Bipolar DC Power Conversion: State-of-the-Art and Emerging Technologies

Sebastian Rivera, *Member, IEEE,* Ricardo Lizana, *Member, IEEE,* Samir Kouro, *Senior Member, IEEE,* Tomislav Dragicevic, *Senior Member, IEEE,* and Bin Wu, *Fellow, IEEE*

***Abstract*—This paper provides a detailed analysis of the power electronics solutions enabling bipolar dc grids. The bipolar dc grid concept has proven to be more efficient, flexible and higher in quality than the conventional unipolar one. However, despite its many features, these systems still have to overcome their issues with asymmetrical loading to avoid voltage imbalances, besides meeting regulatory and safety requirements that are still under development. Advances in power electronics and the large-scale deployment of dc consumer appliances has put this growing architecture in the spotlight, as it has drawn the attention of different research groups recently. The following pages provide an insightful discussion regarding the topologies that enable these architectures, their regulatory requirements besides their features and level of development. Additionally, some future trends and challenges in the further development of this technology are discussed to motivate future contributions that address open problems and explore new possibilities**

***Index Terms*—Bipolar DC bus, DC Distribution, DC micro-grids, Smart grid, Low voltage DC.**

I. Introduction

THE SEARCH for sustainable ways of generating electricity while promoting a transversal use of clean technologies is deeply transforming the electric system [1], [2]. The decarbonization of the electric energy market is not only promoting the large-scale deployment of renewable energy sources (RES) in the generation matrix, but also advocating for the modernization at the consumers end . These changes are being enabled by an extensive use of power electronics, providing fast and precise responses to changes in generation, or tightly regulating the power being provided to the loads [3], [4]. This directly translates into a more complex ac power system, posing challenges in terms of reliability, safety and stability [3]. These reasons have motivated the re-evaluation of using low voltage direct-current (LVDC) active grids at distribution level.

Sustainable distributed generation systems such as photovoltaic and wind, as well as energy storage systems can be integrated more directly (fewer conversion stages) into dc distribution systems [2] . Furthermore, most of the existing loads both at industrial and residential level are either inherently dc in nature or ac fed through an inverter [5]. In addition, other rising applications such as large-scale data centers [5]–[10], electric vehicle charging infrastructure [11]–[17] or Net Zero Energy Buildings [18]–[21], also have the boosted interest in dc distribution systems [22], [23]. The fact that the integration of the different generators, loads and storage systems into dc networks require fewer conversion stages (in many cases just one), do not require synchronization or reactive power control (just voltage regulation), have lower control complexity, smaller footprint (less transformers and filters), and are more immune to power quality issues, compared to ac systems, have also been factors driving the attention towards dc distribution systems [24], [25]. Because all the aforementioned reasons, they could have a significant impact on the performance, efficiency, reliability, power density, and cost of future power systems [5], [7], [8], [26].

Despite the fact that virtually all of the existing consumer appliances or industrial equipment is designed and standardized for ac systems, or the protections and safety-related issues remain a big concern for dc grids, some important signs toward a dc shift have appeared over the last years. Among the pioneers in this regard, the European Union, has defined the voltage limits between 75 V and 1500 V for LVDC systems (LVD 2014/35/EU) [27]. Moreover, the Netherlands is the first country that published a national practice guideline for LVDC systems [28], establishing voltage levels for distribution dc grids: 350 V to 1400 V with respect to earth for monopolar and bipolar grids, defining zones within the grid to set the ground for protections and safety, imposing the requirement of galvanic isolation between ac and dc parts, and is currently preparing guidelines for safe working and inspection of dc installations. Other organization making significant efforts in the same direction is the International Electrotechnical Commission, which through several committees are working to standardize common practices for dc installations [29]. Finally, the Institute of Electrical and Electronics Engineers and EMerge Alliance, are also among other important stakeholders committed to advance towards a more dc distribution based power system [2].

Currently there are two mainstream dc distribution architectures or configurations, namely the unipolar (also known as monopolar) and the bipolar [30]. The first is characterized by providing a single dc voltage level between two conductors, while the second generates two dc voltages across a three-wire

S. Rivera is with the Faculty of Engineering and Applied Sciences, Universidad de los Andes, 7620086 Santiago, Chile (e-mail: s.rivera.i@ieee.org).
R. Lizana is with the Department of Electrical Engineering, Universidad Catolica de la Santisima Concepcion, 4090541 Concepcion, Chile, e-mail: ricardolizana@ucsc.cl
S. Kouro is with the Department of Electronic Engineering, Universidad Tecnica Federico Santa Maria, 2390123 Valparaiso, Chile (e-mail: samir.kouro@ieee.org).
T. Dragicevic is with the Department of Electrical Engineering, Denmark Technical University, 2800 Kgs. Lyngby, Denmark (e-mail: tomdr@elektro.dtu.dk).
B. Wu is with the Department of Electrical, Computer and Biomedical Engineering, Ryerson University, Toronto, ON M5B2K3, Canada, e-mail: bwu@ee.ryerson.ca

