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Published in:
Proceedings of the 5th IEEE International Conference on Consumer Electronics (IEEE ICCE-Berlin 2015)

DOI (link to publication from Publisher):
10.1109/ICCE-Berlin.2015.7391268

Publication date:
2015

Document Version
Accepted author manuscript, peer reviewed version

An Overview of Low Voltage DC Distribution Systems for Residential Applications

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***Abstract*—The concept of a microgrid has drawn the interest of research community in recent years. The most interesting aspects are the integration of renewable energy sources and energy storage systems at the consumption level, aiming to increase power quality, reliability and efficiency. On top of this, the increasing of DC-based loads has re-open the discussion of DC vs AC distribution systems. As a consequence a lot of research has been done on DC distribution systems and its potential for residential applications. This paper presents an overview of the LVDC distribution systems used in residential applications. Several publications that study the potential energy savings and overall advantages of the LVDC distribution systems are analysed. Different power architectures and topologies are discussed. The existing demonstration facilities where LVDC distribution systems have been implemented are also shown.**

***Keywords*—DC Microgrid, Smart homes, DC homes, LVDC.**

I. Introduction

Nowadays, there is an open discussion on whether to use AC or DC electrical power systems. This matter can be traced back to the battle between Edison and Tesla/Westinghouse more than a century ago [1]. The technology available back then, made the AC option far more advantageous, consequently the electrical power systems worldwide are AC-based. Nevertheless, today's scenario has changed, and DC based power systems offer interesting advantages regarding simplicity, cost reduction, and efficiency improvement [2].

So, what has changed that makes DC distribution systems a stronger candidate?. There are several factors that influence whether an AC or DC system is advantageous, and the change of today's scenario makes those factors yield to a LVDC distribution system in the future. For instance, DC systems increase de efficiency of the energy distribution systems, and easy the integration of decentralise and renewable energy sources, aiming to reduce the dependency from fossil fuels, and limit greenhouse gasses emissions.

There are several factors which empower the use of DC systems instead of AC systems: i) suitable renewable energy generators, as Photovoltaic Panels (PV) and Fuel Cells (FC), and energy storage systems, as batteries, are DC-based, ii) DC loads currently represent 50% of the whole building consumption, iii) the future integration of the electric vehicle in the power system, will increase the consumption of DC devices (batteries) in the buildings, iv) DC distribution systems are intrinsically more efficient than their AC counterparts, since in DC there are not reactive power or skin effects, v) interconnecting and distributing the energy between mostly DC-based agents (sources, loads, storage) through a DC power system avoids unnecessary DC-AC and AC-DC conversions which are a wasteful of energy. Fig. 1 gives a clearer picture of the above mentioned aspects showing the reduction of the conversion stages in the power converters of loads, storage systems, and sources, when switching from AC to DC distribution systems in residential applications.

LVDC electrical power systems have been widely used in applications such as, aerospace, automotive and marine [3]. Lately these systems have made their way into electrical power systems for industrial applications, especially in the telecommunication industry. In data centres, LVDC architectures have been widely studied [4], [5], and several facilities are currently using LVDC distribution systems. Data centres demand high reliable systems, where the integration of UPS systems is a priority, hence the installation of DC distribution systems reduce the conversion stages significantly, making the system more efficient. For instance, the Lawrence Berkeley National Laboratory has shown that a 28% efficiency improvement can be achieved by switching from AC to a DC distribution system [6].

Introducing the LVDC distribution systems also for commercial and residential applications seem like the next reasonable step. Brian T. Patterson, founder of Emerge Alliance, has shown the importance of the DC technology in a future electrical grid "enernet", and the Zero-Net-Energy buildings (ZEBs) [7].

AC distribution systems have been recently loosing ground against DC, however, regarding residential applications, DC systems still have a long run ahead. The lack of regulation and standardization, and development of protections, are probably the main challenges that DC power systems need to overcome, before being considered a suitable option to replace AC power systems.

II. Advantages, Challenges and Barriers of LVDC Distribution Systems for Residential Applications

The advantages of LVDC distribution systems have been already pointed out, however a deeper discussion and analysis is required, in order to see the true potential of this technology. Several studies have addressed the efficiency improvement and energy savings of switching from AC to DC systems in residential applications.

