SAND2013-5733C

Hamiltonian-based Power Flow Control for DC Microgrids with Renewable Generation, SAND2013-5733 C

ABSTRACT

Achieving high performance operation of microgrids containing stochastic sources and loads is a challenge that impacts cost and complexity. Developing alternative methods for controlling and analyzing these systems will provide insight into tradeoffs that can be made during the design phase. This paper presents a design methodology for a hierarchical control scheme that regulates renewable energy sources and energy storage in a DC microgrid. Recent literature has indicated that there exists a trade-off in information and power flow and that intelligent, coordinated control of power flow in a microgrid system can modify energy storage hardware requirements.

I. INTRODUCTION

The electric power grid is evolving to a state which has yet to be defined. Unidirectional power and information flow will be replaced by bi-directional flow as new generation sources distribute throughout the electric grid of the future. Renewable and other distributed energy sources cannot be economically and reliably integrated into the existing grid because it has been optimized over decades to large centralized generation sources. Today's grid model is based on excess generation capacity (largely fossil fuel), static distribution/transmission systems, and essentially open loop control of power flow between sources and loads. Research investments in grid modernization and microgrids are presently being made by the Department of Energy, Department of Defense, industry, universities, and others [1],[2]. Emphasis of this research is to develop mathematical tools that can optimize designs specific to an application.

Achieving regulation and power balance in a system with high penetration levels of stochastic renewable sources are some of the challenges addressed by this research. The problem is solved provided "enough" energy storage is available; unfortunately, energy storage systems incur cost, and the minimum required energy storage is dependent on performance objectives. Herein, the problem of increasing renewable energy penetration in a microgrid is addressed. The proposed method distributes the control of energy storage and power converters and attempts to minimize energy storage using controls. In effect, the physical energy storage may be mitigated by increasing information flow between controllers [1].

Regulation of energy storage and power conversion in the microgrid is divided into two parts: the *guidance control* the *Hamiltonian-based control*, and the *servo control*. A centralized controller provides *guidance control* by computing reference duty cycle values and reference states that optimize some criteria (ie. minimizes some cost function or maximizes some value function); the guidance control identifies the optimal operating point and is determined using SQP or dynamic programming methods [5]. The Hamiltonian-based control is a local feedback controller that is designed to minimize variability in the power delivered to the boost converters [1],[3]-[5]. The servo control supports the Hamiltonian-based control by regulating certain components to specified voltages.

In this digest, the hardware testbed is presented in section II, guidance control and Hamiltonian-based controls are discussed in section III, Section IV includes some experimental results, and Section V provides conclusions.

II. MICROGRID DESCRIPTION and SIMPLIFIED DYNAMIC MODEL

A comprehensive microgrid testbed has been constructed which includes a reconfigurable bus, two mechanical source emulators capable of emulating a wind turbine or a diesel engine, a high-power digital resistor rated to 6.7 kW at 400V bus voltage, an energy storage emulator capable of sourcing or sinking 5kW of power, and master control console that scripts the experiments [6]-[8]. The system under consideration for this paper has two wind turbine generators, three energy storage systems and a resistive load; see Figures 1 and 2.

