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Transient Stability and Control of Wind Turbine Generation Based on Hamiltonian Surface Shaping and Power Flow Control

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***Abstract*—The swing equations for renewable generators connected to the grid are developed and a simple wind turbine with UPFC is used as an example. The swing equations for renewable generator are formulated as a natural Hamiltonian system with externally applied non-conservative forces. A two-step process referred to as Hamiltonian Surface Shaping and Power Flow Control (HSSPFC) is used to analyze and design feedback controllers for the renewable generators system. This formulation extends previous results on the analytical verification of the Potential Energy Boundary Surface (PEBS) method to nonlinear control analysis and design and justifies the decomposition of the system into conservative and nonconservative systems to enable a two-step, serial analysis and design procedure. This paper presents the analysis and numerical simulation results for a nonlinear control design example that includes the One-Machine Infinite Bus (OMIB) system with a Unified Power Flow Control (UPFC) and applied to a simplified wind turbine generator. The needed power and energy storage/charging responses are also determined.**

I. Introduction

Some of the most challenging problems the United States and other countries are facing is the integration of green renewable resources into existing aging Electric Power Grid (EPG) infrastructures. Many states within the US are faced with fast approaching deadlines due to Renewable Porfolio Standards (RPS) which are forcing the retrofit and patch in of renewables the best that can be done with existing options. Many of the proposed “Smart Grids” are simply overlaying information networks onto existing EPG infrastructures. What is needed is a paradigm shift in our current approach to the grid. At the heart of the EPG is the coordination and control of centralized dispatchable generation to meet customer loads via power engineering techniques. A new approach will be required to formally address the green grid of the future with distributed variable generation, buying and selling of power (bi-directional flow), and decentralization of the EPG.

The goal of this paper is to present a step toward addressing the integration of renewable resources into the EPG by applying a new nonlinear power flow control technique to the analysis of the swing equations for renewable generators connected to the EPG and using simple wind turbine characteristics as an example. The results of this research include the determination of the required performance of a proposed FACTS/Storage device to enable the maximum power output of a wind turbine while meeting the power system constraints on frequency and phase. The FACTS/Storage device is required to operate as both a generator and load (energy storage) on the power system in this design.

As wind turbines and other variable generation systems are influencing the behavior of the electric power grid by, interacting with conventional generation and loads, relevant models and details that can be integrated into power system simulations are needed. New modeling and control design methodologies which may include Unified Power Flow Control (UPFC) based on power electronics are being investigated [1], [2], [3], [4] to help improve transient stability of renewable microgrids and inter-area power systems.

In this paper, the swing equations for the renewable generators are formulated as a natural Hamiltonian system with externally applied non-conservative forces. A two-step process referred to as Hamiltonian Surface Shaping and Power Flow Control is used to analyze and design feedback controllers for the renewable generators system. This formulation extends previous results on the analytical verification of the Potential Energy Boundary Surface method to nonlinear control analysis and design and justifies the decomposition of the system into conservative and non-conservative systems to enable a two-step, serial analysis and design procedure. In particular, this approach extends the work done by [5] by developing a formulation which applies to a larger set of Hamiltonian Systems that has Nearly Hamiltonian Systems as a subset.

The first step is to analyze the system as a conservative natural Hamiltonian system with no externally applied non-conservative forces. The Hamiltonian surface of the swing equations is related to the Equal-Area Criterion and the PEBS method to formulate the nonlinear transient stability problem by recognizing that the path of the system is constrainted to the Hamiltonian surface. This formulation demonstrates the effectiveness of proportional feedback control to expand the stability region. Also, the two-step process directly includes non-conservative power flows in the analysis to determine the path of the system across the Hamiltonian surface to better determine the stability regions.

