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ON THE VIABILITY OF DC HOMES: AN ECONOMIC PERSPECTIVE FROM DOMESTIC ELECTRICAL APPLIANCES

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ABSTRACT

The past few years witnessed a growing acclaim for dc power systems, which is mainly justified by the increasing use of energy storage systems and renewable energy sources based mainly on solar photovoltaic technologies. However, there is also a motivation from the point of view of domestic electrical appliances. Since the vast majority of these appliances is comprised by an ac-dc converter, it can be convenient to shift the domestic power supply from ac to dc. In this context, this paper presents an economic assessment of dc homes from the energy consumption perspective and its comparison with traditional homes supplied by ac electrical power grids. In order to perform such assessment, the main type of electronic loads is powered both by ac voltage and by dc voltage, comparing the efficiency and estimated energy cost for each case. The removal of the ac-dc converter present in these loads is also analyzed and compared with the two previously referred cases, supporting the supply of dc power to this type of loads. The analysis is performed by means of experimental results obtained with a laboratorial setup, aiming to validate the feasibility of dc homes under realistic operating conditions of the loads.

INTRODUCTION

Ac power transmission systems have represented a mature solution for more than one century, mainly due to the use of transformers, which consists in a reliable, robust and efficient means of adapting voltage and current levels in order to optimize the electrical power flow in transmission and distribution systems. However, these transformers are heavy and bulky, since they operate at low frequencies (e.g., 50 Hz or 60 Hz). The development of power electronics made possible the high voltage dc (HVDC) power transmission, in which several international standards were defined and are still active (IEC and IEEE 2017; IEEE Standards Association 1991, 1997, 2000). The research on HVDC power transmission has been spread from more than half a century (Ekstrom and Liss 1970; Foerst et al. 1969; Hingorani 1970; Reeve, Baron, and Krishnayya 1969) to the present days (Belda, Plet, and Smeets 2018; Flourentzou, Agelidis, and Demetriades 2009; Franck 2011; Guo et al. 2012; Liu et al. 2017). Since in HVDC power transmission systems there are no voltage drops due to line impedance reactance, this type of power transmission is a key application of superconductivity, provided that resistive voltage drops are also inexistent (Baek et al. 2018; Malek and Johnson 2013; Marian et al. 2018). Nevertheless, independently of the type of power transmission, low frequency transformers are commonly used. However, in order to attain a more compact and lighter solution, high frequency transformers can be applied instead of the traditional low frequency ones. The use of high frequency transformers with the respective power converters makes possible the implementation of solid state transformers, which consists in a promising solution for power transmission and distribution systems in smart grids, either in ac or dc (Falcones, Ayyanar, and Mao 2013; Huber and Kolar 2016).

Besides the advantages in power transmission and distribution, the importance of dc power systems is significant nowadays, taking into account the paradigm of distributed generation. Energy storage systems, such as batteries and fuel cells, and also renewable energy sources, like solar photovoltaic panels operate in dc power, which favors the adoption of dc microgrids (Dong, Cvetkovic, et al. 2013; Dong, Luo, et al. 2013; Dragicevic et al. 2014; Jovcic et al. 2015; Kumar, Zare, and Ghosh 2017; Wang et al. 2017). Since the number of power conversions can be reduced, a dc power grid offers an improvement in the system efficiency, as well as in its cost and complexity. In fact, computer datacenters are undergoing a shift from ac to dc due to the efficiency improvements of the latter (Fairley 2011; Patterson 2012). Furthermore, the paradigm of dc power grids is also suitable for the vast majority of domestic electrical appliances. With the advances experienced by power electronics, domestic electrical appliances became less power consuming, giving rise to the concept of nonlinear loads. Although these types of electrical loads usually demand lower values of power when compared with linear loads, they cause power quality problems because of their nonlinear

characteristics, i.e., the current absorbed by these types of loads does not present sinusoidal waveform, originating harmonic currents to flow in the power grid. This happens because these loads contain a passive ac-dc converter to rectify the power grid voltage into dc voltage. Therefore, it can be advantageous to shift the power grid from ac to dc at the residential level, since the vast majority of domestic electrical appliances (e.g., computers, televisions, compact fluorescent and LED lamps) are nonlinear loads. With this approach, the ac-dc converter comprising these loads can be eliminated, reducing the cost and the size of the electrical loads, and also improving their efficiency, which, consequently, decreases their energy consumption. Moreover, the harmonic currents problem is no longer existent, since the system operates in dc. The paradigm of dc homes is already addressed and supported in the literature (Fairley 2012; Ghazanfari and Mohamed 2017; Patterson 2012; Rodriguez-Diaz, Vasquez, and Guerrero 2016). A study considering the characterization of nonlinear loads connected to ac power grids is presented in (Andrejevic-Stosovic et al. 2016); however, little interest has been given to dc power systems regarding nonlinear loads.
In this context, this paper presents an economic assessment of dc homes from the electrical loads perspective and its comparison with traditional homes supplied by ac power grids. In order to perform such assessment, the main type of electronic loads that comprise many domestic electrical appliances is powered both by ac voltage and by dc voltage, in order to compare the efficiency and estimated energy cost for each case. The removal of the ac-dc converter present in these nonlinear loads is also analyzed and compared with the two previously referred cases. This analysis is performed by means of experimental results attained with a laboratorial setup, aiming to validate the feasibility of dc homes under realistic operation conditions of the loads.

