Advanced Control Architectures for Intelligent MicroGrids – Part I: Decentralized and Hierarchical Control

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***Abstract*— This paper presents a review of advanced control techniques for microgrids. The paper covers decentralized, distributed, and hierarchical control of grid connected and islanded microgrids. At first, decentralized control techniques for microgrids are reviewed. Then, the recent developments in the stability analysis of decentralized controlled microgrids are discussed. Finally, hierarchical control for microgrids that mimic the behavior of the mains grid is reviewed.**

***Index Terms*—Microgrids, Hierarchical Control, Distributed Control, Electrical Distribution Networks, Droop Method.**

I. Introduction

THE promise of the smart grid is round the corner. However, research and society cannot wait for the approval of many standards and grid codes, especially when these codes can restrict more the independence of the electricity users from the suppliers. In this sense, the demand side management can be satisfied by using local energy storage and generation systems, thus performing small grids or microgrids. Microgrids should able to locally solve energy problems, hence increase flexibility and flexibility. Power electronics plays an important role to achieve this revolutionary technology. We can imagine the future grid as a number of interconnected microgrids in which every user is responsible for the generation and storage part of the energy that is consumed, and to share the energy with the neighbors [1].

Hence, microgrids are key elements to integrate renewable and distributed energy resources as well as distributed energy storage systems. In this sense, new power electronic equipment will dominate the electrical grid in the next decades. The trend of this new grid is to become more and more distributed, and hence the energy generation and consumption areas cannot be conceived separately [5]-[7]. Nowadays electrical and energy engineers have to face a new scenario in which small distributed power generators and dispersed energy storage devices have to be integrated together into the grid. The new electrical grid, also named smart-grid (SG), will deliver electricity from suppliers to consumers using digital technology to control appliances at consumer's homes to save energy, reducing cost and increase reliability and transparency. In this sense, the expected whole energy system will be more interactive, intelligent, and distributed. The use of distributed generation (DG) makes no sense without using distributed storage (DS) systems to cope with the energy balances.

Microgrids, also named minigrids, are becoming an important concept to integrate DG and DS systems. The concept has been developed to cope with the penetration of renewable energy systems, which can be realistic if the final user is able to generate, store, control, and manage part of the energy that will consume. This change of paradigm, allows the final user be not only a consumer but also a part of the grid.

Islanded microgrids have been used in applications like avionic, automotive, marine, or rural areas [2]-[8]. The interfaces between the prime movers and the microgrids are often based on power electronics converters acting as voltage sources (voltage source inverters, VSI, in case of AC-microgrids) [9], [10]. These power electronics converters are parallel connected through the microgrid. In order to avoid circulating currents among the converters without the use of any critical communication between them, the droop control method is often applied [11]-[15].

In case of paralleling inverters, the droop method consist of subtracting proportional parts of the output average active and reactive powers to the frequency and amplitude of each module to emulate virtual inertias. These control loops, also called *P–f* and *Q–E* droops, have been applied to parallel-connected uninterruptible power systems (UPS) in order to avoid mutual control wires while obtaining good power sharing [16]-[20]. However, although this technique achieves high reliability and flexibility, it has several drawbacks that limit its application.

For instance, the conventional droop method is not suitable when the paralleled-system must share nonlinear loads, because the control units should take into account harmonic currents, and, at the same time, to balance active and reactive power. Thus, harmonic current sharing techniques have been proposed to avoid the circulating distortion power when sharing

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nonlinear loads. All of them consist in distorting the voltage to enhance the harmonic current sharing accuracy, resulting in a trade-off. Recently, novel control loops that adjust the output impedance of the units by adding output virtual reactors [17] or resistors [16] have been included into the droop method, with the purpose of sharing the harmonic current content properly. Further, by using the droop method, the power sharing is affected by the output impedance of the units and the line impedances. Hence, those virtual output impedance loops can solve this problem. In this sense, the output impedance can be seen as another control variable.

Besides, another important disadvantage of the droop method is its load-dependent frequency and amplitude deviations. In order to solve this problem, a secondary controller implemented in the microgrid central control can restore the frequency and amplitude in the microgrid.

In this paper, a review of advanced control techniques for microgrids is provided. The paper is organized as follows. In Section II decentralized control techniques for microgrid are reviewed. In Section III recent developments in the stability analysis of decentralized controlled microgrids are discussed. Section IV presents the hierarchical control architecture for microgrids. Finally, Section V presents the conclusions of the paper.