The second step is to analyze the system as a natural Hamiltonian system with externally applied non-conservative forces. The time derivative of the Hamiltonian produces the work/rate (power flow) equations which is used to ensure balanced power flows from the renewable generators to the loads. The Second Law of Thermodynamics is applied in order to partition the power flow into three types [6], [7], [8], [9]; i) the energy storage rate of change, ii) power generation and iii) power dissipation. This step extends the the work done by Alberto and Bretas [10] by developing a formulation which expands beyond the analysis of small perturbations of conservative Hamiltonian systems. The Melnikov number for this class of systems is directly related to the balance of power flows for the stability (limit cycles) of natural Hamiltonian systems with externally applied non-conservative forces. The Second Law of Thermodynamics is applied to the power flow equations to determine the stability boundaries (limit cycles) of the renewable generators system and enable design of feedback controllers that meet stability requirements while maximizing the power generation and flow to the load. Necessary and sufficient conditions for stability of renewable generators systems are determined based on the concepts of Hamiltonian systems, power flow, exergy (the maximum work that can be extracted from an energy flow) rate, and entropy rate.

As a comparison to several recent developments in nonlinear control; controlled Lagrangian [11], energy-shaping [12], and energy-balancing [12], [13] can be used to construct a feedback controller that meets the sufficient conditions for stability, however these tools do not recognize the importance of the Hamiltonian surface. Basically, any proportional feedback controller that derives from a C^2 function (and some C^1 functions) meets the requirements of static stability and can be used to increase performance by reducing the stability margin and even driving the system unstable for a portion of the path.

This paper is divided into four sections. Section II develops HSSPFC for a OMIB and UPFC system. The OMIB system with a UPFC is an extention to the work done by Ghandhari [14] by developing a formulation which applies to a larger set of nonlinear control systems that has passivity controllers as a subset. Section III performs the numerical simulations and section IV summarizes the results with concluding remarks.

II. HSSPFC Applied to UPFC and Variable Generation

This section investigates power engineering models [14] that best reflect the new nonlinear power flow control methodology. Given

$$T_m - T_e = J\dot{\omega}_{RM} + B\omega_{RM} \tag{1}$$

$$\omega_{RM} = \frac{\omega}{N_p/2} \quad ; \quad \omega = \omega_{ref} + \dot{\delta} \tag{2}$$

and

$$T_m - T_e = \hat{J}\left(\dot{\omega}_{ref} + \ddot{\delta}\right) + \hat{B}\left(\omega_{ref} + \dot{\delta}\right) \tag{3}$$

then define the Hamiltonian as

$$\mathcal{H} = \frac{1}{2}\hat{J}\omega^2 \tag{4}$$

where the power flow or Hamiltonian rate becomes

$$\begin{aligned} \dot{\mathcal{H}} &= \hat{J}\dot{\omega}\omega \\ &= \left[T_m - T_e - \hat{B}(\omega_{ref} + \dot{\delta})\right]\left(\omega_{ref} + \dot{\delta}\right) \\ &= P_m - P_e - \hat{B}\omega^2. \end{aligned} \tag{5}$$

Next, add the approximate power flows from the generator, mechanical controls, and UPFC [14]

$$\begin{aligned} P_m &= P_{mc} + u_m(\omega_{ref} + \dot{\delta}) \\ P_e &= P_{ec}\sin\delta + u_{e1}P_{ec}\sin\delta - u_{e2}P_{ec}\cos\delta. \end{aligned} \tag{6}$$

Starting with the reference power flow equation

$$T_{m_{ref}} - T_{e_{ref}} = \hat{J}\dot{\omega}_{ref} + \hat{B}\omega_{ref} \tag{7}$$

with ω_{ref} = *constant* and $\omega_{ref} >> \dot{\delta}$ and solving for the acceleration term gives

$$\hat{J}\ddot{\delta} = -\hat{B}\dot{\delta} + P_{m_e} + u_m\omega_{ref} - P_{e_c}\left[(1 + u_{e_1})\sin\delta - u_{e_2}\cos\delta\right].$$

Next define the Hamiltonian as

$$\mathcal{H} = \frac{1}{2}\hat{J}\dot{\delta}^2$$

then the derivative of the Hamiltonian becomes

$$\begin{aligned} \dot{\mathcal{H}} &= \hat{J}\ddot{\delta}\dot{\delta} \\ &= \left[-\hat{B}\dot{\delta} + P_{m_c} + u_m\omega_{ref} - \right. \\ &\quad \left. P_{e_c}\left((1 + u_{e_1})\sin\delta - u_{e_2}\cos\delta\right)\right]\dot{\delta}. \end{aligned}$$

