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Impact of electric-drive vehicles on power system reliability

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ABSTRACT

The paper assesses the impact of electric-drive vehicles (EDVs) on power system reliability. For this purpose, it introduces direct optimization of reliability indices LOLE (Loss of Load Expectation) and EENS (Expected Energy Not Served). The analysis is performed by the proposed optimization model applied in different strategies of charging/discharging of EDV batteries. In general, it is observed that numerous EDVs increase the system loading resulting in weakening of the system reliability. However, the paper comes to the conclusion that EDVs could support the system to some extent, depending on the penetration level of EDVs, if an appropriate charging/discharging strategy is applied. Besides this technical question the paper also addresses the costs of the system reserve provision required for the system reliability support. A system operator could engage additional power plants in order to maintain the system reliability or, if this is more cost effective, the support could be provided by EDVs applying the appropriate charging/discharging strategy. The paper proposes a new approach for the techno-economic assessment of possible solutions that are ranked by its price-performance ratio.

1. Introduction

With increasing environmental awareness, technology advances and high liquid fuel prices, EDVs (electric-drive vehicles) are gaining ground as a promising alternative to internal combustion engine vehicles. The transition from fossil fuels to electrical energy in automotive sector will bring many obvious benefits to the society such as reduction of CO_2 emissions, cleaner environment, lower transport costs, etc.

However, EDVs impact also power systems. It is discussable weather EDVs bring some benefits to the power system operation, what are the impacts of EDVs on power systems in general. These questions have been investigated in numerous papers from different perspectives. Exploitation of EDVs in frequency regulation and ancillary service provision was addressed in Refs. [1–4], since the idea of using EDVs for energy storage is increasingly promising due to intensive development of energy storage technologies, [5]. It is also emphasized the importance of further development of V2G (vehicle to grid) concept [6,7]. With current technology, EDV's batteries are not suited for providing base-load power, which is shown in Ref. [8], but represent a strong candidate for the provision of frequency regulation services and load peak-shavings [6]. Involvement of EDVs in unit commitment was considered in Refs. [9–12], where new approaches for implementing the V2G in the short term unit commitment problem are presented. New approaches strive to achieve reduction of operational costs and an increase of profit, spinning reserve and system reliability. An interesting idea was presented in Ref. [13] that proposed the activation of EDVs in the concept of VPPs (virtual power plants). The findings show that with the inclusion of EDVs in VPP, economic gains can be achieved. The study also focuses on determination of optimal number of EDVs in VPP portfolio to minimize the total costs of the VPP. Recently, the exploitation of EDVs in electricity markets has been frequently examined [14–18]. The results showed that with proper charging and discharging of EDVs economic gains can be achieved. The use of EDVs for maximization of exploitation of renewable energy is addressed in Refs. [19,20], where two optimization algorithms for charging and discharging of EDVs for maximization of use of renewable energy are presented. Refs. [21,22] present the impact of EDVs on distribution networks from the perspective of investment planning, energy losses, harmonic distortion levels, thermal loading, unbalance, and voltage regulation. Ref. [23] discusses how a large-scale implementation of PHEVs (plug-in hybrid electric vehicles) affects power system operation and investment planning. Results show that when charged/discharged intelligently, EVs can facilitate wind power investments

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already at low vehicle fleet shares and due to vehicle-to-grid capability; EVs can reduce the need for new coal/natural gas power capacities. Ref. [24] evaluates the impact of PHEVs on generation capacity requirements, fuel types used, generation technologies and emissions.

Since this paper addresses the impact of EDVs on power system reliability, a special attention was paid to the papers addressing this subject, [25–27]. Ref. [25] analyses the possibility of using EDVs to improve distribution system reliability by supplying energy to islands that might occur in distribution system in fault cases. The authors conclude that the EDVs could increase energy utilization, reduce the power shortage in load peak and improve the reliability of the distribution system. Ref. [26] uses reliability index EENS (Expected Energy Not Served) to determine the effects of battery exchange mode for charging of EDVs on power system reliability. The article also introduces a UDNS (User Demand Not Satisfied) index that represents the possibility that the charging demand of EDVs might not be fully satisfied since less energy can be charged into batteries during emergency dispatching. Results show that the use of battery exchange mode with combination of off-peak charging can significantly improve power system reliability. The authors have also emphasized that EENS improvements are achieved at the expense of index UDNS, which represents the dissatisfaction of EDV users. Ref. [27] focuses on estimating the available power capacity that EDVs can provide for the reserve market and evaluating its impact on power system reliability. Power system reliability is measured with LOLE (Loss of Load Expectation) index. The results show that the whole system's reliability can be greatly improved, if EDVs are able to provide energy back to grid.

