Supervisory Control of an Adaptive-Droop Regulated DC Microgrid with Battery Management Capability

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***Abstract*—DC power systems are gaining an increasing interest in renewable energy applications because of the good matching with dc output type sources such as photovoltaic (PV) systems and secondary batteries. In this paper, several distributed generators (DGs) have been merged together with a pair of batteries and loads to form an autonomous dc Microgrid (MG). To overcome the control challenge associated with coordination of multiple batteries within one stand-alone MG, a double-layer hierarchical control strategy was proposed; 1) The unit-level primary control layer was established by an adaptive voltage-droop (VD) method aimed to regulate the common bus voltage and to sustain the states of charge (SOCs) of batteries close to each other during moderate replenishment. The control of every unit was expanded with unit-specific algorithm, i.e. finish-of-charging for batteries and maximum power point tracking (MPPT) for renewable energy sources (RESs), with which a smooth on-line overlap was designed; 2) the supervisory control layer was designed to use the low bandwidth communication interface between the central controller and sources in order to collect data needed for adaptive calculation of virtual resistances (VRs) as well as transit criteria for changing unit-level operating modes. A small-signal stability for the whole range of VRs. The performance of developed control was assessed through experimental results.**

***Index Terms*—Adaptive droop control, battery charger, distributed generation (DG), Microgrid (MG), supervisory control.**

I. Introduction

TECHNOLOGICAL advancement in power electronics during the past decade has led to a condition where renewable energy sources (RES) such as wind and photovoltaic (PV) can be virtually considered as completely controllable, within the limits imposed by natural phenomenon [1]. Thus, RES integrated together with other distributed generation (DG) are steadily becoming even competitors in new electricity grids that tend to minimize the consumption of fossil fuels while trying to be more flexible and distributed at the same time.

Objecting to the traditional one way power/information flow, it was conceived that a large-scale integration of new technologies into a smart grid (SG) will be quite difficult if it is done independently. Thus, an idea of merging small variable nature sources with energy storage system (ESS) into a singular controllable entity that can work autonomously or grid-connected brought to a Microgrid (MG) concept [2]. Depending on the voltage type on common bus, ac and dc MGs can be distinguished. While a lot of work has been done previously in improving the operation of ac MGs [3]–[7], dc MG field has started attracting considerable attention recently, particularly due to a potential of bringing many advantages such as higher efficiency, more natural interface of RES, better compliance with consumer electronics, etc. [8]–[13]. Furthermore, reactive power flow, power quality and frequency control are not an issue in dc systems, making the corresponding primary control notably less complex than its ac version. Currently, most common applications of dc MGs are electrical power supply of isolated systems like vehicles, space crafts, data centers, telecom systems or rural areas [14]–[17].

In both ac and dc applications, tightest control can be achieved if fast intercommunication links between paralleled sources are available. However, with the increasing number of units and/or their spatial diffusion, wiring hardware becomes serious limitation. Moreover, physical differences between converters and lines can trigger the circulating current problem [18]. Hence, to overcome these constraints, a droop control method, taken from traditional power system control [19], has been proposed in both dc and ac MGs [20]. Specifically, the dc MG droop control is usually based on subtracting part of the converter output current proportional to virtual resistance (VR) from voltage reference. Some authors have also proposed multiplication of measured voltage deviation to a value reciprocal to VR [21].

However, it is desirable to extract all available power from RESs, referred to as maximum power point tracking (MPPT) [22], [23], but not always appropriate in isolated systems, as it can lead to an unmanageable excess of energy, resulting in possible overcharging of ESS. On the other hand, a battery, an ESS that is used in this paper, has specific requirements for recharging completion to obtain optimum life [24]. So, there should be an option to control the units in the system according to their specific features as well. For this purpose, a dual control on primary level has been developed in this paper. An attention has been devoted to enable smooth on-line switching between voltage-droop (VD) and unit specific control (MPPT or regulated charging).

The cost of the batteries usually has a big share in the overall cost of isolated systems [25]. Also, their optimal sizing

Manuscript received September 28, 2012; revised January 25, 2013; accepted April 7, 2013. The work of T. Dragičević was supported by the Croatian Science Foundation under grant No. I-4463-2011 (MICROGRID).

