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Integration of 100% micro-distributed energy resources in the low voltage distribution network: A Danish case study

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HIGHLIGHTS

- Detailed modelling of electric vehicle and heat pump systems based on practical information.
- Identification the electrical bottlenecks for high penetration of micro-sized distributed energy resources.
- Proposals for appropriate easy to be implemented control solutions for congestion alleviation.
- Quantitative comparison among different integration strategies using economic and network performance metrics.
- Sensitivity analysis of integration impacts considering a variety of charging options for electric vehicles.

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ABSTRACT

The existing electricity infrastructure may to a great extent limit a high penetration of the micro-sized distributed energy resources (DERs), due to the physical bottlenecks, e.g. thermal capacitates of cables, transformers and the voltage limitations. In this study, the integration impacts of heat pumps (HPs) and plug-in electric vehicles (PEVs) at 100% penetration level on a representative urban residential low voltage (LV) distribution network of Denmark are investigated by performing a steady-state load flow analysis through an integrated simulation setup. Three DERs integration strategies, namely dumb operation, half-direct controlled operation (i.e. controlling HPs only) and full-direct controlled operation (i.e. controlling both EVs and HPs), are modelled and simulated. The quantitative comparison proves that, by implementing a simple merit of order based congestion management oriented integration strategies, having 100% integration of DER in the provided LV network is feasible.

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1. Introduction

In places where there is a desire of “green revolution” for heating and transportation sectors, heat pumps (HPs) and plug-in electric vehicles (PEVs) have become two of the most attractive alternatives in recent years. In the customers’ premises, oil/gas-fired boilers are replaced by HPs and petrol-powered vehicles are substituted by PEVs. For the HPs, there exists a variety of technological setups [1] associated with relatively high environmental and economic benefits [2,3]. For the PEVs, the roadmap report published by International Energy Agency (IEA), as in Ref. [4], presents a detailed description for the two PEV technologies, i.e. battery-powered EV (BEV) and plug-in hybrid EV (PHEV), with respect to the infrastructure requirement, economies of scale, battery technology, vehicle performance and consumer adoption, etc. Meanwhile, Ref. [4] concludes both PEV technologies could have a very fast growing market. However, if large number of HPs and PEVs (especially BEVs) are to be rapidly retro-fitted into the present electrical infrastructure, the potential integration impacts and the existing bottlenecks as well the integration strategies must be carefully analysed, identified and developed respectively beforehand. This is primarily due to the fact that the planning horizon for distribution networks is normally long (e.g. 6–20 years for feeder system and 1–4 years for laterals and small feeder segments) [5], and a rapid increase of electrical demand with an unaccustomed load pattern may not be anticipated in the planning period. For an electrical distribution network (EDN) whose distribution capability is bounded by the physical limits of its network assets (e.g. thermal capacities of cables and transformers) and the performance criteria such as power quality, integrating such kind of distributed energy resources (DERs) into it could easily result in network congestions [6–8] and will require network reinforcement or other alternatives.

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Taking the existing infrastructure as a starting point, a number of studies have investigated the issues surrounding the connection of large scale HPs and PEVs respectively. These studies generally follow the analytical framework depicted in Ref. [9] to integrate simulations of various distributed energy resources (DERs) into an EDN analysis in order to examine the potential integration impacts and to identify the physical bottlenecks within the network assets. For the HPs [10], reports that a large-scaled rollout (i.e. up to 50% penetration) of HPs in UK will lead to 38% increase of the winter peak electricity demand after considering the diversity of 91 field-test HP systems dispersed across UK. The study [11] estimates potential integration impacts of HPs in UK by using two artificially generated urban and rural LV networks as representative infrastructure boundaries. The results show that a 10% penetration of HPs will require almost 10% of the urban network elements (i.e. transformers and LV power lines) to be upgraded due to the perceived network congestions, while for the rural case the required reinforcement degree is almost doubled. For the PEVs, studies [12,13] have identified PEVs' integration impact on rural and urban networks using practical distribution models respectively. The former study uses the aggregated charging profiles of PEVs for a load-flow analysis at the medium voltage (MV) level of the Danish island Bornholm with a 10% penetration of PEVs; while the latter study estimates the maximum number of PEVs allowed to be deployed in the city of Gothenburg by considering the N-1 reliability criteria. On the contrary to using deterministic approaches [14], utilizes a probabilistic approach to characterize the uncertainties of the residential PEV charging profiles and to estimate the associated impacts on a generic UK distribution network.