In [8], [9], the energy savings obtained by using a DC distribution system in residences in United States were studied. The study was carried out for several different locations across the country, and for different system's topologies. Distribution topologies with and without energy storage systems were

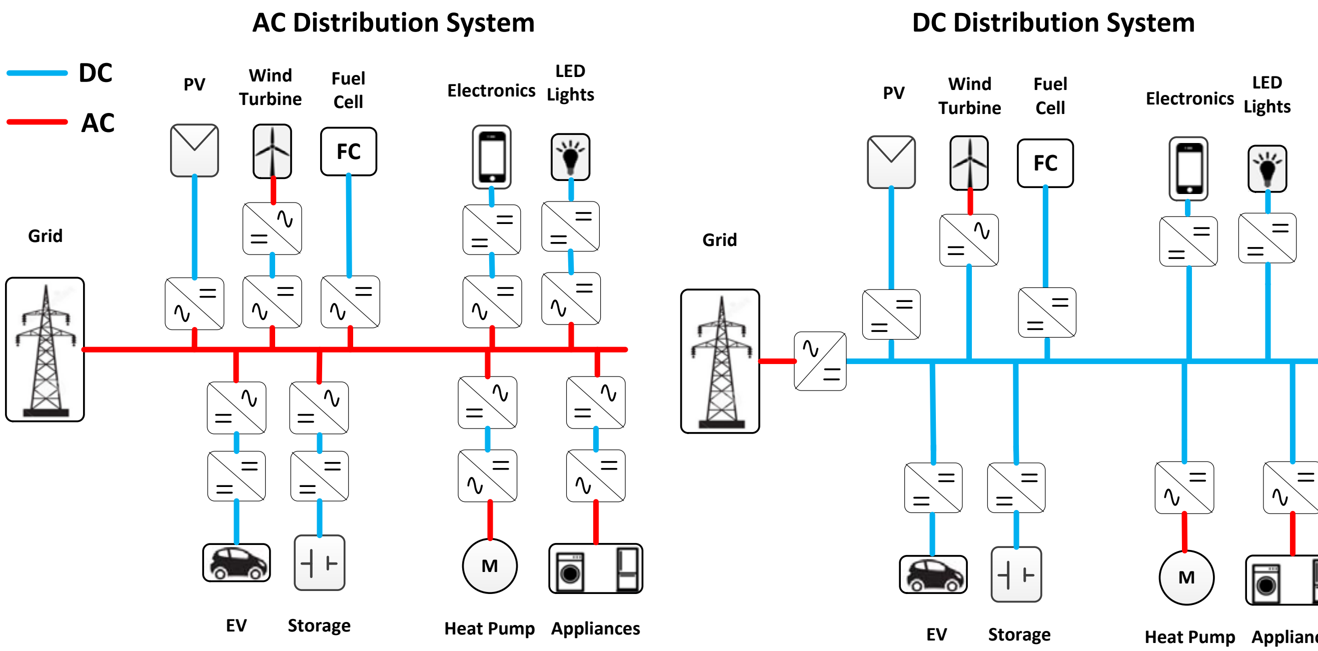

Fig. 1. Conversion stages reduction when switching from AC to DC distribution systems for residential applications.

considered. The results showed that the use of DC could yield to great efficiency improvement, especially when an energy storage system is installed. The energy savings estimation are 5% for the case of a non-storing system, and 14% for the storing system. The difference of energy savings is a consequence of the consumption profile of the residential loads, which peak in the afternoon and evening, while the PV production peaks at noon. Therefore, with an energy storage system, the excess power generated by the PV panels can be stored and used afterwards, avoiding the DC-AC-DC conversion losses of sending the excess power into the grid. There are more optimistic studies that aim to achieve 25-30% energy savings [10], [11]. However, the environment conditioning loads (cooling and heating) need to be taken into account. Also, in order to obtain a fair comparison between the different AC/DC distribution systems, comparable AC and DC loads need to be use for both systems. The energy savings achieved by using extremely efficient DC loads, instead of regular AC loads, should be not taken into account.

