Applied Energy 127 (2014) 249–266

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Probabilistic modeling and assessment of the impact of electric heat pumps on low voltage distribution networks

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HIGHLIGHTS

- High-resolution calculation of power requirements for ASHP and GSHP.
- 5 min-time series simulations by using 3 phase unbalanced power flow in OpenDSS.
- Modelling of load diversity and uncertainties through a Monte Carlo approach.
- Probabilistic assessment of impacts of EHPs in a suburban LV network.
- Sensitivity analysis for insulation level, temperature, size, power factor, etc.

ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form 10 March 2014
Accepted 9 April 2014
Available online 4 May 2014

Keywords:
Air source heat pump
Auxiliary heater
Ground source heat pump
Low voltage distribution networks
OpenDSS
Unbalanced power flow

ABSTRACT

Electrification of heating by making use of the Electric Heat Pump (EHP) technology powered by increasing shares of electricity renewable sources is seen as a potential key approach to decarbonise the energy sector in many countries, and especially in the UK. However, the widespread use of EHPs in substitution of fuel boilers might cause significant issues in terms of electrical distribution network impact, particularly at the low voltage (LV) level. This has not been addressed properly in the studies carried out so far also due to lack of available data and suitable models. In this light, this paper introduces a novel and comprehensive probabilistic methodology based on Monte Carlo simulations and a relevant tool to assess the impact of EHPs on LV distribution networks. Real electricity and heat profiles are taken as a starting point of the studies. Both Air Source Heat Pump (ASHP) and Ground Source Heat Pump (GSHP) types are modeled as black boxes with performance and heat capacity characteristics changing with operating conditions according to manufacturers' curves, addressing in particular the need for and impact of different types of Auxiliary Heating (AH) systems. A specific LV network analysis tool has been built that integrates the three-phase unbalanced power flow solution engine OpenDSS with the developed EHP models and is capable of properly addressing single-phase connections, adequately modeling the unbalanced nature of LV networks. Different metrics are used to quantify the impact of the considered technologies, with emphasis on thermal and voltage limits, according to current engineering standards. To cope with the many relevant uncertainties (EHP size, location in the network, operation pattern, reactive power consumption, network headroom, etc.), various case studies and sensitivity analyses have been carried out for representative suburban areas in the UK and for different scenarios in order to exemplify the developed methodology and illustrate the main drivers for impact and trends in the different cases. The tool can be adapted to perform studies for different situations and scenarios and can be used as decision making support by network operators, energy planners, policy makers, and so on, to better quantify the potential implications of large scale electrification of heating.

1. Introduction

In order to meet the challenging environmental targets that have been set out by Governments worldwide in the attempt to fight climate change, there are clear paths towards decarbonising the electricity sector by means of renewable sources such as wind. However, in order to drastically reduce the environmental impact of the *entire* energy sector, decarbonisation of the heat sector represents an even more strategic and challenging point, particularly in the UK and for the domestic sector. Various "heat strategies" documents have therefore been issued (see for instance [1]) in

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http://dx.doi.org/10.1016/j.apenergy.2014.04.026
0306-2619/

Nomenclature

Acronyms

ADMD	After Diversity Maximum Demand
AH	Auxiliary Heating
ASHP	Air Source Heat Pump
COP	Coefficient of Performance
DNO	Distribution Network Operator
EHP	Electric Heat Pump
GSHP	Ground Source Heat Pump

the attempt of steering the most cost effective evolution towards low carbon domestic heating. In the envisioned energy futures, there is a widespread utilization of the Electric Heat Pump (EHP) technology, with an extreme scenario, an *electric-only future*, where EHPs supplied by renewable electricity, and in case supported by thermal storage [2] and/or possibly coupled to heat networks [3], allow supply of virtually zero carbon heating. However, an open key point to address is the impact that widespread adoption of EHPs would have on the electrical distribution network, particularly at the low voltage (LV) level in the case of domestic systems. In fact, the additional electrical load at households could be substantial [4] and trigger significant technical issues, eventually either calling for network reinforcements or impeding further EHP connections beyond a certain level.