METHODOLOGY AND EXPERIMENTAL SETUP

This section describes the adopted methodology and the experimental setup to evaluate the main types of nonlinear loads when powered by ac and dc power grids. The considered load is comprised by a diode full-bridge ac-dc converter with output capacitive filter, followed by a buck dc-dc converter and a resistive load, as it can be seen in Figure 1.
The three following cases were considered: Case 1 – the nonlinear load is powered by an ac power grid, which corresponds to the traditional situation of a domestic load (Figure 1 (a)); Case 2 – the nonlinear load is powered by a dc power grid, representing a migration from ac to dc power grids while maintaining the same type of load (Figure 1 (b)); Case 3 – the nonlinear load is adapted to be powered only by a dc power grid (Figure 1 (c)). This last case represents a

(a)
(b)
(c)

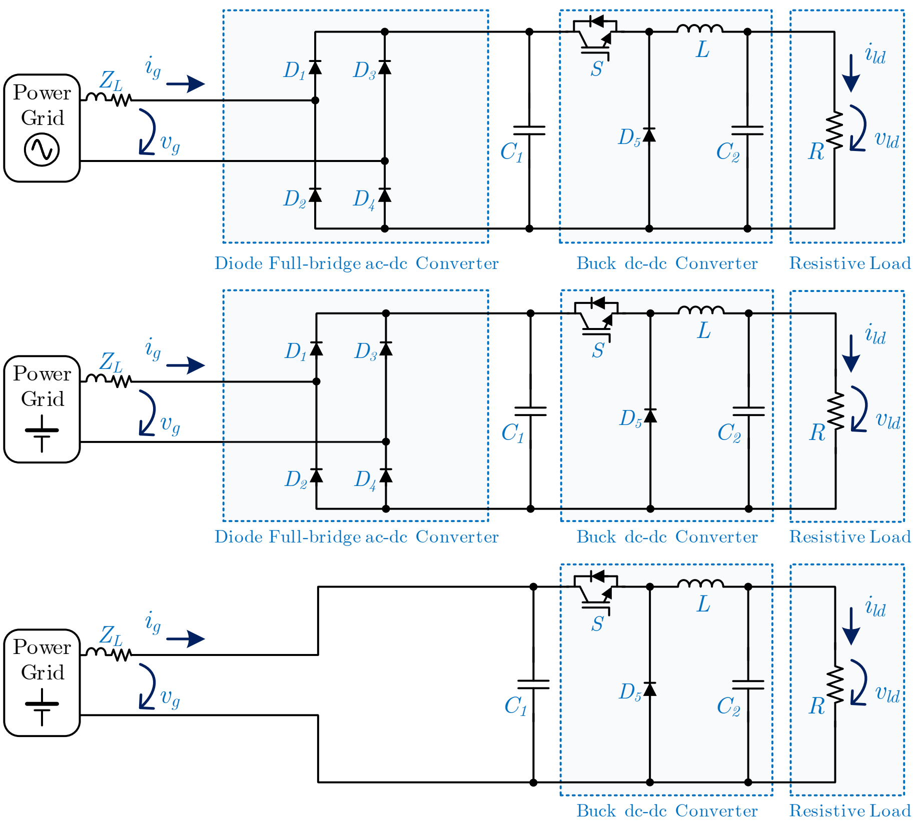

Figure 1: Connection of the nonlinear load to the power grid: (a) Case 1 – nonlinear load powered by an ac power grid; (b) Case 2 – nonlinear load powered by a dc power grid; (c) Case 3 – nonlinear load adapted to be powered only by a dc power grid.

further improvement for dc power grids, provided that the input ac-dc converter present in the vast majority of nonlinear loads is redundant when supplied by a dc voltage. Therefore, the removal of the input ac-dc converter presents two advantages: first, the load cost is reduced, since it has less components than the traditional nonlinear loads; second, the load efficiency is incresead, since there are no input diodes and, therefore, less power losses.