LVDC distribution system still need to face important challenges and barriers before been implemented in residential systems. the main challenges and barriers can be summarised as follows:

- The lack of standards and code is probably the main issue that needs to be solved. Several organizations as Emerge Alliance (EA), the European Telecommunications Standards Institute (ETSI), the International Electrotechnical Commission (IEC), IEEE and others, are already actively developing the necessary regulation and standards.
- Safety and protection issues derived from the use of DC. New DC protection devices and schemes are required, in order to ensure people's safety [12].
- The lack of industry and products for DC distribution systems. When analysing DC systems in residential applications, it is easy to notice that there are barely commercial products ready to be used with DC voltage. For instance, in DC appliances/devices, small modifications are required to make them "DC-ready", since most of them already have a DC/CC conversion stage connected to a rectifier stage [13], [14]. However, there are no DC products in the market, aside from recreational vehicle appliances running on 12 VDC.

III. Voltage Level in LVDC Distribution System for Residential Applications

The lack of standardization is evident when observing the voltage levels used for LVDC distribution systems. As mentioned before, most of the configurations use the data centres voltage levels (i.e., 380-400 VDC), however is it really necessary?. Power consumption of a regular home is much lower than the consumption of the data centre, therefore, lower DC voltages could be used, without significantly increasing the distribution losses, while increasing safety in the system. For instance, power distribution up to several hundred watts, can be efficiently performed using 48 VDC [15], which would cover all the IT, electronics and entertainment equipment.

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In [16], an analysis of the influence of the voltage level on the efficiency has been performed. The study shows that, using 380 VDC as voltage levels for supplying energy to the high power loads (kitchen appliances and air conditioner) only brings a efficiency improvement of 0.3 %, when compared with 120 VDC. 120VDC is still considered extra-low voltage,

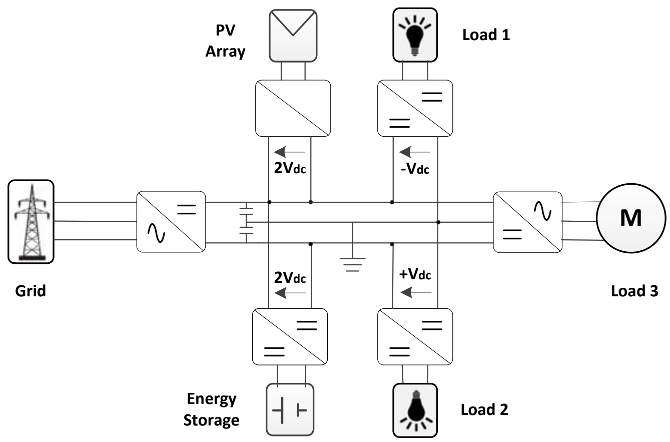

Fig. 2. Bipolar Type DC Microgrid Concept.

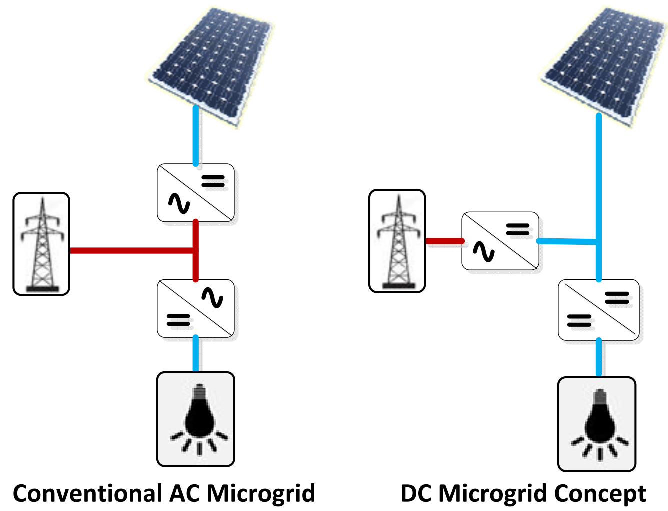

Fig. 3. Variable DC Bus Voltage Microgrid developed by Robert Bosch LLC.

hence, the damage cause by a electrical shock is reduced. Different studies also conclude that, for residential applications, 48-120 VDC systems distribute the energy efficiently [17]. In addition, the Emerge Alliance 24 VDC Occupied Space Standard is intended to be used to supply energy to IT and electronic equipment, therefore, the energy of low-power loads/appliances, typically in bedrooms and living rooms, can be also distributed safely and efficiently at lower voltages.

