Electrical Power and Energy Systems 93 (2017) 459–467

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Analysis of the demand charge in DC railway systems and reduction of its economic impact with Energy Storage Systems

David Roch-Dupré, Álvaro J. López-López, Ramón R. Pecharromán *, Asunción P. Cucala, Antonio Fernández-Cardador

Institute for Research in Technology, ICAI School of Engineering, Comillas Pontifical University, Alberto Aguilera 23, 28015 Madrid, Spain

ARTICLE INFO

Article history:
Received 23 January 2017
Received in revised form 21 March 2017
Accepted 16 June 2017

Keywords:
Railway power systems
Demand charge
Power peaks
Load levelling
Energy Storage Systems

ABSTRACT

In addition to energy consumption, DC railway operators must also pay for the demand charge. This term of the electricity bill has not been studied in detail in the literature and penalizes power peaks. The big fluctuations on the power demand which characterize railway systems make the demand charge important for railway operators. This paper studies the impact of the demand charge on DC railway systems and proposes a solution based on Energy Storage Systems (ESSs) to reduce it. An analysis of the main parameters of the ESS regarding the reduction of the demand charge is provided, as well as an explanation of the effects of different control strategies on the system performance. Most of the savings obtained with the installation of ESSs come from the reduction in the energy consumption; nevertheless, the savings coming from the reduction in the demand charge are significant and contribute to the economic viability of the investment.

1. Introduction

Consumption in trains is very irregular because they can change rapidly their state as they can be braking or coasting at one moment and motoring at the following instant. As a consequence of this, the power demanded in traction substations (SSs) is very variable, too. There are a lot of problems directly related to this fact, the main ones being:

- The necessity of oversizing the electrical elements of the infrastructure so that they can cope with very high instantaneous currents, which results in an additional cost.
- The economic impact associated with the power peaks, which is reflected in the electricity bill in the term corresponding to the demand charge.

The additional cost associated with the first problem is directly related to the necessity of ensuring the operation anytime. Nevertheless, this affects mainly the design phase, when the decisions on the characteristics of the electrical infrastructure are taken.

The second problem is a real concern for railway operators and has not been studied in detail in the literature. Contrary to what happens with the first problem, the economic impact of power peaks can be tackled at any time, even when the railway system is already built and in operation.

The reduction of peak consumption is closely related to energy efficiency as reducing the power peaks usually implies an increase of it. There are three main approaches to improve the efficiency:

- **Improving the train design:** reducing the train mass, optimizing the aerodynamics [1,2] or including on-board ESSs [3–5].
- **Improving the operation:** it involves the optimization of timetables, basically in order to maximize the use of the regenerated energy [6–11] and *eco-driving* [12–18].
- **Improving the infrastructure:** it covers several fields such as studies about the conductor sections and the optimal electrification voltages [19]. Nevertheless, the two main ways of improving the energy performance in the DC railways infrastructure is to harness the regenerated energy by the installation of reversible substations [20–23] or wayside ESSs [20,21,24–32].

Although reversible substations are preferred in terms of energy efficiency, they practically have no impact on reducing the power peaks. It is interesting to note that even for AC railways, where the SSs are intrinsically reversible, it is still felt worth considering optimising schedules to reduce peak power [33]. On-board ESSs as well as reducing energy consumption, can reduce the power peaks

* Corresponding author.
E-mail address: ramon@comillas.edu (R.R. Pecharromán).

http://dx.doi.org/10.1016/j.ijepes.2017.06.022
0142-0615/

of the trains in which they are installed. However, demand charge does not depend so much on reducing the power peaks of each train independently but on reducing the peak consumption in the SSs as a whole, for which it is preferable to use wayside ESSs installed in the SSs.

Wayside ESSs present a wide variety of uses: voltage stabilization [27,32], energy saving [24,25,27–30] and load levelling [24–26,31]. Among these uses, load levelling is directly related to the reduction of the power peaks and their associated economic impact.

Consequently, this paper is going to focus on the analysis of the economic impact of the power peaks and on the measures that can be implemented to reduce it, specifically by means of installing wayside ESSs.

In Section 2, the structure of the demand charge is explained in detail to make it clear how power peaks impact on it.

In Section 3 the case study is presented, as well as some concepts required to properly understand the subsequent sections.

In Section 4, the demand charge applied to the case study is analyzed according to the different concepts presented in Section 2 and Section 3.

In Section 5, the reduction in the electricity bill obtained with the installation of ESSs is explained as well as the impact of varying their main parameters. Special attention will be paid to the reductions achieved in the demand charge.

In Section 6 the economic viability of investing in ESSs to reduce the electricity bill is studied.

Finally, Section 7 contains the main conclusions.