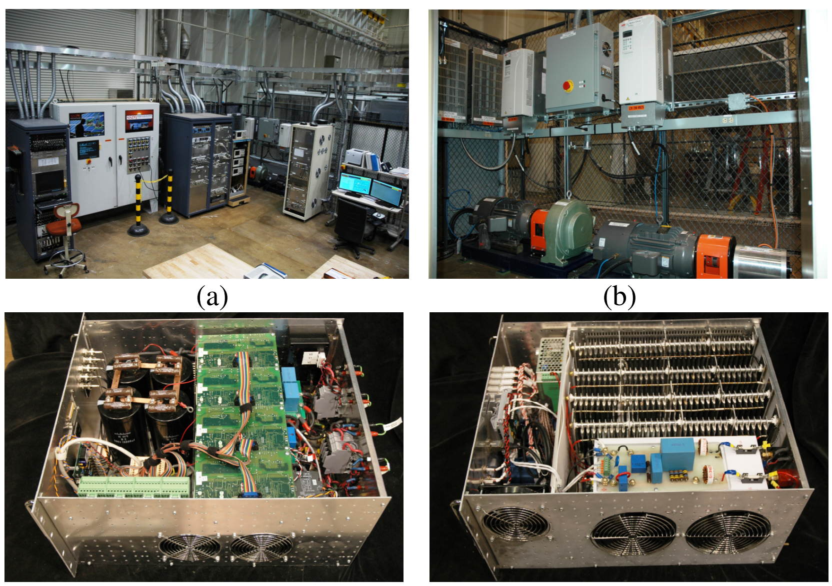

Figure 1: Photos of (a) the microgrid testbed including (b) mechanical source emulators, (c) energy storage emulator, and (d) high power digital resistor

As will be explained in the next section, the control scheme has three layers including a guidance control, a Hamiltonian-based control and a servo control. The servo-control operates on the fastest timescale.