Now assume that OMIB is combined with UPFC and $u_m = 0$ then

$$\hat{J}\ddot{\delta} + P_{e_c}\sin\delta - P_{m_c} = -\hat{B}\dot{\delta} - P_{e_c}\left[u_{e_1}\sin\delta - u_{e_2}\cos\delta\right]. \tag{8}$$

Next select the following nonlinear PID control laws from HSSPFC

$$\begin{aligned} u_{e_1} &= K_{P_e}\cos\delta_s + K_{D_e}\sin\delta\dot{\delta} + K_{I_e}\sin\delta\int_0^t \Delta d\tau \\ u_{e_2} &= K_{P_e}\sin\delta_s - K_{D_e}\cos\delta\dot{\delta} - K_{I_e}\cos\delta\int_0^t \Delta d\tau. \end{aligned} \tag{9}$$

where $\Delta = \delta - \delta_s$. Finally, substitute Eq. (9) into Eq. (8) yields the following

$$\begin{aligned} &\hat{J}\ddot{\delta} + \left[P_{e_c}\sin\delta - P_{m_c}\right] + P_{e_c}K_{P_e}\sin(\delta - \delta_s) \\ &= -\left[\hat{B} + P_{e_c}K_{D_e}\right]\dot{\delta} - K_{I_e}\int_0^t (\delta - \delta_s)\, d\tau. \end{aligned}$$

The static stability condition becomes

$$\mathcal{H} = \frac{1}{2}\hat{J}\dot{\delta}^2 + P_{e_c}\left(1 + K_{P_e}\right)\left(1 - \cos(\delta - \delta_s)\right) \tag{10}$$

with $\mathcal{H}$ being positive definite and

$$\delta_s = \sin^{-1}\left(P_{m_c}/P_{e_c}\right).$$

The dynamic stability condition for a passively stable control design yields

$$\oint_\tau \left[\hat{B} + P_{e_c}K_{D_e}\right]\dot{\delta}^2 dt > -\oint_\tau \left[P_{e_c}K_{I_e}\int_0^t (\delta - \delta_s) d\tau\right]\dot{\delta} dt. \tag{11}$$

Clearly, the UPFC nonlinear PID controller expands the region of stability by increasing the PEBS from P_{e_c} to $P_{e_c}(1 + K_{P_e})$

and enabling the system to respond more quickly by adding an integrator to the dissipator of reference [14].

A feedforward control term can be added to the UPFC controllers, Eq. (9), for u_{e_1} and u_{e_2} by

$$\begin{aligned} u_{e_1} &= u_{e_1} - [(P_{m_{ref}} - P_m(t))/P_{max}] \sin\delta \\ u_{e_2} &= u_{e_2} + [(P_{m_{ref}} - P_m(t))/P_{max}] \cos\delta \end{aligned} \quad (12)$$

where $P_{m_{ref}}$ is designed to emulate a constant input and $P_m(t)$ can become variable such as from wind or solar generation. In the next section these effects are explored further with simple wind turbine characteristics through a $P_m(t)$ variation.

III. Numerical Simulations

A numerical example (based on an example in [14] all parameters are given in the Appendix) for a OMIB with a UPFC controller is used to demonstrate the controllers defined in earlier sections. In addition, simple wind turbine generator characteristics are investigated by allowing the P_m term to become time-varying in the swing equations. The OMIB system is shown schematically in Fig. 1.