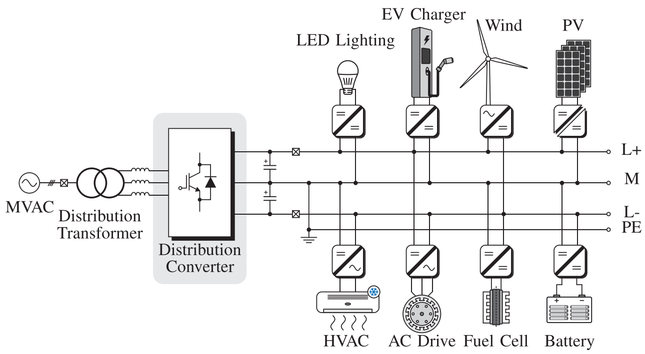

Figure 1. General structure of a low-voltage bipolar dc grid

configuration [31], [32]. Unipolar dc networks are inherently less complex in structure and easier to control, but lack the flexibility and resilience given by the three wire approach, which enables operation under a line fault, and provide a more options for loads and distributed generation, due to the two different voltage levels [31]. Furthermore the bipolar configuration enables both the implementation of a lower dc bus voltage or a higher dc bus voltage, depending which set of two wires are used for connection [31], reducing the voltage conversion range requirements of the connected loads and generators making the operation of power converters more efficient [26]. This also allows a broader range of applications to be interfaced with existing of-the-shelf power converter technology.

One of the major challenges for dc systems is related to protections against short circuit faults and grounding [30]. Again, the bipolar dc configuration provides an advantage over unipolar, due to the existing neutral conductor [22], enabling an easier and faster clearance against faults [22], [32], [33]. On the other hand, the three-wire two-voltage configuration of bipolar grids can lead to voltage unbalances between both voltage levels, given that both loads and generators connected to each pole can draw or inject different power levels causing the imbalance if not addressed properly [15], [32], [34]. Imbalances are usually solved by controlling properly the current circulating through the neutral or middle conductor, which affects the efficiency [35]. The voltage imbalance and its control remains as one of the main challenges facing this technology [25], and will be further elaborated in this paper in the following sections.

Considering the tremendous potential that bipolar LVDC grids hold for the development of dc distribution systems, this paper focuses on providing a state-of-the-art overview of the latest developments, by addressing their main features and drawbacks, while addressing open problems and opportunities that can provide a reference for researchers and practicing engineers on where this technology is heading.

The remainder of this paper has the following structure: Section II presents a discussion of bipolar LVDC systems, including a brief description of the requirements imposed by developing regulation. Section III covers topological aspects of the different converters involved in such grids. Then, future trends and upcoming works are presented in section IV. Finally, section V presents the summary of the study, and highlights the main contributions of this paper.

II. Bipolar type dc distribution systems

The bipolar architecture for dc distribution networks offers interesting features over the conventional unipolar counterpart. This structure is exhibited in Fig. 1, and it is seen that the utility ac voltage is converted to dc with the use of a distribution transformer and an active rectifier, also called distribution converter. Then, at dc level the system adopts a three-wire structure composed by the positive conductor (L+), the negative conductor (L-) and the neutral conductor (M). Please note that despite the higher complexity of the bipolar grid, this configuration presents clear advantages in terms of efficiency, reliability, safety and transmission capacity when compared to conventional two-wire systems, as it will be demonstrated through the paper. Advances in power electronics and their decreasing costs have allowed an increased penetration of power converters in different applications, thus enabling the consequent expansion of dc systems at distribution level [22].

Among the benefits offered by the system displayed in Figure 1, the main feature is its the three-wire configuration. This resembles the traditional ac system in the sense that it provides the connection to two different regulated voltages. The voltage between the positive and negative poles is analogous to the line-to-line voltage, while the voltage of a pole with respect to the neutral connector is analogous to the phase-to-neutral one [32]. This allows to accommodate a wide set of DGs and loads with different voltage and power ratings combinations in a single dc network [36]–[38].

From an economical point of view, bipolar systems secure the cost competitiveness of the converters interfacing the different stages of the network. This is related with the reduction of the voltage ratings of the power electronic components, the efficiency improvement due the reduction of the rated current, besides the elimination of unnecessary dc-ac stages [26]. The latter is because most of the stages involved in DGs are either dc-based, e.g., photovoltaic (PV) panels, fuel cells (FC) and batteries or generate outputs with variable voltage/frequency, e.g., wind, small hydro, wave/tidal energy conversion systems, hence require power electronics devices to accommodate their output to network conditions [26]. In addition, the presence of batteries and storage stages further enhances the benefits of dc distribution, as it yields to greater efficiency improvements [39], [40] and enhanced stability [30]. The result is a substantial enhancement in the quality of the electric system and at the same time, reduction of the costs when compared to conventional ac solutions [31].

The aforementioned resemblance with three-phase ac systems is also beneficial for the migration process to bipolar dc networks. Considering a conventional TN-S grounded three-phase system, which requires five conductors for its realization (three phase conductors, one neutral and the protective earth or grounding conductor). These available cables can serve in a retrofitted dc system that will be superior in terms of power ratings capability and efficiency than the original one [26]. For example, a typical multi-wire 230 V ac installation