2. Economic impact of power peaks

In most countries the method for charging the demand charge consists in averaging the power demanded at the SSs over a predetermined period of time ($\boldsymbol{t_{averaging}}$). This means that very high instantaneous values of power peaks can be compensated during the rest of the time in the same period. In this vein, [34,35] explain that industrial users are charged according to their highest power demand, usually averaged on 15-min $\boldsymbol{t_{averaging}}$ periods. The general formula of the demand charge in the electricity bill is expressed in Eq. (1).

$$Demand\ charge_{Electricity\ Bill}|_T = \overline{P}_{MAX} \cdot P_{Fee} \tag{1}$$

Where:

- $\boldsymbol{T}$ is the time period evaluated, e.g. a month.
- $\boldsymbol{\overline{P}_{MAX}}$ is the maximum of the averaged powers calculated in successive $\boldsymbol{t_{averaging}}$ periods [kW].
- $\boldsymbol{P_{Fee}}$ is the rate for the demand charge for period $\boldsymbol{T}$ [€/kW T].

A variant of this method consists in paying for an estimated ("a priori") maximum consumption instead of paying "a posteriori" for the average maximum demand measured. In this case, [34] indicates that if the maximum real demand exceeds the contracted limit, the costumer is charged with extra penalties that penalizes the moments when the average power demand in any of the time periods, $\boldsymbol{t_{averaging}}$, exceeds the contract power. Therefore, the power term in the electricity bill is split into two terms:

- The charge for the estimated maximum demand.
- The charge for the power excesses.

According to [36] the annual charge for the estimated maximum demand is obtained applying Eq. (2).

$$F_P = \sum_i t_{pi} \cdot P_{ci} \tag{2}$$

Where:

- $\boldsymbol{i}$ represents each of the billing periods in which a day is divided.
- $\boldsymbol{P_{ci}}$ is the value of the power that must be charged in each of the billing periods $\boldsymbol{i}$ included within a year. In the case concerning this research (high voltage consumers), this value corresponds to the "a priori" contract power in each billing period $\boldsymbol{i}$ [kW].
- $\boldsymbol{t_{pi}}$ is the annual price of a kW in each billing period $\boldsymbol{i}$ [€/(kW year)].

According to [36] the charge for each and every power excess can be calculated according to Eq. (3).

$$F_{EP}|_T = \sum_i (K_i \cdot 1.4064 \cdot A_{ei}) \tag{3}$$

Where:

- $\boldsymbol{F_{EP}}$ is the charge for exceeding the contracted limit during the time period evaluated $\boldsymbol{T}$ [€].
- $\boldsymbol{K_i}$ is a variable coefficient which will take different values depending on the billing periods $\boldsymbol{i}$ included within $\boldsymbol{T}$ (see Table 1).
- 1.4064 is a factor which transforms the kW exceeded into €.
- $\boldsymbol{A_{ei}}$ is calculated from Eq. (4):

$$A_{ei} = \sqrt{\sum_{j=1}^{j=n} (Pd_j - Pc_i)^2} \tag{4}$$

Where:

- $\boldsymbol{Pd_j}$ is the average power demand in each $\boldsymbol{t_{averaging}}$ of the billing period $\boldsymbol{i}$ in which Pc_i has been exceeded [kW].
- $\boldsymbol{n}$ is the number of $\boldsymbol{t_{averaging}}$ in which the average power demand exceeds the contract power $\boldsymbol{P_{ci}}$ in each billing period $\boldsymbol{i}$.

Finally, regarding the price of each kW of contract power, [37] presents the price of the demand charge as a constant value independent of the time of occurrence. The same applies in [34,35], where $\boldsymbol{P_{Fee}}$ is also presented as a constant value. Nevertheless, according to [38], there is a current need to create a structure of network prices reflecting more closely the marginal costs that would allow the promotion of demand response and energy efficiency. Three different approaches are proposed in [38] to determine the value of the rate for the demand charge:

- **Flat rate:** fixed price for a predefined power value (this method is also used in [34,35,37]).
- **Variable rate:** different power levels defined, one price for each level.
- **ToU (Time-of-Use) rate:** price per kW depending on time of consumption.

Naturally, the new types of capacity tariffs look for reducing the power peaks when their occurrence is more harmful to the system. An example of the ToU rate is presented in Eqs. (2) and (3), where $\boldsymbol{P_{ci}}$ and $\boldsymbol{K_i}$ vary depending on the billing period $\boldsymbol{i}$.

3. Case study

3.1. Simulator

All the results in this paper have been obtained by means of an electrical multi-train simulator developed in the Institute for

Table 1
Values of the coefficient K_i .

Billing period i	1	2	3	4	5	6
$\boldsymbol{K_i}$	1	0.5	0.37	0.37	0.37	0.17