IV. LVDC Distribution System Topologies

It has been pointed out before that there is a lack of regulation and standardization on this technology. Therefore, there are several different configurations and voltage levels that can be employed. Since DC distribution systems have been widely implemented in the telecommunication industry, the voltage levels used for residential application seems to converge to the standards used in data centres (380-400 VDC). However it is still far from being standardised, and several topologies of LVDC distribution system are being studied.

A. Bipolar Type Distribution Systems

The concept of using a bipolar type distribution system brings some advantages over the unipolar type counterpart. The distribution system concept is shown in Fig. 2. The distribution in the system is made by a 3-wire line, with positive, negative and neutral line. It can be easily appreciated that this concept reduces the voltage level respect to ground, which makes the distribution system safer for the users. Also, this concept allows the converter on the load side to choose from three different voltage levels, $+V_{dc}$, $-V_{dc}$ and $2V_{dc}$, furthermore, the system increases the reliability of the power supply, because, in case of a fault in one the lines, the energy can still be supply using the other two lines [18].

B. Unipolar Low Voltage DC Distribution Systems

This configuration has been designed for low power systems. In India has aimed to installed 20 GW of solar power installations by 2022, by means of the Jawaharlal Nehru National Solar Mission (JNNSM). The JNNSM intends to bring electricity to rural areas, where there was not electricity available before. This program has motivated the research and development on LVDC systems, as they easy the integration of renewable energy sources and storage systems, achieving a simpler, cheaper and more efficient systems.

An analysis of the deployment of a 48 VDC system for integration of PV panels and high-efficient DC loads in multi-storied building in India has been performed [19]. The studied showed that the DC system is more efficient and also brings cost savings for the users, by reducing the electricity bills, and the cost of the system. In [20], the conceptual implementation of low power solar system is shown. The system is designed to cover the minimum needs of a low-income household in India. The system is formed by a 125 W PV Panel, 48 V battery, 18 W LED tube, 5 W LED bulb light, 32 W BLDC fan, and one cell phone charger.

Even though, this system can not cover the power requirement of a household in the well-developed countries, it shows that when aiming for minimizing the cost of the system, LVDC distributions systems have no competitors.

C. Variable DC Bus Voltage Distribution Systems

The concept of a variable voltage DC bus distribution system aims to maximize the energy efficiency by eliminating the converter of the renewable energy generator. Robert Bosch LLC has implemented this concept in a DC demonstration microgrid in Charlotte, North Carolina, USA. The system is shown in Fig. 3. This concept allows to supply the energy with only one conversion stage between the PV array and the load, which minimizes the conversion losses. The AC/DC converter performs the voltage regulation of the DC bus voltage according to a maximum power point tracking (MPPT) algorithm for the PV generator. In contrast with the conventional microgrid configuration, the MPPT converter, is not in the path from PV to load, which enables higher efficiency and higer reliability

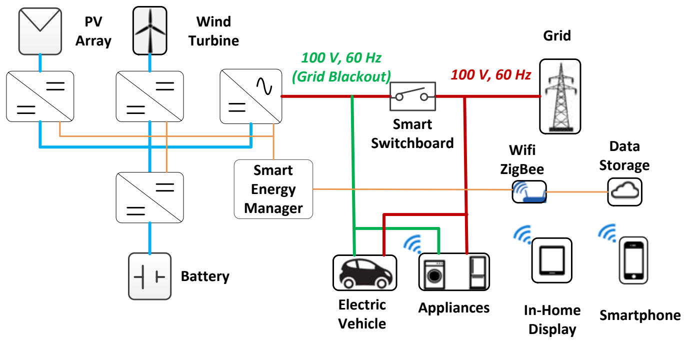

Fig. 4. LVDC Energy Distribution System in Fukuoka Smart House.

than systems using a dedicated MPPT converter [21]. The analysis showed that the system can improved PV energy utilization up to 8%.

V. Existing Facilities with LVDC Distribution Systems

Japan is one of the leading countries regarding LVDC distributions systems implementations. A demonstration facility has been built in island City in Fukuoka City. The facility was inaugurated in April 14th of 2012. The power architecture of the house is shown in Fig. 4. It consists of a hybrid AC-DC distribution system, renewable energy sources, an energy management system, and loads. The AC system, which is fed from an inverter connected to a common DC bus, is only used to supply power to the AC loads in the house. The common DC bus is running at 380 VDC which interconnects the renewable generation, the energy storage systems and the DC loads.