Table 1 shows the main parameters used in the experimental setup for the analysis. Since the considered type of nonlinear load is associated to low power electronic loads, a lower voltage for the power grid (v_g) was considered. In this way, the ac power grid was obtained by means of a 230 V // 30 V transformer. On the other hand, the dc power grid was obtained with a 30 V dc power supply, allowing to perform a comparison for the same RMS value of the power grid voltage. In all three cases, the buck dc-dc converter was controlled in order to maintain a load voltage (v_{ld}) with an average value of 20 V. Besides, three distinct values were used for the resistive load (R) in order to establish three different values of consumed power (approximately 15 W, 30 W and 45 W).

Table 1: Parameters used in the experimental setup.

Parameter	Value
V_g	30 V
V_{ld}^*	20 V
C_1	3.28 mF
C_2	10 mF
L	5 mH
R	26 Ω or 13 Ω or 8.67 Ω
Switching frequency	20 kHz

Figure 2 shows the workbench containing the developed experimental setup. In the power circuit, it can be seen a 230 V // 30 V transformer, a dc power supply ISO-TECH IPS2303, a diode full-bridge ac-dc converter (Comchip model GBPC5010) and a buck dc-dc converter, which is comprised by IGBTs model FGA25N120 from the company ON Semiconductor, and the respective internal antiparallel diode (where one is used as an active switch and the other as a diode), an inductor and a set of capacitors, and, finally, the used resistive load. Besides the hardware comprising the power circuit, measurement equipment can also be seen. In order to obtain the values of power for both input and output of the nonlinear load, a precision wattmeter was used (Zimmer model LMG95). For controlling the buck dc-dc converter, a digital signal generator model SFG-1013 from GWInstek was used, which in turn was connected to an Avago HCPL3120 driver board in order to drive the IGBT gate. The figure also shows some additional equipment that was used for validating the proper operation of the load, such as a digital oscilloscope, a multimeter and a current probe, whose contribution is not framed in the scope of this paper.

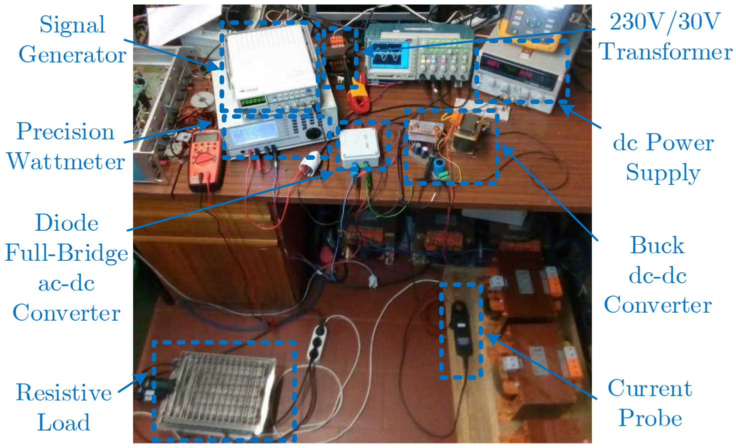

Figure 2: Experimental setup developed for the analysis.

EXPERIMENTAL RESULTS

This section presents the results obtained with the developed laboratorial setup. The obtained values of power, both for the input and output of the nonlinear load, can be seen in Table 2. The values of input apparent power are also shown and, as expected, these are substantially higher for Case 1, where the nonlinear load is connected to an ac power grid. In this case, the power factor is 0.65 for the lowest load power (1) and 0.79 for the highest load power (3). For Case 2 and Case 3, the measured values of apparent power and active power at the input are not equal because of the pulsed current consumption that is characteristic of the buck dc-dc converter, which is albeit significantly reduced by the set of capacitors connected between the diode full-bridge ac-dc converter and the buck dc-dc converter (C_1). Besides, it can be seen that Case 3 presents the lowest values of input power for approximately the same output power, which corroborates the fact that it is advantageous to adapt nonlinear loads to dc power grids.

Table 2: Input apparent power, input active power and output power values obtained with the three aforementioned cases for three values of load power.

CASE	QUANTITY	LOAD POWER 1 (26 Ω)	LOAD POWER 2 (13 Ω)	LOAD POWER 3 (8.67 Ω)
1	Input Apparent Power	26.70 VA	49.94 VA	66.80 VA
	Input Active Power	17.47 W	34.95 W	52.55 W
	Output Active Power	15.08 W	29.39 W	43.13 W
2	Input Apparent Power	19.21 VA	37.01 VA	53.65 VA
	Input Active Power	19.18 W	36.95 W	53.53 W
	Output Active Power	15.36 W	29.15 W	41.52 W
3	Input Apparent Power	16.99 VA	32.80 VA	47.30 VA
	Input Active Power	16.95 W	32.64 W	47.09 W
	Output Active Power	15.47 W	29.38 W	41.91 W

In order to compare the three cases more accurately, Figure 3 shows the efficiency values obtained for the results presented in Table 2. As expected, the highest efficiency values are obtained with Case 3 (between 89% and 91%), when the nonlinear load is adapted to be powered exclusively by dc power grids. Besides, the efficiency tends to decrease with the output power for all three cases. It can also be seen that Case 1 presents higher efficiency than Case 2, meaning that, for the same load, the connection to an ac power grid results in a higher efficiency than the connection to a dc power grid. However, a higher slope is visible for the curve of Case 1, suggesting that this fact is only true for low values of output power.

