Electric Power Systems Research xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Impact of dynamic and static fast inductive charging of electric vehicles on the distribution network

I. Karakitsios*, E. Karfopoulos, N. Hatziargyriou

National Technical University of Athens, School of Electrical and Computer Engineering, Greece

ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form
15 November 2015
Accepted 18 June 2016
Available online xxx

Keywords:
Electric vehicles
Inductive charging
Distribution network

ABSTRACT

Fast inductive charging technologies allow the exchange of high power quantities (>20 kW) between an Electric Vehicle and the electrical grid in contactless way. This demand can significantly modify the load profile of a distribution network and affect its operation and planning. Thus, it is necessary to quantify the grid impact of a network of fast inductive chargers and define the maximum allowable deployment level which does not violate the technical constraints of the network. This paper introduces a methodology for grid impact analysis of fast inductive charging technologies into distribution networks. The proposed methodology is implemented in a realistic model of a Greek MV distribution feeder providing indicative qualitative and quantitative results.

1. Introduction

The charging duration which is one of the major electric vehicle (EV) driver's concerns, can be significantly reduced by fast charging. There are two fast charging alternatives, namely conductive and inductive charging. Conductive charging of electric vehicles implies the direct contact between the EV and the station established with the interconnection of a charging cable [1]. An extended analysis of conductive charging technologies (i.e. unidirectional and bidirectional power electronic topologies) is presented in [1]. The main drawback of such solutions lies in the need of active involvement of the EV user in the initiation of the charging process, while the cable used could present a risk of electrocution, when used in rainy or snowy environments. On the contrary, inductive charging infrastructures enable the transfer of power between the station and the vehicle without the need of a physical connection [1–3]. The operational principle of a typical inductive charging infrastructure lies in the wireless transfer of energy between two magnetically coupled coils: the primary coil which supplies the power and it is placed at the charging station's side and the secondary coil which receives the power and it is placed onboard of the car. The operation principle of an inductive charging station is similar to the one of a typical transformer. The main difference lies in the coupling medium between the two coils (i.e. air) resulting in a lower coupling co-efficient between them in the case of inductive charging compared to the typical transformer. For this reason, the inductive power transfer system is referred in the literature as loosely coupled system [3].

Inductive charging technologies are classified into two subcategories: the static chargers [4–9], where EVs charge during non-commuting hours and the dynamic (or on-route) ones, which enable EV battery charging, while the EV is moving on the road [4,10–17]. The wireless power exchange between the EV and the grid which enables the dynamic charging of the battery increases the driving autonomy of electric vehicles satisfying the driver's demand for maximum travel distance.

The positioning (i.e. the air gap and the misalignment) of the inductive charging equipment of the electric vehicles over the inductive part of the charging station defines the charging power rate as a fraction of the nominal power of the charging station. Different EV placement approaches are introduced in the literature [18,19] aiming to achieve the maximum charging power rate.

In the literature, there are several studies concerning the grid impact of fast conductive chargers [20–29], but there is limited research concerning fast inductive charging, especially dynamic one [30–34]. The studies in [20–24] examine the operation of fast conductive chargers and their real-time impact on the grid, in terms of voltage or current variations. Other studies [25–29] assess the impact of fast conductive charging on the daily load profile. This is estimated based on refueling needs [25,26], home arrival time of commuters [27] or real/statistical mobility patterns for conventional vehicles [28]. In [28,29], a lowest bound for the

---

* Corresponding author. Tel.: +30 2107723696.
E-mail addresses: jkarak@power.ece.ntua.gr (I. Karakitsios), ekarfop@power.ece.ntua.gr (E. Karfopoulos), nh@power.ece.ntua.gr (N. Hatziargyriou).

http://dx.doi.org/10.1016/j.epsr.2016.06.034
0378-7796/

Please cite this article in press as: I. Karakitsios, et al., Impact of dynamic and static fast inductive charging of electric vehicles on the distribution network, Electr. Power Syst. Res. (2016), http://dx.doi.org/10.1016/j.epsr.2016.06.034

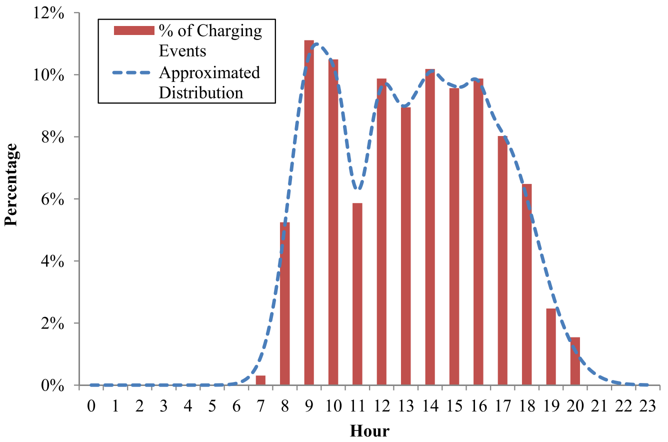

Fig. 1. Charging events occurring during the day, and the relevant approximated distribution.

state-of-charge (SOC) of an EV battery is considered as a criterion for charging request. The demand profile of static inductive chargers and its impact on the daily load curve are presented in [30], while the energy needs of dynamic ones are analysed in [31,32]. In [33,34], the provision of real-time V2G services, regarding dynamic inductive chargers, is examined. It should be mentioned, that in all the aforementioned studies [30–34], the impact of the charging load profile of inductive chargers on network operation is not assessed.

