHEVs), which enable the interactions of transportation and electric sectors. The extra loads for charging massive PHEVs could compromise the power system reliability and impose considerable stress on the power system. Transmission line congestions and generation capacity inadequacy could be caused under this circumstance. However, there is little literature which comprehensively studies the impact of large-scale PHEVs on the bulk power system reliability when smart grid technologies are incorporated including smart charging and flexible transmission topology control technologies. This work studies the impacts of different charging strategies and transmission network operation strategies on the bulk power system reliability with high PHEVs integration. An evolution strategy particle swarm optimization (ESPSO) algorithm is applied to optimize the charging load of PHEVs and shave the peak load. A network topology optimization (NTO) operation strategy is employed to lessen the transmission congestions and reduce the load curtailment. Based on the sequential Monte Carlo simulation method, these technologies are integrated into the reliability evaluation process. Numerical studies and sensitivity analysis are conducted on modified IEEE RTS-79 systems. The results verify the effectiveness of the technologies to realize the potential of existing power system infrastructures so as to relieve the stress caused by the PHEVs load, increase the available penetration of PHEVs and promote the bulk power system reliability which is meaningful for power system planning and risk management.

1. Introduction

With the global warming problem and environmental protection issue becoming increasingly intractable, PHEV attracts significant attention due to its energy conservation and environmental protection characteristics. According to the prediction of Electric Power Research Institute (EPRI), the PHEV fleet's penetration level in the U.S. will be up to 62% by 2050 in medium penetration scenario [1].

Although the large-scale utilization of PHEVs could bring about considerable benefits, the huge power demand from PHEVs will also bring considerable stress to the whole power system. According to the technical report of Oak Ridge National Laboratory, if the charging load of PHEV is not well controlled, the peak load could be easily increased which might cause generation inadequacy problem and lessen the generation system reliability [2–4]. At the same time, it will also pose adverse impact on distribution system and result in overloads on residential feeder circuit and transformers [5–7]. At a broader level, the transmission lines which feed the local substations may also be constrained if they are not well designed to accommodate the extra growth in PHEVs load [2]. Consequently, PHEVs integration will have significant impacts to the power system reliability which should be studied comprehensively at different levels.

More recently, new smart grid technologies are boosting the technology revolution of the power grid. PHEV could be regarded as a flexible, distributed energy storage and the smart charging strategy can help power system to operate in a more economic and reliable way. Some other transmission system control technology including dynamic thermal rating (DTR) [8], network topology optimization (NTO) [9], etc. can provide a more flexible operation mode to realize the potential transmission capacity of existing power system infrastructures to relieve the stress caused by the PHEV and enhance the system reliability. Therefore, this paper is focused on the significant and meaningful topic to study the impact of PHEV charging strategies and power system topology operation strategies on the bulk power system reliability.

Much research has been involved in the multiple issues with the PHEVs integration in the power system. The general impact of PHEVs

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on regional electricity supplies was studied in Ref. [1]. In Ref. [10] a probability distribution based PHEV charging load model in distribution system is established. Monte Carlo Simulation (MCS) is applied to simulate the charging power consumed by PHEVs considering different driving habits, daily mileages, ambient temperature effect, etc. In Ref. [11], deterministic and stochastic analytical methods are used to analyze the influence of PHEVs on distribution system operation issues including system losses, overloading levels, etc. The PHEVs integrated power system's spinning reserve requirement optimization problem is studied in Ref. [12]. Reference [13] proposes a coordinated charging model of PHEVs which is beneficial to the operational performance of distribution systems by minimizing system losses.

As for the impact of PHEVs integration on power system reliability, the risk assessment is implemented in different main functional zones which contain generation systems, bulk power systems (or composite generation and transmission systems), and distribution systems [14]. Most of the research on the reliability assessment considering PHEVs integration are focused on the distribution level [15–21]. A probability model of PHEV charging load was applied in Ref. [16] to study the influence of different electric vehicle types, penetration levels and locations on the reliability. The charging process of PHEV could also be scientifically controlled to mitigate its impact on distribution assets by performance and emission constraints [17]. In Ref. [18], two charging topologies (dispersed and centralized EV charging) are considered to study the potential of local vehicle-to-grid (V2G), and/or vehicle-to-home (V2H) on the reliability enhancement. The charging service reliability and the impact of battery-exchange mode on distribution system reliability are studied in Refs. [19,20], respectively. The public charging station planning is studied in Ref. [21] considering the distribution network reliability. At the generation level, reference [22] presents a probabilistic analytical approach of PHEV charging power to quantify its impact on the generation system reliability. In Ref. [23], the PHEV charging power is managed according to the generation capacity shortage signal. The impact of aggregation and bidirectional charging power control on the generation system adequacy is then analyzed. The coordination of PHEVs and reliability cost evaluation are studied in Ref. [24]. The available power capacity that electric vehicles can provide in the reserve market and its impact on reliability are analyzed in Ref. [25]. However, there is a lack of adequate study about the impact of PHEV's charging on the bulk power system level. In Refs. [26,27], basic probabilistic models are applied to simulate the charging load of PHEVs and evaluate its influence on bulk power system reliability. Under this circumstance, the charging load of PHEVs are based on the probability distribution of driving behavior and is not controllable. In Ref. [28], the authors also use probability based charging model and conclude that the control of charging start time and public charging percentage could help enhance the power system reliability. Nevertheless, as the most promising charging technology, smart charging should be considered in reliability evaluation due to its great potential in reducing the peak load and improving the system adequacy. Meanwhile, some charging characteristic including charging cost and participation benefit of V2G should be considered in the optimization model to derive more accurate PHEVs charging load patterns.