In Tohoku Fukusi University in Sendai City, a microgrid has been implemented and it has been running since 2008 [22]. The microgrid has several generation sources, gas engines, phosphoric acid fuel cell (PAFC), and PV arrays, and an AC an DC distribution systems. The DC loads, and buildings are supplied by the IPS, which is essentially a DC microgrid formed by a 400 VDC bus which interconnects the loads, renewable energy sources (PV), and a Valve-Regulated Lead Acid (VRLA) battery as an energy storage system. The facility in particular, and the technology in general, gathered the attention of the Japanese government, since it kept working autonomously from the grid during the earthquake in the Tohoku area in 2011, while the main grid was down for three days.

In Taiwan there is a demonstration facility built by the Elegant Power Application Research Center (EPARC). The system is formed by energy generators (PV panels, wind turbine and a fuel cell), energy storage devices (Li-ion battery and flywheel), DC loads (appliances and equipment), a monitor and control center, and a interconnection with the main grid [23].

In Europe, in comparison with Asia there are barely demonstration sites of LVDC microgrids. However, Philips Research has built an office lighting test bed installation in Eindhoven. The system uses both 380 VDC and 230/400 VAC for distribution of the energy generated by the PV panel to the LED lighting. The results have shown that the efficiency of the LVDC distribution system is 2% higher than the AC counterpart. The energy savings are achieved by mainly reducing the conversion stages between generator and load, and the transmission losses in the cables [24].

VI. Conclusion

This papers has reviewed the benefits and current topologies of LVDC distribution systems for residential applications. Various studies, regarding the potential energy savings and voltage levels, have been presented, as well as the demonstration facilities in which LVDC distribution systems have been already implemented. The studies have shown that a DC system will definitely increase the efficiency, power quality and reliability, however the challenges that DC-based systems need to overcome compared to the existing AC-based systems are still lacking, such as the safety and protection coordination aspects.

Several power topologies were shown, however a deeper analysis is required about which topology/configuration can optimize the efficiency, minimize the cost and investment, and maximize power quality and reliability. An interesting observation comes from a comparison among ultra-low voltage levels (i.e., 48-120 VDC) and conventional voltage levels in telecommunication industry (i.e., 380V) which helps to point out the improvements of using low voltage DC systems, such as higher safety without compromising the efficiency enhancement.

The lack of standardization and regulation is still the main challenge that this technology needs to face. LVDC distributions systems show great advantages when the integration of renewable energy sources, together with storage systems, are required. The development of commercial available solutions and devices, is the next step to boost the installation of LVDC systems, especially when minor modifications are needed in the devices' power converters.

In remote areas, where the main electricity grid is not available or nearly not available, hence, the energy is supplied by renewable energy sources. In this applications, LVDC systems system are already the first choice for distributing the energy, especially for extremely low-cost systems.

References

[1] T. Reynolds and T. Bernstein, "The damnable alternating current," *In Proc. of the IEEE*, vol. 64, no. 9, pp. 1339–1343, Sept 1976.

[2] P. Fairley, "DC Versus AC: The second war of currents has already begun [in my view]," *Power and Energy Magazine, IEEE*, vol. 10, no. 6, pp. 104–103, Nov 2012.

[3] A. Ghareeb, A. Mohamed, and O. Mohammed, "DC microgrids and distribution systems: An overview," in *Power and Energy Society General Meeting (PES), 2013 IEEE*, Jul 2013, pp. 1–5.

[4] D. Becker and B. Sonnenberg, "DC microgrids in buildings and data centers," in *IEEE Proc. Int. Telecommun. Energy Conf.*, Oct 2011, pp. 1–7.

[5] A. Pratt, P. Kumar, and T. Aldridge, "Evaluation of 400V DC distribution in telco and data centers to improve energy efficiency," in *Proc. Int. Telecommun. Energy Conf.*, Sept 2007, pp. 32–39.

[6] B. Fortenbery, E. C. EPRI, and W. Tschudi, "DC power for improved data center efficiency," 2008.

[7] B. T. Patterson, "DC, come home: DC microgrids and the birth of the "enernet"," *Power and Energy Magazine, IEEE*, vol. 10, no. 6, pp. 60–69, 2012.