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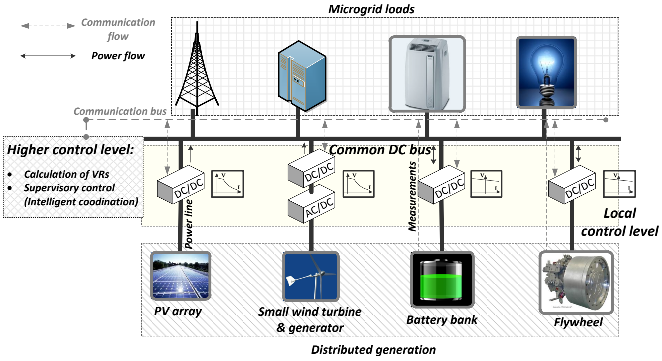

Fig. 1. Diagram of a dc microgrid.

depends on system consumption and production capacity of generating units. Possible increase of consumption within the isolated system will therefore yield a need for storage expansion. Due to hardware limitations, usually the only option to do this is an addition of separate ESS. However, although increased storage capacity gives more flexibility and provides more resilience to prolonged periods without production, its regular re-charging requirements may be too high for small isolated systems with limited power from RESs. As stability of the common bus voltage and its maintenance within acceptable limits should have the highest priority, it is often necessary to distribute the recharging efforts through time. To the best knowledge of the authors, the issue of managing multiple battery stacks within one autonomous system has been out of the scope of most related research up to date. For that purpose, a triple-role supervisory control strategy was developed on top of primary control for a dc MG that consists of RESs and two separate batteries. Its first function includes a novel on-line adaptation of VRs which is designed to achieve asymptotic approaching of batteries' states of charge (SOCs) and is intended for moderate replenishment periods. The second and third function, active at high SOCs, are responsible for distributing the charging and discharging tokens and transitions of operating modes respectively.

The paper is organized as follows. In section II, dc MG configuration is shown and classification of units according to their changing operating states is given. Also, VD control is revised in more detail. Section III provides the ESS modelling and control with the proposal of an adaptive VRs calculation . In Section IV, all details of primary control and functionalities of the supervisory control are revealed. Section V gives a small-signal analysis which is a useful supplement to determine the degree to which VRs can be changed not to compromise the system stability. Experimental results are presented in Section VI in order to validate the feasibility of the proposed approach. Finally, Section VII gives the conclusion.

II. DC Microgrid Configuration and Control

A dc MG is showed in Fig. 1. It consists of PV and WTG subsystems, two battery banks, a common power bus, a communication link and variety of loads. To achieve parallel operation of diverse sources within the MG, power interfaces are required in between. They consist of several control stages and associated converters. PV system is made of a PV array and a buck converter. WTG system consists of a small wind turbine and permanent magnet synchronous generator (PMSG) connected to a diode rectifier and buck converter. Both batteries are connected to the common bus through synchronous buck converters to realize bidirectional power flow. DC/DC converters are crucial elements here as they link the common bus with sources and control the current flow between them.

Proposed control structure is divided into two layers; a dual functionality primary control for automatic regulation over current injection into the common bus and a supervisory control for coordination of power generation and provision of specific requirements to the sources using a low-bandwidth communication interface.

Primary control is made of two nested control loops; the outer one responsible for creating a current reference and the inner one which makes sure that the output current follows that reference. Depending on the control strategy incorporated in outer loop, a common classification of units can be made on voltage source converters (VSCs) and current source converters (CSCs). Generally, RESs operating in MPPT mode and batteries during regulated charging act as CSCs as their power injection/extraction does not depend on on-going grid condition. On the other hand, an ability of regulating the coupling point voltage makes VSC units important when forming stand-alone systems. Unlike the traditional approach where only one of these control strategies is applied to a specific unit, all DGs within this MG are able to operate in both VSC and CSC mode and seamlessly overlap between them during the operation.

A. Conventional Droop Control

In order to connect a number of VSCs in parallel and accomplish current sharing between them in distributed way, voltage control should not be stiff. So, the output voltage reference of every converter should follow VD characteristic defined with VR, which sets its stiffness measure. This concept stems from a practice of forming an electrical power system through speed-droop regulated governors of a number of parallel connected rotating synchronous generators [19]. Unlike the speed of rotating generators, the output voltage of converter is regulated here with respect to on-going condition of the grid, and is used as a system-wide control signal. This control concept utilizes two outer control loops which, when combined together, produce an output current reference. An output VR loop creates a voltage reference which is followed by the voltage loop:

$$v_{out}^{*} = v_{ref} - R_d i_o \tag{1}$$

where v_{out}^{*} is the voltage reference for voltage loop, v_{ref} is the outer voltage reference, i_o is the output current and R_d is the VR.

Two specific cases of (1) can be distinguished. When VR takes the zero value, it corresponds to VSC. If it takes the infinite value, it corresponds to CSC. If the latter instance is considered, current reference will be generally set in such a