Furthermore, the existing work related to the impact of PHEVs charging load on the bulk power system is all based on a fixed transmission topology. However, some smart grid based technologies such as network topology control technology could optimize the system operation by changing the transmission network configuration, which is quite different from traditional optimal power flow (OPF) operation strategy based on fixed transmission topology. One effective way to change the transmission topology is to switch on/off the transmission lines. This dispatchable transmission idea is envisioned in Ref. [29] and it is formulated to be a mixed integer linear programming (MILP) problem called optimal transmission switching (OTS) in Ref. [30]. OTS can be adopted for meeting multiple operating requirements. In Ref. [31], OTS is incorporated into the unit commitment problem to reduce the congestion and generation cost. In Ref. [32], OTS is applied in dispatch and contingency analysis to satisfy the N-1 standard and cut the operation cost. In addition, reference [33] shows the effectiveness of OTS in power system planning to reduce the congestion and increase renewable energy utilization. Its impact on overall system reliability is also studied in Ref. [34]. Reconfiguration of high voltage substations is another way to enable the network topology control. As the transmission lines, load demands and generating units are connected to busbars by switchable equipment such as circuit breakers, different configurations could be realized by different states of switching devices, such as busbar switching. In Refs. [35,36], the busbar switching method is adopted in optimal operation of electric power system as a congestion mitigating tool to reduce operation cost and lessen the load curtailment. In Ref. [9], the integrated network topology optimization strategy including OTS and optimal busbar switching is formulated systematically as the NTO technology. More importantly, the realization of NTO does not require significant extra investment to upgrade the existing transmission network infrastructure. NTO technology will be an effective and economically feasible way to relieve the stress caused by the high PHEV penetration.

In this paper, the impact of different PHEVs charging strategies including probability distribution of PHEVs behavior based uncontrolled charging and ESPSO based smart charging on the bulk power system reliability is studied systematically. Meanwhile, a novel transmission topology operation strategy termed NTO is incorporated to promote the system reliability. The main contributions of this paper are listed as follows:

1) The PHEV charging on bulk power system reliability is studied in a more comprehensive manner by accounting for different charging strategies including smart charging.
2) NTO is considered in the PHEVs integrated reliability evaluation process for the first time.
3) Both smart charging and NTO are promising strategies for more fully utilizing the existing power system facilities so as to relieve the stress caused by massive PHEVs and improve the bulk power system reliability.
4) Monte Carlo simulation based evaluation process can capture the sequential characteristic of both PHEV charging load, initial system load, and system component states, which eventually leads to a more accurate reliability evaluation.

The rest of the paper is organized as follows: the PHEV load demand model is discussed in Section 2; the PHEV charging scenarios and solving algorithm are presented in Section 3; the NTO model is introduced in Section 4; the PHEV charging and NTO incorporated bulk power system reliability evaluation procedures are shown in Section 5; the case studies are illustrated in Section 6; the discussion is presented in Section 7 and conclusion and future work are drawn in Section 8.

2. PHEV load demand model

2.1. Driving characteristic analysis of PHEVs

National Household Travel Survey (NHTS) 2009 [37] contains the comprehensive and authoritative vehicle travel data in the U.S. so far. The charging process of PHEVs has a tight relationship with the daily driving characteristics, such as the departure time, arrival time, and daily travel mileages. Hence, such data was analyzed to generate the probability distribution of these influencing factors. Since a car may have multiple trips in one day, the daily mileage is defined as the summation of all trip mileages in a day. It is also defined that the departure time is the starting time of the first trip, and the arrival time is the ending time of the last trip. Based on the data in NHTS 2009, MATLAB best-fit criterion and analysis were applied to generate the probability distribution functions (PDFs) of these daily driving