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Hamiltonian Control Design for DC Microgrids with Stochastic Sources and Loads with Applications

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***Abstract*— To achieve high performance operation of microgrids that contain stochastic sources and loads is a challenge that will impact 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, based on Hamiltonian Surface Shaping and Power Flow Control (HSSPFC) [1] 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. Two experimental scenarios will be considered; i) simple two stochastic source with variable load renewable DC Microgrid example and ii) a three zone electric ship with DC Microgrid and varying pulse load profiles.**

Keywords—decentralized control; microgrid; nonlinear control; energy storage; stochastic sources

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 three 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 Sequential Quadratic Programing (SQP) or dynamic programming methods [5, 9]. 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 paper the hardware testbed and Microgrid description are presented in section II, guidance control and Hamiltonian-based controls based on HSSPFC are discussed in section III, Section IV includes some experimental results, and Section V provides conclusions.

II. MICROGRID SYSTEM AND REDUCED ORDER 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. 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.

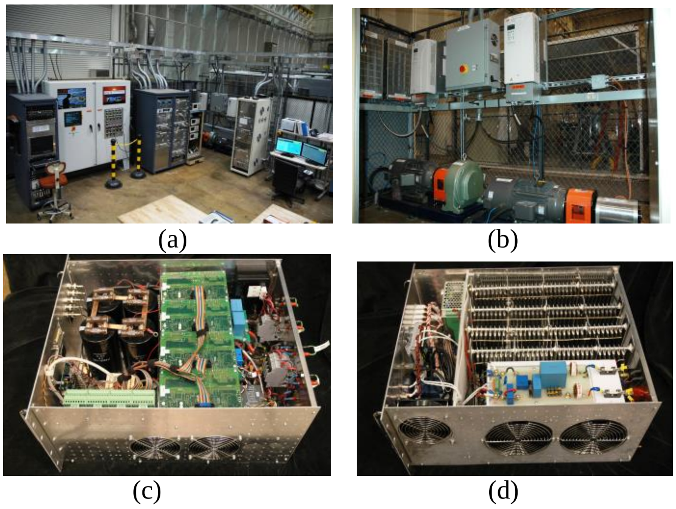

Fig. 1. Photos of (a) the microgrid testbed including (b) mechanical source emulators, (c) energy storage emulator, and (d) high power digital resistor.

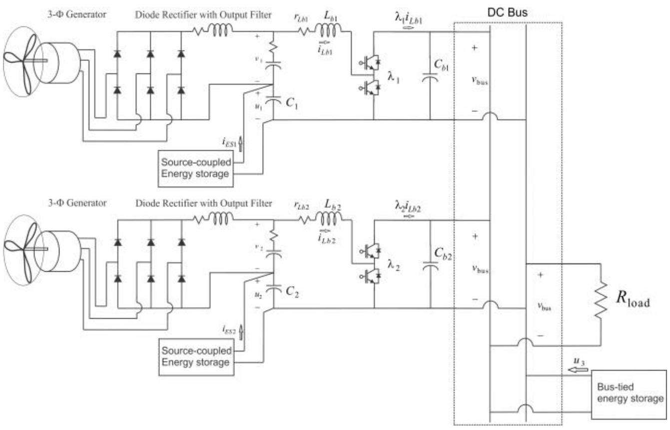

Fig. 2. Schematic of example microgrid.

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

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

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 and(1) can be written in matrix form:

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

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

III. Hamiltonian Surface Shaping and Power Flow Control

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

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

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]:

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

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

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]:

$$\tilde{\mathbf{u}} = -\mathbf{K_p}\tilde{\mathbf{x}} - \mathbf{K_I}\int_0^t \tilde{\mathbf{x}}\,d\tau \quad (6)$$

The resulting time derivative of the Hamiltonian is given by:

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

where $\mathbf{R} = diag\left[-r_{Lb1} \quad -r_{Lb2} \quad -R_{load}^{-1}\right]$. 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 extended abstract, 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 (i.e., 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.