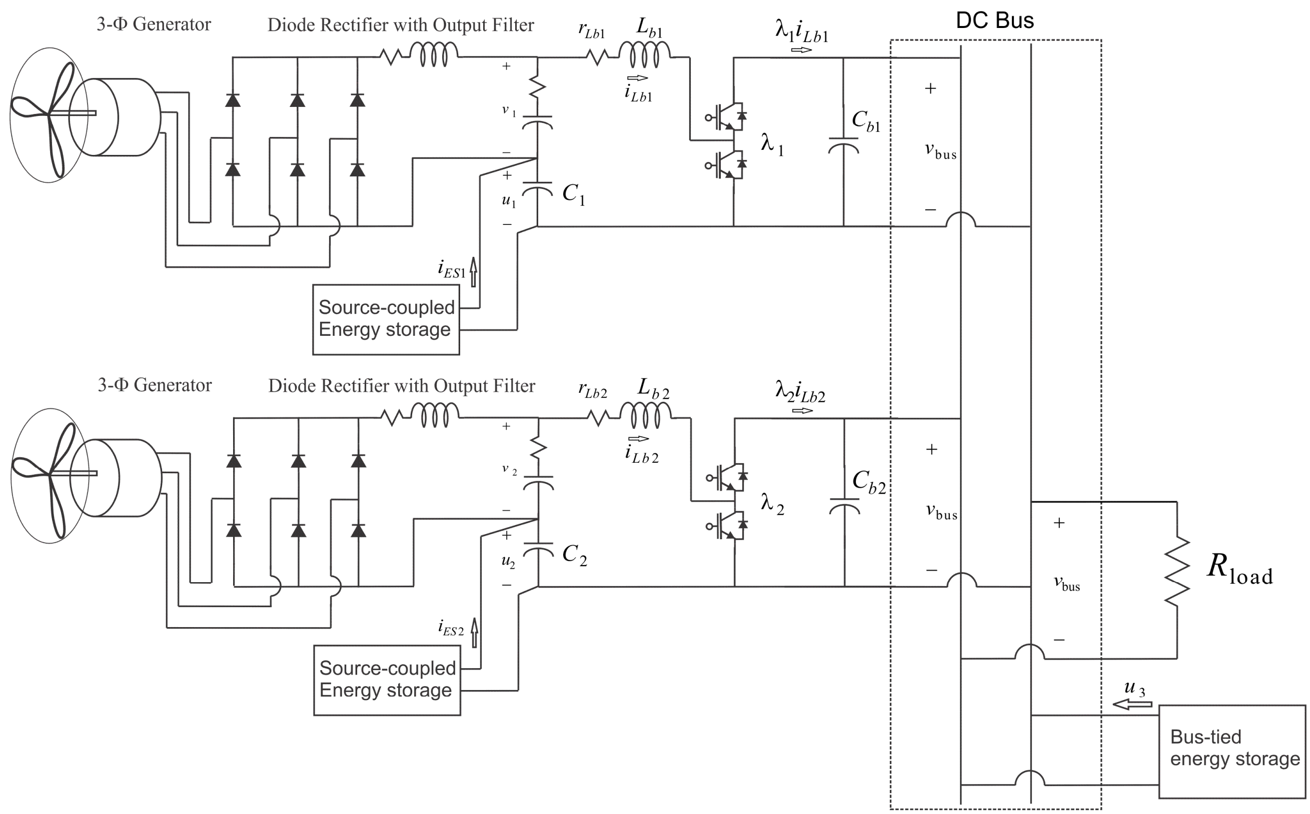

Figure 2: Schematic of example microgrid

Since voltages u_1, u_2 are maintained using the servo-controller, the simplified model for Hamiltonian control is:

$$\begin{bmatrix} L_{b1} & 0 & 0 \\ 0 & L_{b2} & 0 \\ 0 & 0 & C_{b1}+C_{b2} \end{bmatrix} \begin{bmatrix} \dot{i}_{Lb1} \\ \dot{i}_{Lb2} \\ \dot{v}_{\text{bus}} \end{bmatrix} = \begin{bmatrix} -r_{Lb1} & 0 & -\lambda_1 \\ 0 & -r_{Lb2} & -\lambda_2 \\ \lambda_1 & \lambda_2 & -R_{\text{load}}^{-1} \end{bmatrix} \begin{bmatrix} i_{Lb1} \\ i_{Lb2} \\ v_{\text{bus}} \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \\ 0 \end{bmatrix} + \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \tag{1}$$

where λ_1 and λ_2 are right side duty-cycles for the first and second boost converter respectively, R_{load} is assumed piecewise constant and all *L*, *C*, and remaining resistor values are assumed constant. Equation (1) may be written:

$$\mathbf{M}\dot{\mathbf{x}} = \left[\bar{\mathbf{A}}(R_{\text{load}}) + \tilde{\mathbf{A}}(\boldsymbol{\lambda})\right]\mathbf{x} + \mathbf{v} + \mathbf{u} \tag{2}$$

where $\boldsymbol{\lambda} = [\lambda_1 \quad \lambda_2]^T$ and $\tilde{\mathbf{A}}(\boldsymbol{\lambda})$ is the skew-symmetric component of the $\left[\bar{\mathbf{A}}(R_{\text{load}}) + \tilde{\mathbf{A}}(\boldsymbol{\lambda})\right]$ matrix.

III. GUIDANCE CONTROL and HAMILTONIAN CONTROL

The system error state and control inputs are defined as $\tilde{\mathbf{x}} = \mathbf{x}_{\text{ref}} - \mathbf{x}$ and $\tilde{\mathbf{u}} = \mathbf{u}_{\text{ref}} - \mathbf{u}$. Given a load resistance R_{load} and variable source $\mathbf{v}$, the reference values are computed first by setting $\dot{\mathbf{x}} = \mathbf{0}$, $v_{\text{bus}} = (v_{\text{bus}})_{\text{ref}}$, and $\mathbf{u} = \mathbf{0}$ and solving the following for $\boldsymbol{\lambda}$ and $\mathbf{x}_{\text{ref}}$ [5]:

$$\left[\bar{\mathbf{A}}(R_{\text{load}})+\tilde{\mathbf{A}}(\boldsymbol{\lambda})\right]\mathbf{x}_{\text{ref}}+\mathbf{v}=\mathbf{0} \tag{3}$$

The feedback control is developed using a Hamiltonian formulation. The reference input takes the form given in (4), and the Hamiltonian is defined in (5) [5]:

$$\mathbf{u}_{\text{ref}}=-\left[\bar{\mathbf{A}}(R_{\text{load}})+\tilde{\mathbf{A}}(\boldsymbol{\lambda})\right]\mathbf{x}_{\text{ref}}-\mathbf{v} \tag{4}$$

$$H=\frac{1}{2}\tilde{\mathbf{x}}^{\mathbf{T}}\mathbf{M}\tilde{\mathbf{x}}+\frac{1}{2}\left(\int\tilde{\mathbf{x}}d\tau\right)^{T}\mathbf{K_I}\left(\int\tilde{\mathbf{x}}d\tau\right) \tag{5}$$