This paper introduces a methodology for estimating the charging demand of fast static and dynamic inductive chargers and assesses its impact on the operation of a distribution network, in terms of voltage profile, line loading and network losses. The demand due to conductive and inductive charging are considered in parallel and/or separately, simulating more realistic conditions for the 24-h grid impact analysis.

In Section 2 the methodology for estimating the charging demand profile of fast inductive chargers is introduced. The EV charging demand is superimposed on the given network load profile of a realistic MV distribution feeder operating in Greece. The technical characteristics of the network and the simulation scenarios are presented in Section 3. The results of the analysis are presented and analyzed in Section 4. Conclusions are drawn in Section 5.

2. Estimation tool

2.1. Static inductive charging

Inductive charging is a recently developed technology with few actual applications, thus, there is no real world operational experience. For the purpose of this paper, the operational behaviour of fast stationary inductive charging can be assumed similar to the one of fast conductive charging. Consequently, the power profile analysis can be performed based on an equivalent demand profile derived from real fast conductive charging stations. In this respect, data on more than 20 actual fast conductive charging stations for a period of a month were processed, in order to observe the hour of the day and the duration of the charging sessions. This data was provided by DBT, a French company offering charging station solutions, within the FastInCharge[1] project. Due to the commercial nature of this information, only limited aggregated and processed data can be published (Figs. 1 and 2).

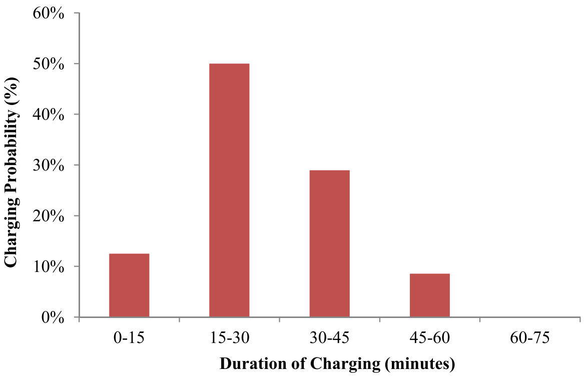

Fig. 2. Amount of time the vehicles remain on the stations.

Table 1
Gaussian distribution parameters regarding charging session initiation.

Component	Parameter		
	p	μ	σ
1	0.267656	9.197	0.987121
2	0.032443	10.3	0.443215
3	0.000872	14.05	0.179605
4	0.333774	16.73	1.636245
5	0.137854	11.93	0.697561
6	0.015256	15.95	0.429638
7	0.036219	15.05	0.640073
8	0.177336	13.66	0.909339

The charging sessions, as a percentage of all charging events reported in the examined period, are presented in Fig. 1. It is evident that all charging events occur between 7 am and 9 pm. Furthermore, two peak periods can be observed during the day: a peak in the morning demand (8.00–10.00 a.m.) and a peak in the middle-day demand (12.00–18.00 am).

In order to define when a particular charging event is expected to occur during the day, a Gaussian probability distribution, with n components, is assumed. The probability density function of such a distribution is defined as:

$$f(x) = \sum_{i=1}^{n} p_i \times \frac{1}{\sigma\sqrt{2\pi}} \times e^{-((x-\mu)^2/2\sigma^2)} \qquad (1)$$

where μ and σ are the mean and standard deviation of each component (the variance is, therefore, σ^2) and p specifies the mixing proportions of each component. A Gaussian distribution with 8 components, with values presented in Table 1, is a good approximation to the distribution depicted in Fig. 1.

The second parameter, which is necessary to estimate the energy demands for static inductive charging, is the expected duration of each charging event. The available data about fast conductive charging stations (Fig. 2) indicates that half of the EVs remain in the stations around 30 min, while none of them remains more than 1 h. Around 30% of the vehicles charge for 30–45 min, while 12.5% and 8.5% of the charging events have durations of 0–15 and 45–60 min, respectively. The Gaussian distribution of the duration of the charging events is approximated by the four parameters presented in Table 2.

The tool developed in order to define the total EV demand is presented in Fig. 3.

Two main EV users can be distinguished:

1. The users adopting home charging (Level 1–3.6 kW or Level 2–11 kW)
2. The users exploiting fast static inductive charging options.

---

[1] http://www.fastincharge.eu/.

Please cite this article in press as: I. Karakitsios, et al., Impact of dynamic and static fast inductive charging of electric vehicles on the distribution network, Electr. Power Syst. Res. (2016), http://dx.doi.org/10.1016/j.epsr.2016.06.034