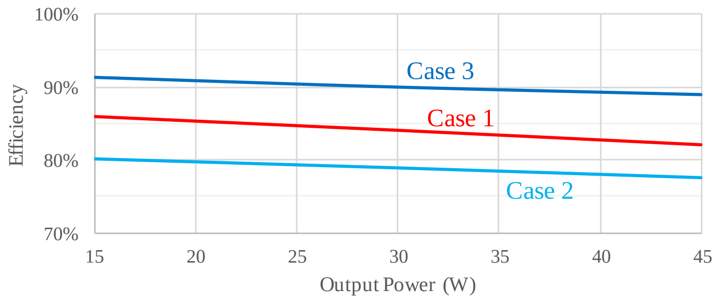

Figure 3: Efficiency values obtained with the three aforementioned cases.

Based on the aforementioned experimental results, an economical analysis was carried out. For this purpose, data regarding domestic electricity consumption in Portugal was gathered, both per capita and total. According to Pordata, the electricity consumption in Portugal during 2017 was estimated to be approximately 1220 kWh per capita and 12.56 TWh in total, considering only domestic consumption (Pordata 2018). Based on this data and the obtained experimental results, Table 3 was built, where two improvement cases (A and B) regarding the adaptation of nonlinear loads to be powered only by dc were considered, and the respective energy and monetary savings were estimated. In Case A, it is considered that the nonlinear loads efficiency rises from 80% to 85%, while Case B considers a rise from 80% to 90%. It was considered that 50% of the demanded power is due to nonlinear loads. Based on the estimated energy savings, monetary savings are calculated considering a price of 0.2284 €/kWh, which is the registered average energy price in Portugal during 2017 for domestic consumption, also according to Pordata. As it can be seen, the household savings are not much significant per year (8.2 € or 15.5 €). However, in a global scenario, the energy savings in Portugal can reach hundreds of gigawatts, which reflects in savings higher than 100 million euros. Therefore, despite not being a significant change for a household, it can bring large energy and monetary savings, which is not only beneficial to energy producers but also at the environmental level.

Table 3: Estimated electricity consumption at the domestic level in Portugal during 2017 and estimated savings with the adaption of nonlinear loads to be powered only in dc.

ESTIMATED	REGISTED VALUES	ENERGY SAVINGS	MONETARY SAVINGS

Electricity Consumption in 2017		A	B	A	B
per capita	1220 kWh	36 kWh	68 kWh	8.2 €	15.5 €
Total	12.56 TWh	369 GWh	698 GWh	84.3 M€	159.4 M€

CONCLUSIONS AND FURTHER RESEARCH

This paper presented a study on the vialibility of dc homes, focusing on the electrical appliances used at the residential level. An experimental setup was assembled in order to evaluate the convenience of dc power grids over ac power grids at homes. Since the vast majority of electrical appliances are nonlinear loads, comprised by a diode full-bridge ac-dc converter at the input, a load of this type was assembled, containing also a buck dc-dc converter connected to a resistive load in order to approach a real scenario of an electrical appliance. The methodology of research was based on three considered cases: Case 1 – the nonlinear load is powered by an ac power grid; Case 2 – the nonlinear load is powered by a dc power grid; Case 3 – the nonlinear load is adapted to be powered only by a dc power grid. The experimental results consist of values of input apparent power, input active power and output active power for each case, and for three values of load power. Based on these values, the efficiency was calculated for each case and for each value of load power, where better results were attained for Case 3. An economical analysis was performed based on the obtained results, and it was concluded that the removal of the input diode full-bridge ac-dc converter in this type of loads does not led to substantial economical savings in a Portuguese home but leds to huge savings at the total national level. Furthermore, it should be noted that the referred savings are obtained not with a more sophisticated equipment, but instead with a simpler equipment, which would also decrease the cost of the equipment itself. Further research will consider higher values of load power for evaluating the efficiency both in absolute terms, i.e., to evaluate if the obtained efficiency values are still valid for higher powers, and in relative terms, both for the three cases and between Case 1 and Case 2, in order to find out if Case 1 is still more efficient than Case 2 for higher power values.

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