Since $\mathbf{M}$ is positive definite, the *static stability condition* is met [5]. For dynamic stability, the condition $\dot{H}<0$ must be met and is done through proper definition of the feedback control law, which may take the form of a Proportional+Integral (PI) control [5] in (6). The resulting time derivative of the Hamiltonian is given by (7).

$$\tilde{\mathbf{u}}=-\mathbf{K_p}\tilde{\mathbf{x}}-\mathbf{K_I}\int_0^t\tilde{\mathbf{x}}d\tau \tag{6}$$

$$\dot{H}=\tilde{\mathbf{x}}^{\mathbf{T}}\left(\mathbf{M}\dot{\tilde{\mathbf{x}}}+\mathbf{K_I}\left(\int\tilde{\mathbf{x}}d\tau\right)\right)=\tilde{\mathbf{x}}^{\mathbf{T}}\left[\mathbf{R}-\mathbf{K_P}\right]\tilde{\mathbf{x}} \tag{7}$$

where $\mathbf{R}=diag\begin{bmatrix}-r_{Lb1} & -r_{Lb2} & -R_{load}^{-1}\end{bmatrix}$. Solution of (3) and (4) (which includes the determination of $\boldsymbol{\lambda}$) constitutes the guidance command, and this solution is fully coupled in the states [5]. The control law for $\tilde{\mathbf{u}}$ (6) that satisfies $\dot{H}<0$ constitutes the Hamiltonian-based control and is decoupled, allowing for a distributed control.

The $\tilde{\mathbf{u}}$ commands are realized by a servo-controller that manages the energy storage units with a closed-loop bandwidth sufficiently high to satisfy the separation principle. In the interests of brevity, the servo-control cannot be discussed at length in this digest, but will be disclosed in the final manuscript.

IV. EXPERIMENTAL RESULTS

The two sources in this experiment are both stochastic sources (i.e. wind turbine) based on the system defined in [7] and the digital resistor is capable of 64 resistance values that may be scripted from the master control console. Figure 3 shows a screenshot from the master control console control software depicting a simple experiment that includes multiple emulator profiles (ie wind speed) and a load profile. Figure 4 shows data about the wind emulator (with maximum power tracking employed by the guidance control), bus voltage and load current. For the final manuscript, greater detail will be given about the Hamiltonian-based control employed in this experiment.

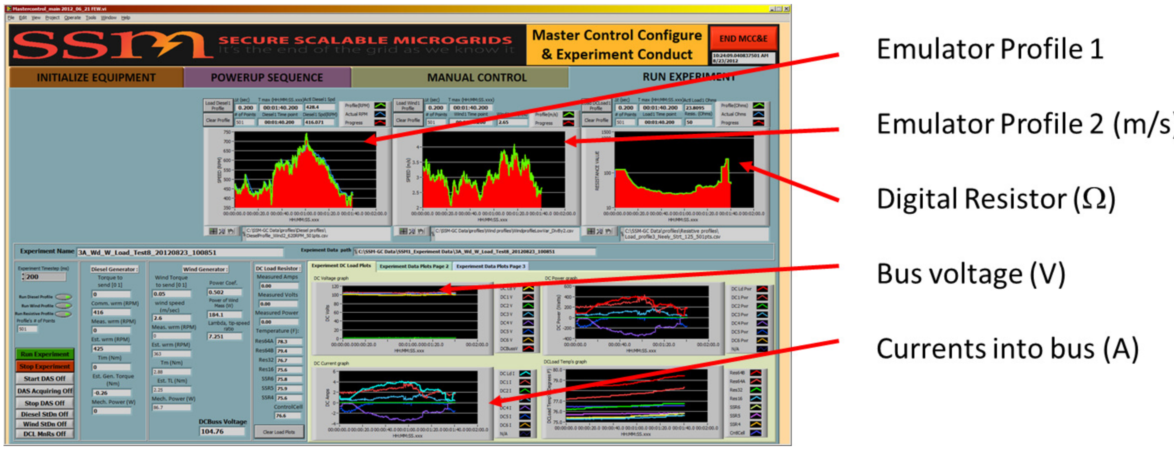

Figure 3: Demonstration of simple experiment from the master control console with Hamiltonian control