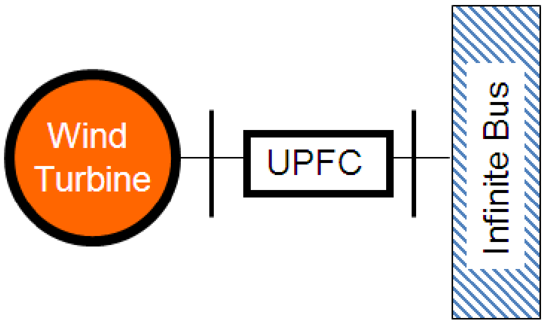

Fig. 1. One machine infinite bus model with UPFC and wind turbine generator

Initially, the OMIB is given a faulted initial condition that is away from the stable equilibrium point. This results in an unstable response, where the Hamiltonian (stored energy) surface (δ, ω) and corresponding Hamiltonian rate (power flow) trajectory (blue dashed trace along the surface) are shown in Fig. 2. The first step in the HSSPFC process is to add the UPFC controller and increase the stable boundary region with the addition of K_{P_e}. This is defined and labeled as δ_1 responses. The next step is to define the dynamic stability and transient performance by adding K_{D_e} and K_{I_e}, defined and labeled as δ_2 responses. The stable response is shown for δ_2 in Fig. 3. The phase plane and transient responses for both δ_1 and δ_2 are given in Figs. 4 and 5, respectively. The corresponding power flow and energy responses for each of the UPFC systems are shown in Fig. 6.

As an initial investigation for simple wind turbine generator characteristics a random input response for $P_m(t)$ was created and a second-order filter (with a roll-off frequency of 2 Hz) was used in series to provide the effect for the wind turbine. In the plots δ_3 represents the feedback UPFC controller design and δ_4 represents the addition of the feedforward control. The

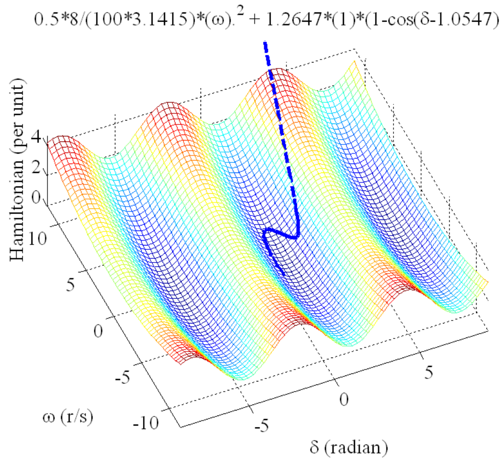

Fig. 2. OMIB Hamiltonian energy storage surface and power flow path where initially without any UPFC the machine goes unstable

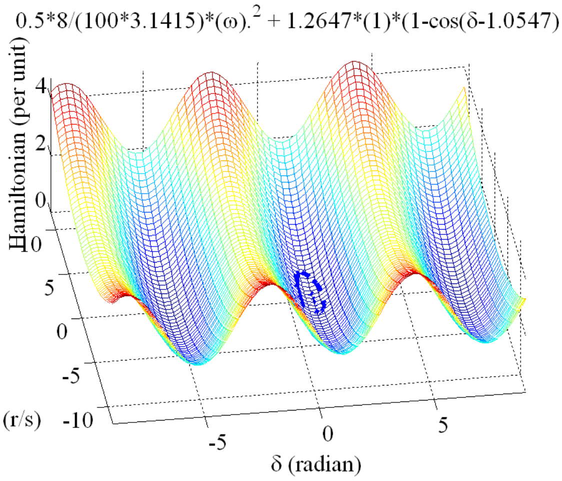

Fig. 3. OMIB Hamiltonian energy storage surface and power flow path where with the addition of UPFC the machine maintains stability and performance

corresponding phase plane and transient responses are given in Figs. 7 and 8, respectively. The corresponding power flow and energy responses for each of the UPFC systems are given in Fig. 9. The addition of the feedfoward control is to help $P_m(t)$ respond as a constant (see Fig. 10).

IV. Summary and Conclusions

The swing equations for renewable generators connected to the grid were developed and simple wind turbine characteristics were used as an example. The swing equations for the renewable generators were formulated as a natural Hamiltonian system with externally applied non-conservative forces. A two-step process referred to as Hamiltonian Surface Shaping and Power Flow Control was used to analyze and design feedback controllers for the renewable generators system. This formulation extended previous results on the analytical verification of the PEBS method to nonlinear control analysis and design and

