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Experimental validation of a single phase Intelligent Power Router

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ABSTRACT

Current power networks are facing numerous challenges in transmission and distribution in order to accommodate distributed generation from renewables. As a result, the current grid needs to evolve towards a system with more control and resiliency. The Intelligent Power Router device, located at strategic nodes, permits to add novel functionalities. This device allows to fully control the power flow by the means of Voltage Source Converters. In this article, the operation modes of the Intelligent Power Router are proposed and discussed. Moreover, this paper presents the design of a single phase Intelligent Power Router, simulations that prove its capability to control the power flow; and finally, an experimental validation of the device operation is also offered.

1. Introduction

The traditional electrical distribution network is evolving towards a more automated model, where control and monitoring will be essential [1]. This development, partially motivated because of the increasing ratio of Distributed Renewable Energy Sources (DRES), is encouraging the reduction of fossil fuel generation and indirectly the reduction of the energy price [1,2]. Furthermore, the emerging energy scenario is introducing new energy trends as the "prosumers", defined by Nguyen et al. as consumers that actively participate on distributed electricity generation [3]. In order to be able of managing the future grid, more control must be provided which can be achieved using new technical concepts as the Intelligent Power Router (IPR) presented herein.

IPRs [3,4], also known as Power Routers [5–9], Digital Grid Routers [10] and Energy Routers [11–13], are power electronics devices that allow to control the energy flow through power distribution networks. The energy routing concept could have different approaches ranging from residential applications up to bulk power energy transmission [10,11,4]. The role of IPRs in transport and distribution energy applications consists of receiving information from neighbouring networks and modifying the power flow based on economics, energy availability, system security or other criteria that could be of interest. Thereby, IPRs will improve the energy quality provided by DRES, increasing its penetration ratio and offering new trading systems for the electricity markets [10].

The system based on IPRs has its foundations on energy packets transmission. In such a way, the energy is described as pulses which last a certain time, also known as "energy discretization" [10,14,15]. These pulses, also called packets, could have an associated direction so that they can be sent to specific locations through networks like data packets in Internet, enabling a smarter use of the current energy grid [12,16]. In addition, valuable information related to the location, time, generation source, CO_2 emissions or green certificates can be sent together with the energy packets in order to enhance the transmission system [10].

Current research in the operation of IPRs is focused on dividing the interconnected grids into several areas, also called cells, which could be asynchronous amongst them. Despite being asynchronous, the different cells can be connected because of IPRs. It is important to notice that communication amongst IPRs is essential to achieve the optimum energy packet transfer amongst cells [10]. Nevertheless, the future grid concept is not only based on communications and power electronics but also on storage units. The future grid model will be coordinated by an Energy Management System (EMS), that will manage the energy packets from power

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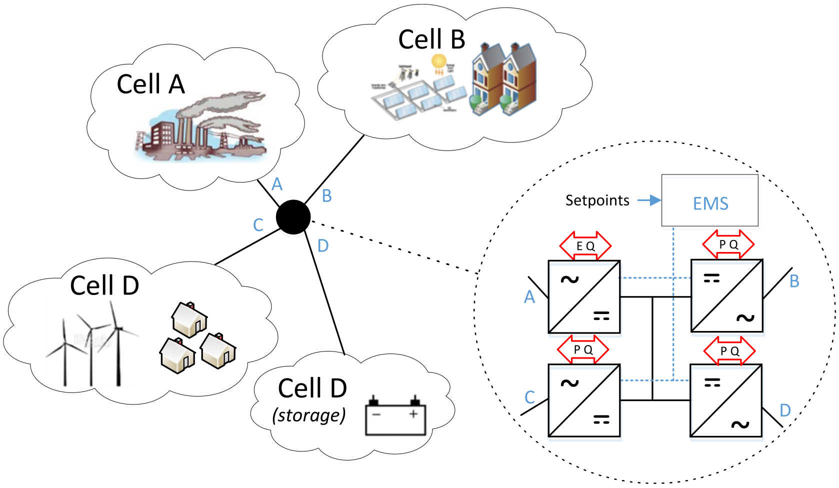

Fig. 1. Example of an IPR connecting different cells.

plants, storage systems or distributed generation to the loads located at different cells. An example of the ongoing research is being developed in the Digital Grid consortium [17]. Similarly, T. Takuno et al. [7] introduce a system where storage can be managed by IPRs to compensate fluctuations of renewable generation.