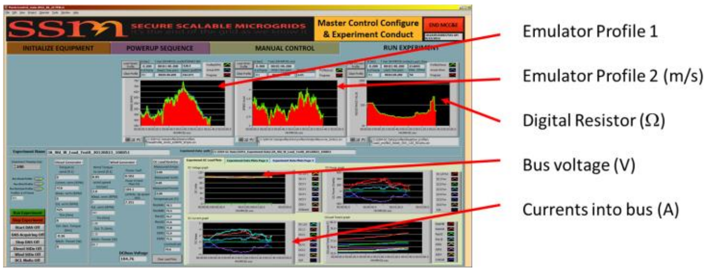

Fig. 3. Demonstration of simple experiment from master control console with HSSPFC control

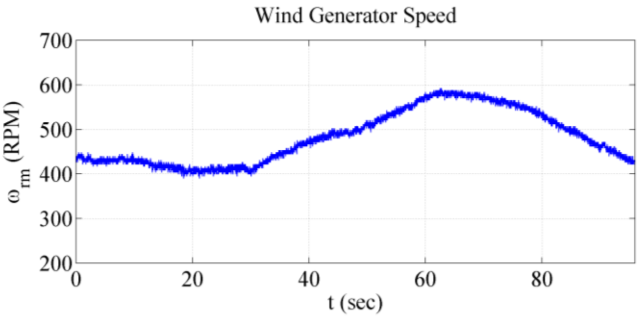

Fig. 4. Wind generator speed experimental results

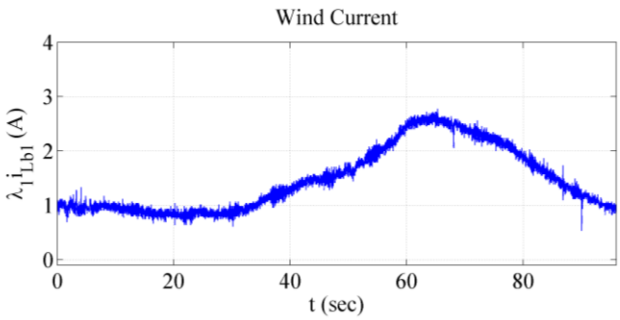

Fig. 5. Bus current shown for emulator wind profile 1 depicted in Fig. 3. experimental results

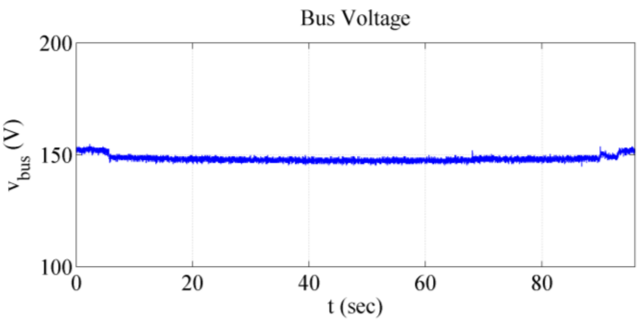

Fig. 6. Regulated bus voltage shown for emulator wind profile 1 depicted in Fig. 3. Experimental results

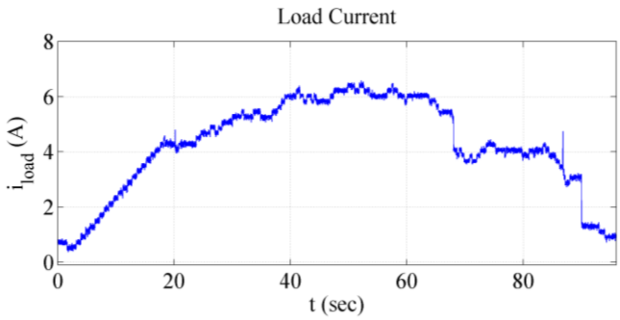

Fig. 7. Load current experimental results

V. CONCLUSIONS

In this extend abstract, a method for designing feedback controllers for integration of stochastic sources into a DC microgrid are 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. This will include both a simple renewable Microgrid systems and a DC Microgrid electric ship scenario.

ACKNOWLEDGEMENT

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