[8] V. Vossos, K. Garbesi, and H. Shen, "Energy savings from direct-DC in U.S. residential buildings," *Energy and Buildings*, vol. 68, Part A, pp. 223 – 231, 2014.

[9] E. Vossos, "Optimizing energy savings from Direct-DC in U.S. residential buildings," Master's thesis, San Jose State University, 2011.

[10] K. Garbesi, V. Vossos, and H. Shen, "Catalog of DC appliances and power systems," Oct 2011.

[11] P. Savage, R. R. Nordhaus, and S. P. Jamieson, "DC microgrids: Benefits and barriers," *From Silos to Systems: Issues in Clean Energy and Climate Change*, pp. 51–66, 2010.

[12] D. Salomonsson, L. Soder, and A. Sannino, "Protection of low-voltage DC microgrids," *IEEE Trans. on Power Del.*, vol. 24, no. 3, pp. 1045–1053, July 2009.

[13] L. Mackay, L. Ramirez-Elizondo, and P. Bauer, "DC ready devices - Is redimensioning of the rectification components necessary?" in *Mechatronics - Mechatronika (ME), 2014 16th Int. Conf. on*, Dec 2014, pp. 1–5.

[14] G. Makarabbi, V. Gavade, R. Panguloori, and P. Mishra, "Compatibility and performance study of home appliances in a DC home distribution system," in *2014 IEEE Int. Conf. on Power Electron. Drives and Energy Syst. (PEDES)*, Dec 2014, pp. 1–6.

[15] D. Marquet, T. Tanaka, K. Murai, T. Toru, and T. Babasaki, "DC power wide spread in Telecom/Datacenter and in home/office with renewable energy and energy autonomy," in *in Proc. of 2013 35th Int.l Telecommun. Energy Conf. 'Smart Power and Efficiency' (INTELEC)*, Oct 2013, pp. 1–6.

[16] W. Li, X. Mou, Y. Zhou, and C. Marnay, "On voltage standards for DC home microgrids energized by distributed sources," in *2012 7th Int. Power Electron. and Motion Control Conf. (IPEMC)*, vol. 3, June 2012, pp. 2282–2286.

[17] S. Anand and B. Fernandes, "Optimal voltage level for DC microgrids," in *IECON 2010-36th Annual Conf. on IEEE Ind.l Electron. Society*. IEEE, 2010, pp. 3034–3039.

[18] H. Kakigano, Y. Miura, and T. Ise, "Low-Voltage Bipolar-Type DC Microgrid for Super High Quality Distribution," *IEEE Trans. on Power Electron.*, vol. 25, no. 12, pp. 3066–3075, Dec 2010.

[19] V. Rajaraman, A. Jhunjhunwala, P. Kaur, and U. Rajesh, "Economic analysis of deployment of DC power and appliances along with solar in urban multi-storied buildings," in *DC Microgrids (ICDCM), 2015 IEEE First Int. Conf.*, June 2015, pp. 32–37.

[20] P. Kaur, S. Jain, and A. Jhunjhunwala, "Solar-DC deployment experience in off-grid and near off-grid homes: Economics, technology and policy analysis," in *DC Microgrids (ICDCM), 2015 IEEE First Int. Conf.*, June 2015, pp. 26–31.

[21] D. Fregosi, S. Ravula, D. Brhlik, J. Saussele, S. Frank, E. Bonnema, J. Scheib, and E. Wilson, "A comparative study of DC and AC microgrids in commercial buildings across different climates and operating profiles," in *DC Microgrids (ICDCM), 2015 IEEE First Int. Conf.*, June 2015, pp. 159–164.

[22] K. Hirose, J. Reilly, and H. Irie, "The Sendai microgrid operational experience in the aftermath of the Tohoku earthquake: a case study," *New Energy and Industrial Technology Development Organization*, vol. 308, 2013.

[23] T.-F. Wu, Y. Chen, G.-R. Yu, and Y.-C. Chang, "Design and development of DC-distributed system with grid connection for residential applications," in *in Proc. Power Electron. and ECCE Asia (ICPE ECCE), 2011 IEEE 8th International Conf.*, May 2011, pp. 235–241.

[24] U. Boeke and M. Wendt, "DC power grids for buildings," in *DC Microgrids (ICDCM), 2015 IEEE First Int. Conf.*, June 2015, pp. 210–214.