The main target of this article is to validate experimentally the IPR concept, so that, taking into account the different explanations discussed in the literature, this work is focused on providing a deeper comprehension of the device modelling, operation and control. Different IPR operation modes are proposed in this paper. The device performance is validated through simulations and experimental results are carried out in a laboratory platform.

This paper is structured as follows: the concept of the IPR as well as its operational possibilities are described in Section 2. Section 3 describes the IPR general control approach whereas Section 4 describes the specific tuning of the single-phase IPR used in this study. Next, different simulations proving IPR feasibility are carried out in Section 5. In Section 6 the IPR device is described and Section 7 provides experimental test results. Finally, in Section 8 some concluding remarks are drawn.

2. Intelligent Power Router device

The IPR is a power electronics device that controls and routes the electric energy flow amongst different interconnected networks. It is important to realize that IPRs are compounded by several Voltage Source Converters (VSC) [18] so it is possible to control the active and reactive power flowing through each converter, independently. The IPR must be located at strategic nodes of the grid in order to improve the system performance. Fig. 1 shows the interconnection of different systems by means of an IPR.

IPRs offer new transmission capabilities being able to integrate higher ratios of DRES and offering more resiliency to the electrical system due to the higher interconnection of different areas. Furthermore, IPRs also enable the energy exchange between cells asynchronously connected [4], opening new options for the energy management. The implementation of the IPR also allows to merge grids of different topologies, connecting three-phase systems with single-phase or DC lines [15].

2.1. IPR operation options

Each IPR is able to control the energy flow in any direction amongst the cells connected to its terminals. The power flow setpoints can be obtained based on different criteria according to the EMS operation. Different elements that can affect the EMS decisions could be the DSO restrictions, electricity markets, the state of the energy stored (in case of being connected to storage elements), power plants schedules, renewable sources forecasting, etc.

Besides controlling the power flow, IPRs might be used to control different grid variables, hence different control strategies must be considered. Each VSC compounding the IPR can be operated under different modes depending on the main necessities of the electrical grids. Notice that active and reactive power (in case of AC grids) can be controlled independently.

2.2. IPR DC bus voltage regulation modes

The steady state operation of the IPR is based on ensuring the net power balance within the device, which is guaranteed by

$$\sum_{cell=1}^{n} P_{cell} + P_{losses} = 0. \tag{1}$$

This condition is achieved regulating the IPR DC bus voltage, which ensures that no energy is stored within the IPR in steady state. Although during transients this condition could not be guaranteed, a proper DC bus voltage regulation will establish the net power balance. The DC bus voltage regulation can be achieved through different methodologies as shown in Table 1 and Fig. 2. This table describes the different operation modes and submodes of the IPR converters in charge of the DC bus voltage regulation. Note that one or more converters, either connected to AC grids or DC grids, can perform the DC bus voltage regulation.

Focusing on AC grids, Mode 1 regulates the DC bus voltage through a single converter. Specifically, this converter regulates the DC voltage through injecting/extracting active power to/from the DC bus. Moreover, this converter can track reactive power setpoints (Mode 1.A) or regulate AC voltage (Mode 1.B).

Mode 2 is characterized because at least two converters are regulating the DC bus. This operation mode could be based on many different techniques such as droop control or the voltage margin control [19,20]. In this approach, the droop control is selected as the preferred technique for these type of purposes, as it is widely accepted for multi-terminal DC grids operation [19–22]. Droop control is a proportional controller locally implemented in each converter such that the slope and the reference control input implemented in each converter can be adjusted by the EMS in order to affect the power sharing amongst converters. Furthermore, reactive power could be employed to track references (Mode 2.A)