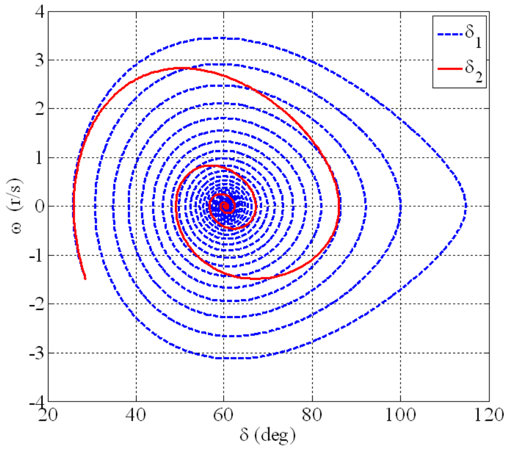

Fig. 4. Phase plane for OMIB with UPFC δ_1 response is increasing the static stability margin with K_{P_e} and δ_2 response is for adding the dynamic stability and performance with K_{D_e} andK_{I_e} controller terms

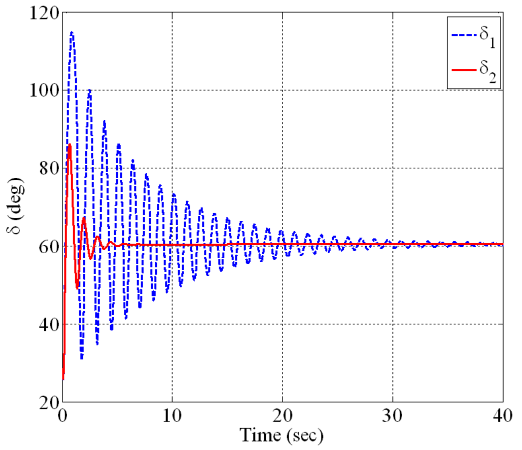

Fig. 5. Transient machine angle responses for OMIB with UPFC δ_1 response is increasing the static stability margin with K_{P_e} and δ_2 response is for adding the dynamic stability and performance with K_{D_e} andK_{I_e} controller terms

justifies the decomposition of the system into conservative and non-conservative systems to enable a two-step, serial analysis and design procedure. Necessary and sufficient conditions for stability of renewable generators systems were determined based on the concepts of; Hamiltonian systems, power flow, exergy (the maximum work that can be extracted from an energy flow) rate, and entropy rate.

A nonlinear control design example was used to demonstrate the HSSPFC technique for the OMIB system with a UPFC and simple wind turbine system characteristics were explored to determine the needed performance of the UPFC to enable the maximum power output of a wind turbine while meeting the power system constraints on frequency and phase. The non-linear PID feedback controller design along with feedfoward control for the OMIB system with a UPFC was shown to

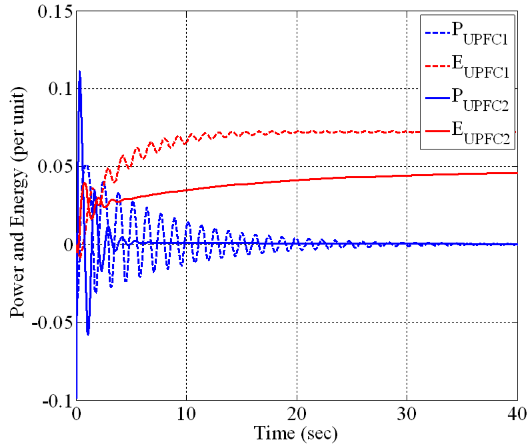

Fig. 6. Transient power flow and energy responses for OMIB with UPFC δ_1 responses and δ_2 responses, respectively

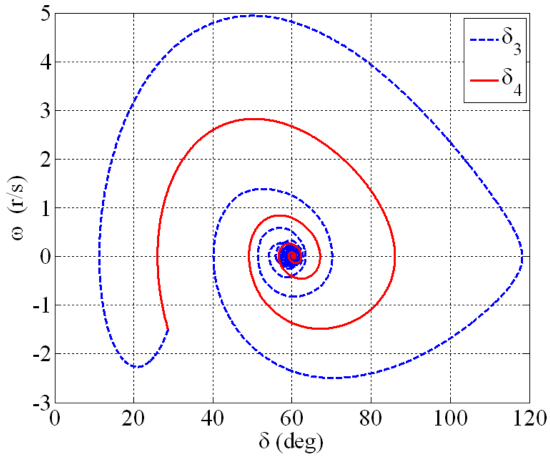

Fig. 7. Phase plane for OMIB with UPFC δ_3 response is with UPFC PID control only and δ_4 response is for adding feedforward control in addition to feedback control

be an extension of the Control Lyapunov Function approach. Numerical simulations for four separate conditions of the renewable microgrid design were reviewed. In the near future, HSSPFC will be applied to multiple machines including gas turbine generators combined with wind turbines and FACTS devices.