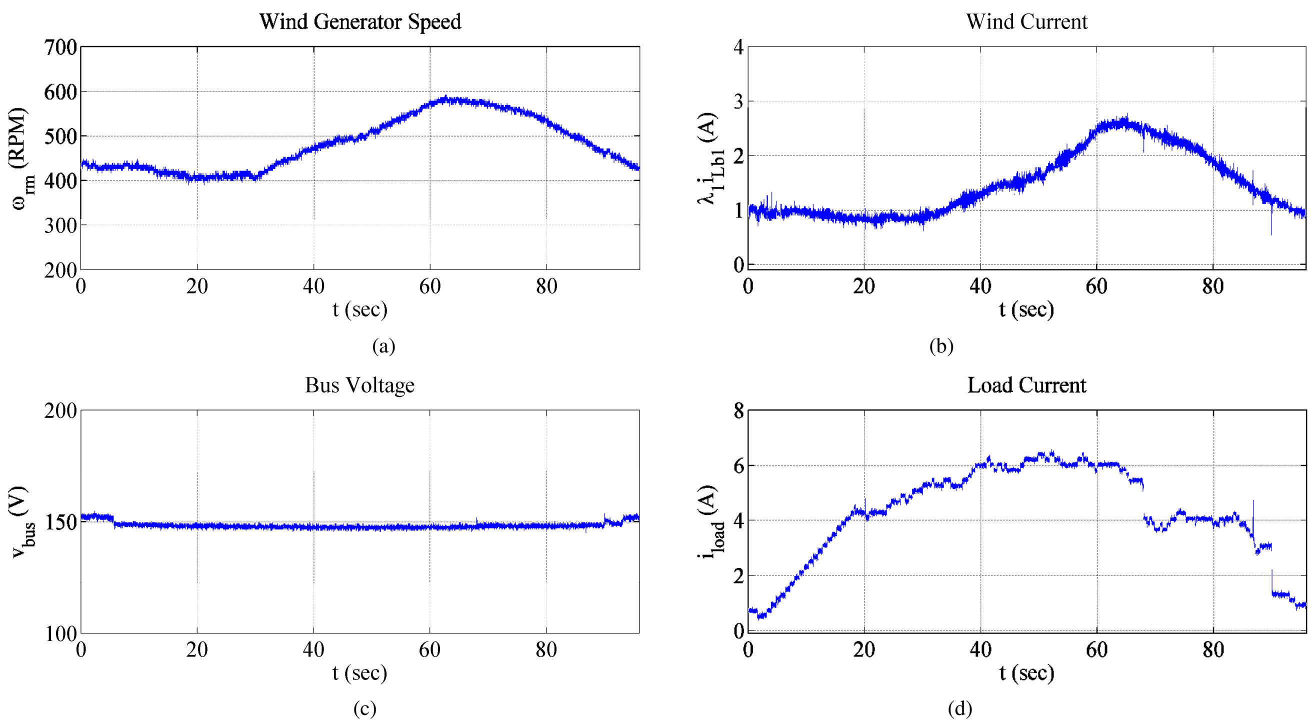

Figure 4: Shows (a) wind generator speed (not turbine speed) and (b) bus current shown for emulator wind profile 1 depicted in Figure 3 as well as (c) bus voltage and (d) load current for same experiment

CONCLUSIONS

In this digest, a method for designing feedback controllers for integration of renewable sources into a DC microgrid is discussed, the system under test is described, and a preliminary demonstration of the intended hardware is provided. In the final paper, a more detailed derivation of the guidance controls, Hamiltonian controls, and servo controls will be provided; both simulation and hardware results will be presented to justify the control approach.

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