The impact of EDVs on load profiles is analysed in various studies [4,28,29], where an efficient peak-load reduction solutions is proposed that results in better system reliability. Reference [30] analyses the potential impacts of PHEVs (plug-in hybrid electric vehicles) on the Portuguese electric consumption profile. The results show that the dispatchable load offered by PHEVs could increase the minimum system load, increase the utilization of base-load units, and decrease plant cycling without increasing the need for new investments in generation. Ref. [31] simulates the effects of Arrive & Plug charging scheme on power system reliability at various penetration levels of PHEVs in power network. The reliability of power system was evaluated using indices LOLE (Loss of Load Expectation), LOLP (Loss of Load Probability) and EENS (Expected Energy Not Served). The results show that with increasing penetration levels of EDVs system reliability deteriorates. Ref. [32] discusses charging costs, charging generation source, total electricity load, load shape and emissions associated with penetration of PHEVs in power system. The authors state that a very large penetration of EDVs would place increased pressure on peaking units if charging is completely uncontrolled. The aforementioned issue is addressed in Ref. [33], where results show that the dispatchable load offered by PHEVs could increase the minimum system load, increase the utilization of base-load units, and decrease plant cycling all without increasing the need for new generation assets. In addition authors claim that EDV discharge ability could replace a substantial fraction of the capacity currently in place to meet system peak reserve margin.

Even though several studies discuss the effects of EDVs on power system reliability and valuable conclusions are drawn, there is a need to investigate these effects from additional technical and economic aspects. The paper is focused on the charging/discharging strategies, their influence on the system reliability and the costs of its provision. The importance of selecting of a certain strategy is emphasized thorough several case studies (CSs) assessed by a stochastic approach. For example, system operators would prefer the strategy that supports the system reliability since in this case the costs for the system reserve provision required for the reliability provision are minimized. On the other hand, EDV users are not concerned with the reliability, they expect that the applied strategy would provide the cheapest transportation possible. For the purpose of performed investigation, the optimization model for EDV charging/discharging for each strategy is developed. In addition, the method for the techno-economic assessment and ranking of possible reserve provisions by their price-performance ratios is proposed.

What distinguishes the paper from the existing ones is (i) a clear mathematical presentation of newly proposed optimization models with straightforward optimization of reliability indices LOLE and EENS incorporated in the objective function and not in the optimization constraints, (ii) the stochastic approach to the problem, and (iii) the proposed method for techno-economic assessment of system reserve provision required for reliable operation of power system.

Besides the advantage of the proposed optimization models, i.e. a direct optimization of indices LOLE and EENS, their drawback should be mentioned. The fact is that a calculation of these indices in their standard form is relatively computationally demanding task when realistic power systems with numerous generators are considered. The reason lies in a numerous possible resource capacity states that should be accounted for by the definition. Since the proposed optimization models adopt a standard form of these indices and since they introduce additional optimization variables, the optimization of indices LOLE and EENS become even more complex. This problem can be efficiently solved by an appropriate computational approach supported by adequate equipment in terms of sufficient computational capacity.

Worth mentioning is also that the proposed optimization of indices LOLE and EENS can be applied on a local grid or on a complete power system. Principles are the same.

The rest of this paper is organized as follows: the optimization procedure of EDV charging/discharging is presented in Section 2, with Subsections 2.1 and 2.2 presenting the optimization models and the economic assessment of the system reserve provision, and Section 3 presents and discusses the obtained results. Conclusions drawn from the study are provided in Section 4.

2. Optimization procedure of charging/discharging of electric-drive vehicles

The optimization procedure proposed in the paper consists of several tasks presented in Fig. 1. Due to uncertainties, a stochastic assessment of input data is performed in the initial step: (i) future energy requirements for transportation – driving patterns, (ii) future energy consumption, and (iii) prices of electric energy. The MC (Monte Carlo) simulation is applied in order to produce sets of input data resulting in numerous scenarios, [15,20].

A random trajectory of the energy required for the transportation in hour h, D_h, is provided by:

$$D_h = \left(\delta_h + RU_{h,k}\right)\cdot\left(1 + RND_{h,k}\right), \quad (1)$$

where δ_h presents the most expected driving pattern of a certain EDV fleet in hour h, and $RU_{h,k}$ and $RND_{h,k}$ are the random components of the pattern in hour h, in scenario k with uniform and normal distribution. If this formulation is not appropriate, some other distribution function that is expected to better describe behavior of EDVs can be applied in the MC simulation.

Since behavior of EDVs is unpredictable and therefore uncertain, these uncertainty needs to be considered when determining the total number of EDVs that are available to participate in charging or discharging procedure in a certain moment. On the basis of findings

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