The use of smart strategies to decrease network impact has also been advocated in [5,6], but practical implementations are still far or might not bring expected benefits [4] while EHPs are already becoming a reality today thanks to technology improvements and financial incentives that are allowing overcoming early stage economic limitations [7]. In this respect, there is lack of suitable tools and relevant studies to actually quantify the impact at a LV level for different scenarios, technologies and types of networks, including a detailed modeling of the LV network. Studies in this direction have been performed for instance in [8] by assuming three-phase balanced connections and based on average profiles only. In addition, those studies and other "classical" studies use hourly profiles, while [9] has indicated that much finer resolution, in the order of 5–10 min, is needed to properly account for the impact at a household level and particularly for individual peaks that might arise. An attempt to consider load diversity has been performed in [10], where the correlation between electricity and heat profiles is modeled through a heuristic approach; no network impact is however analysed. The paper [11] has considered the impact of EHPs on distribution networks based on experimental data available. However, there is no attempt to model the EHP performance characteristics in dependence of operating (and particularly external) conditions and to take into account the need for back-up heating under harsh conditions. Similarly, reference [6] has considered a number of worst-case situations, but without detailing the impact on LV networks. In addition, the impact might change significantly with different types of EHP such as Ground Source Heat Pumps (GSHPs) or Air Source Heat Pumps (ASHPs) and different types of buildings and operating conditions. An interesting analysis of the different types of EHP and their main characteristics for applications in the UK can for instance be found in [12]. No such studies allowing for detailed network impact analysis from different EHP types in different buildings are available in the literature.

On these premises, this paper introduces a comprehensive probabilistic methodology and an associated modeling tool that are capable to understand and quantify in a systematic way the impact on LV distribution networks of different types of EHPs, namely, GSHP and ASHP (but the model could also be extended to other types such as water-source heat pumps, for instance), with and without back-up Auxiliary Heater (AH) of different types (for instance, fuel-based or electricity-based), different conditions (outdoor or ground temperatures, etc.), different types of buildings (for instance, with different insulation levels), and different consumption of reactive power (different power factors). The analysis is carried out starting from real high resolution electricity and heat consumption profiles taken from field trials on micro-generation [13]. An input–output black box approach, such as in [14–16], is then used to model the EHP for different types and operating characteristics, which "transforms" heat profiles into electricity ones taking into account real-time varying performance of the EHP (from manufacturers' curves) and the relevant AH operation. The electricity profiles obtained by combination of the base consumption profiles and the ones from the EHP are then input into an LV network analysis tool specifically developed. The tool is implemented in Microsoft Excel-VBA and integrates the OpenDSS software tool [17] (which is able to solve three-phase unbalanced power flows, intrinsic characteristic of LV networks) as a load flow engine. A number of numerical studies are performed in a Monte Carlo fashion to test the model developed and identify implications of electrification of heating under different conditions and for different applications and scenarios, with particular reference to the UK situation. This Monte Carlo approach is crucial to cope with the uncertainties that Distribution Network Operators (DNOs) could face with respect to EHP location, size, operation pattern, and so forth. Thus, the impact results are given in terms of expected values and relevant uncertainty (measured through the standard deviation indicator) rather than in a deterministic fashion as in most studies.

The paper is organized as follows. Section 2 describes the approach followed to derive electricity, heat and EHP electric load profiles for network studies. Section 3 discusses the methodology developed for LV network impact analysis and the relevant tool that has been built. Section 4 presents and discusses different numerical applications to test the methodology and quantify the impact of different EHP types in different scenarios. Section 5 contains the final remarks and bridges to future work.

2. Electro-thermal load modeling

2.1. Electricity and heat load profiles

A critical aspect to get detailed network impact analysis is to have a proper temporal precision in the electrical load input data, particularly relevant to quantifying voltage quality issues based on equivalent 10-min resolution [18]. However, in most cases DNOs do not have any information at all available for individual residential customers, and in the best case only aggregated profiles at the MV level are available. Likewise, there are currently no detailed data available for EHPs, and it is likely that the statistical value of data available from initial trials would be limited. For instance, recent trials that took place in the UK have been analysed in [19,20], where unexpected operational profiles and smaller coefficient of performance have been pointed out primarily due to down-rating of the EHP. In fact, in [21] a series of improvement for some of the houses in the original trial are carried out in order