In the context of Smart Grid (SG), the necessity of network reinforcement can be addressed by a variety of congestion management solutions that apply control or market-based coordination approaches to a number of micro-sized DERs such as HPs and PEVs. The centralized optimization technique over PEVs introduced in Refs. [15,16] has proved its effectiveness for congestion management at scheduling phases. In Ref. [17], the option of using vehicle-to-grid (V2G) is also considered for congestion management, which however has little consideration of its potential impacts on battery life, driving needs and the energy loss due to low round-trip efficiency etc. The trade-off between enabling V2G and its economic return is analysed by Ref. [18] in the context of sport-price based optimal charging. The study shows, although V2G could to a great extend reduce the charging cost, its severe impact on the battery life noticeably increases the annual cost of using EVs. Decentralized control approaches such as using price signals are proposed in Refs. [19,20] to manage large-scale PEVs and HPs respectively for congestion alleviation. A comprehensive discussion about market-based coordination strategies for congestion management using PEVs is presented in Ref. [21], which is further extended by Ref. [22] with in-depth simulation of a capacity-based market framework for congestion prevention. For most of the coordination approaches, stakeholders like distribution system operators (DSO), PEV fleet operators, market operators need to cooperate closely in a marketplace on a regular basis.

In Denmark, report series [23,24] published by the Danish authorities have estimated a potential saving of approximately 6.1 billion DKK by using SG, comparing with a traditional reinforcement strategy. In this constructed system, the number of PEVs and individual HPs totals 600,000 and 300,000 respectively by 2025, which implies extremely high penetration levels in areas with high population density. To explore the potential worst-case impact and to provide simple and effective integration solutions, in this study, the 100% integration impacts of HPs and BEVs on a Danish representative urban residential low voltage (LV) distribution network are investigated. The term "100%" is defined as a circumstance wherein each household has a PEV and a HP system. Three integration strategies are formulated in this paper to analyse the impacts of 100% integration of HPs and BEVs in this real LV radial feeder, namely

- Dumb operation, i.e. the charging of BEVs overnight follows the end users' instant demand and the operation of HP systems is heat-driven,
- Half-direct controlled operation, i.e. only the HP systems are directly controlled by the network operators in case of grid congestions,
- Full-direct controlled operation, i.e. the BEVs and the HP systems are co-ordinately controlled by the network operators in case of grid congestions.

Models for the LV network, BEVs and HP systems under different integration strategies are described in Section 2. An experimental case study is presented and analysed subsequently to quantify the impacts, followed by a sensitivity analysis to validate the proposed anti-congestion control strategies under different context.

2. Modelling of distribution network and DERs under different integration strategies

2.1. Low voltage distribution networks and the operation criteria

The Danish LV-distribution network operation policies adopted by the distribution system operators (DSOs) mostly follow the European Network Regulation Standard EN50160 [25], with respect to the voltage characteristics. According to the REKOMMANDATION 16, the nominal supply voltage is 230 V between phases and neutral, and 400 V from phase to phase. The limits for both voltage drop and voltage increase measured as a 10-min average must be within the range of ±10% of nominal supply voltage. In this study, the maximum voltage tolerance is set to be in the range of ±5% of nominal supply voltage to compensate the performance deviation introduced by utilizing hourly resolution in simulation.

The selected residential LV network of Denmark is modelled in DIgSILENT Power Factory. As depicted in Fig. 1, it consists of four different types of cables with a total length of 776 m. Such LV feeder network is partially fed by a 10/0.4 kV transformer to supply 42 residential customers. In Table 1, a detailed description of connections between the households and the LV cabinets is given.

2.2. Modelling of different integration strategies for BEVs and HPs

2.2.1. Dumb charging of BEVs overnight

An electrical charging profile of a BEV is highly dependent on the user's driving pattern and the characteristics of the battery. In this study, both factors are included in the EV model. As the BEVs are to replace the gasoline cars without affecting the users' driving experience, practical Danish driving pattern is applied on to estimate the charging pattern of BEV users and the energy amount required for meeting the users' driving needs. Such driving pattern is derived from a statistical analysis, as depicted in Fig. 2, of the 2-year Copenhagen AKTA road pricing experiment [26–18], and is used to generate the annual driving needs for every residential customer via the slice sampling technique [27]. Following the BEV mileage assumption of 11 kWh/100 km, the driving pattern of a BEV is converted to an energy demand profile in time series values. A 28 kWh lithium-ion battery is modelled based on the approach presented in Ref. [18] to represent the battery of a medium size family car in Denmark. The state-of-charge (SOC) range is set to between 10% and 90% for the sake of battery lifetime, and the efficiency of charging and discharging are both assumed as 90%.

Apart from the above mentioned assumptions, the followings are made in modelling the dumb charging of BEVs overnight:

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