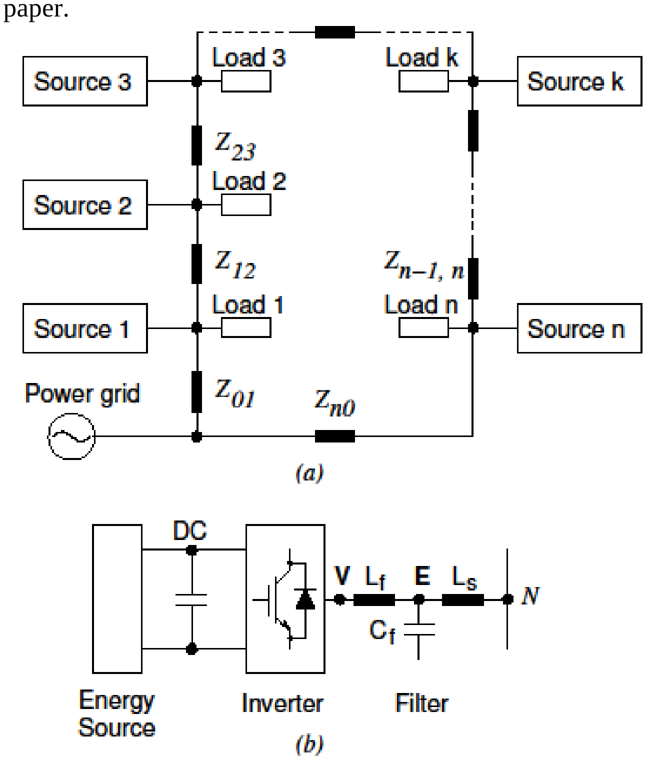

Fig. 1. Microgrid with distributed sources and loads

II. REVIEW OF MICROGRID DECENTRALIZED CONTROL METHODS

The aim of this Section is to review recent work in microgrid decentralized control. The emphasis is on control affecting microgrid dynamic behavior on a relatively fast time scale, while the issue of load planning and scheduling has been left out of this review.

A key feature of microgrids with distributed energy sources is that the sources are dispersed over a wide area. These sources are interconnected to each other and to loads by a distribution network. Further, the distributed microgrid may be connected to the main power grid at some point as well. Fig. 1(a) shows a distributed microgrid structure connected to the main grid. The figure also shows the microgrid line impedances ($Z_{01}, Z_{12}, \ldots Z_{n-1,n}$). The source is connected to the microgrid distribution network by an inverter interface through a filter, e.g. an *LCL* filter, shown in Fig. 1(b).

The control of the inverter+filter interfaces is crucial to the operation of the microgrid. Because of the distributed nature of the system, these interfaces need to be controlled on the basis of local measurements only; it is not desirable to use data communication. The decentralized control of the individual interfaces should address the following basic issues.

- The interfaces should share the total load (linear or nonlinear) in a desired way.
- The decentralized control based on local measurement should guarantee stability on a global scale.
- The inverter control should prevent any dc voltage offsets on the microgrid.
- The inverter control should actively damp oscillations between the output filters.

From the viewpoint of decentralized control, it is convenient to classify distributed generation architectures into three classes with respect to the interconnecting impedances Z_{01} etc., shown in Fig. 1(a). In highly dispersed networks, the impedances are predominantly inductive and the voltage magnitude and phase angle at different source interconnects can be very different. In networks spread over a smaller area, the impedances are still inductive but also have a significant resistive component. The voltage magnitude does not differ much, but the phase angles can be different for different sources. In very small networks, the impedance is small and predominantly resistive. Neither magnitude nor phase angle differences are significant at any point. In all cases, the main common quantity is the steady-state frequency which must be the same for all sources. In the grid-connected mode, the microgrid frequency is decided by the grid. In the islanded mode, the frequency is decided by the microgrid control.

In each of these classes, if every source is connected to at most two other sources as shown in Fig. 1(a), then the microgrid is *radial*. Otherwise, it is *meshed*. If there is a line connecting Source 1 with Source *k* in Fig. 1(a), then it is a meshed microgrid. By far the largest body of research work done in decentralized microgrid control has been for radial architectures of the type described in [1].

Early work on decentralized parallel inverter control concepts suitable for microgrid operation was reported in [2]. This work assumed that the impedance connecting sources was predominantly inductive; resistance was neglected. Based on the decentralized control used in conventional power systems, the use of droops is introduced in the generators, hence adjusting the frequency set-point according to the output active power, and voltage magnitude set-point depending on the output reactive power. It was shown that the distributed system could be operated without the use of phase-locked loops