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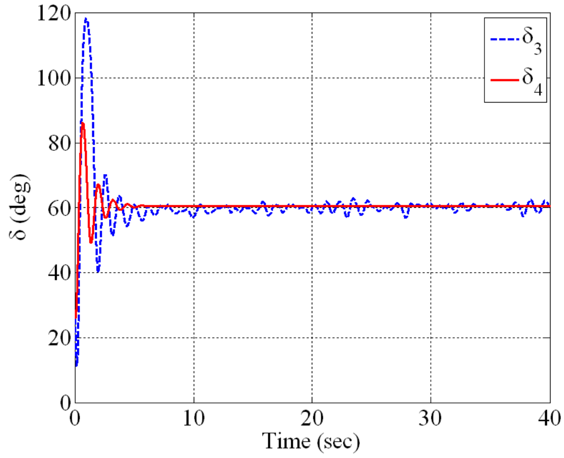

Fig. 8. Transient machine angle responses for OMIB with UPFC PID control only δ_3 response and δ_4 response is for adding feedforward control in addition to feedback control

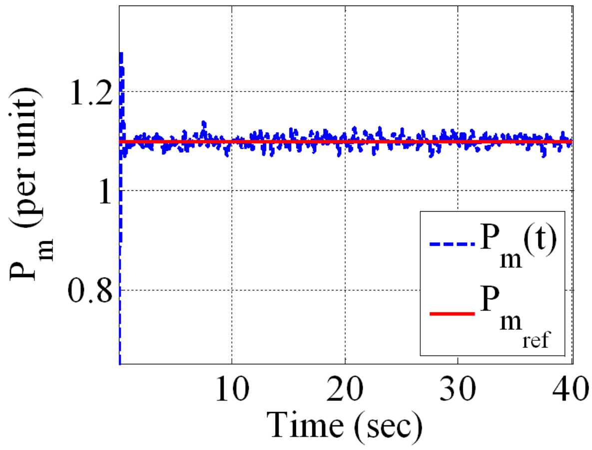

Fig. 10. Constant P_m reference signal compared to stochastic or random P_m response

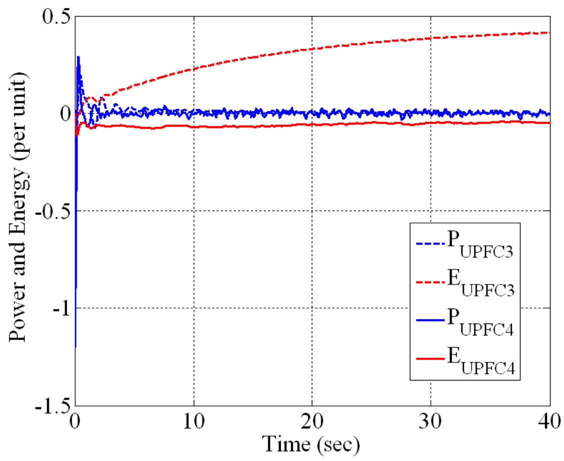

Fig. 9. Transient power flow and energy responses for OMIB with UPFC δ_3 responses and δ_4 responses, respectively

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APPENDIX

The numerical values for existing OMIB system example from [14] are:

$$
\begin{aligned}
\hat{J}' &= \tfrac{2H}{\omega_o} = \tfrac{8}{100\pi} \\
\hat{B}' &= \tfrac{2}{\omega_o} \\
P_m &= 1.1(p.u) \\
P_{max} &= bE'V \\
b &= \tfrac{1}{x_L} = \tfrac{1}{0.85} \\
E' &= 1.075(p.u) \\
V &= 1.0(p.u)
\end{aligned}
$$

where $\hat{J}'$ and $\hat{B}'$ are scaled by $\omega_o = 50Hz \cdot (2\pi)$ rad/sec.