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A Novel Approach to Trace Time-Domain Trajectories of Power Systems in Multiple Time Scales Based Flatness

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Abstract

This paper works on the concept of flatness and its practical application for the design of an optimal transient controller in a synchronous machine. The feedback linearization scheme of interest requires the generation of a flat output from which the feedback control law can easily be designed. Thus the computation of the flat output for reduced order model of the synchronous machine with simplified turbine dynamics is hereby presented. The corresponding linearized compensator is derived as well as the nonlinear controller for transient stabilization of a synchronous machine subjected to large disturbances. The transient behavior of a single machine equipped with the so designed nonlinear controllers feeding an infinite bus is illustrated via simulation in Matlab environment. The results obtained for transient disturbances on the single machine infinite bus system (SMIBS) are presented and compared with other control algorithms to demonstrate the effectiveness of the proposed scheme.

Keywords: Feedback Linearization, Flatness, FLA output, Transient Stability.

1. Introduction

Control objectives on the synchronous machine and its ancillary devices and on the other hand making them practically implementable, in view of limitations in observable outputs, has been a motivating factor for research effort towards more efficient control strategies. Anderson and Fouad, [1] identified three principal controls that directly affect asynchronous generator, the boiler control as well as turbine/governor and exciter controls. However, turbine speed governing, and excitation controls, both play very important roles in dynamic stability studies. The governor controls the torque or the shaft power input by a speed controller, which adjusts the steam turbine valve, and the excitation system controls the field voltage. Modern large power generating units in a complex system cannot rapidly respond increasing demand and complex system interactions. Consequently, the problem of ensuring at all times balance between mechanical and electrical powers on the shaft of a unit turbine-generator is one of the most important challenges for power system control engineers [2]. Presently much work has been done in the use of various control strategies for the stability studies of the synchronous machine. Notable among them include feedback linearization schemes, optimal control, neural networks etc. Many authors [2], [3-8] have applied input-state and input-output feedback linearization schemes for SISO and MIMO systems to the synchronous machine model with good results. Flatness-Based feedback linearization also has received a lot of attention resulting in the earlier work reported by many researchers [9-16]. Although this technique has been applied to several nonlinear and linear mechanical systems [10-14], its application to synchronous machines is yet to gain ground. The input–output scheme requires the arbitrary choice of an output whose relationship with the input determined through differentiation leading to the problem of stability of the associated internal dynamics. But the flatness-based approach uses the characterization of system to generate suitable output.

In a situation where the output does not have a physical meaning or interpretation, the linearization could be done through measurable system component that has a relationship to it. This concept is herein applied to a single machine model to facilitate the design of its feedback controller. For the purpose of illustrating the proposed control algorithm, single machine infinite bus system is simulated in the Matlab environment. The simulation results or large transient disturbances at the terminal of the synchronous machine of the sample power system are presented and compared with the conventional control techniques.

2. Dynamics and Flat Output for the System Under Study

The simplified model of the governor steam turbine considered in this work follows from [17] and Figure1 shows the machine configuration connected to the infinite bus. The state equations of asynchronous machine including its turbine dynamics only are given by (1-11) Note that static excitation system is assumed and its dynamics neglected due to small time constants compared with the transient time frame. It is shown in the Appendix that this reduced order synchronous machine model with turbine dynamics possesses a flat output which is a function of load angle which can be computed via a network load flow, and mechanical power which can be measured. The practical significance of the flat output of a dynamical system, which is shown in the next section, is that if the components of the flat output are measurable, then all the system variables required for feedback can be directly computed without integrating any differential equations.

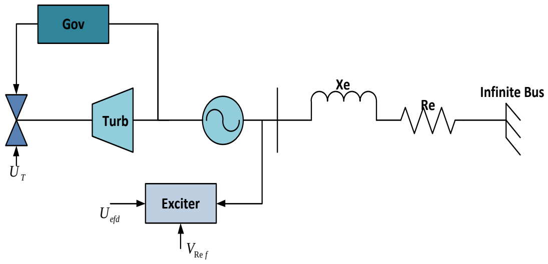

Fig. 1. Synchronous Machine connected to the infinite bus.

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt} = p_m - D(\omega-\omega_s) - i_d e'_d - i_q e'_q \qquad (1)$$

$$\frac{d\delta}{dt} = \omega - \omega_s \qquad (2)$$

$$T'_{d0}\,\dot{e}'_q = E_{FD} - e'_q - (x_d - x'_d)i_d \qquad (3)$$

$$\dot{p}_{gv} = \frac{1}{\tau_g}(u_T - p_{gv} - (\omega-\omega_0)/R_T \qquad (4)$$

$$\dot{p}_m = \frac{1}{\tau_t}(p_{gv} - p_m) \qquad (5)$$

$$i_d = (\frac{1}{k_z})(-(R_e + r_a)(E'_d - V_B\sin\delta) + (x'_q + X_e)(E'_q - V_B\cos\delta) \qquad (6)$$

$$i_q = (\frac{1}{k_z})(-(X_e + x'_d)(E'_d - V_B\sin\delta) + (R_e + r_a)(E'_q - V_B\cos\delta) \qquad (7)$$

$$k_z = \frac{1}{(R_e + r_a)^2} + (X_e + x'_d)(\mathrm{x}_q + X_e) \qquad (8)$$

$$V_d = (R_e i_d + V_B\sin\delta - X_e i_q) \qquad (9)$$

$$V_q = (R_e i_q + X_e i_d + V_B\cos\delta) \qquad (10)$$

$$V_t = \sqrt{(V_d{}^2 + V_q{}^2)} \qquad (11)$$

3. Design of Flatness Based Controller

In this section, we present the one-loop flatness-based controller. The FBC strategy has been chosen because of its usefulness in situations where explicit trajectory generation is required [19], [20]. In fact, the behavior of the system state variables can be planned owing to given reference trajectories. The control structure consists of an electrostatic energy loop which allow flat three-phase voltage network with the desired magnitude and frequency and those with a low harmonic distortion rate. The concept of flat systems was introduced by Fliess et al [19] using the formalism of differential algebra. In differentia algebra, a system is considered to be differentially flat if a set of variables (flat output components) can be found such that all state variable and input components can be determined from these output components without any integration [19]. The state and input variables can be directly expressed, without integrating any differential equation, in terms of the flat output and a finite number of its derivatives. Moreover, in our particular application, the number of sensors is reduced. The implementation of the control law does not use inductive current measurements. Only load current sensors are used for generating the control law another interesting point to underline is that the use of reference trajectories of the flat outputs allows ensuring safe operation during the start-up (see experimental part). The fact that the flat controllers use the reference reactions instead of disturbance reactions reduces the noise impact. Indeed, the derivative terms in control laws are less affected by noise. For the control of differentially flat systems, one concentrates on generating feasible trajectories rather than trying to force the system trajectory to converge toward given operating point. With the flat approach, transient state scan be analytically foreseen which is not the case with classical approaches Contrary to classical approaches where the dq output volt-ages are controlled, we propose to control the dq electrostatic stored in the output capacitances. In fact, this choice should lead to a better dynamical behavior as regards load perturbations when the three-phase inverter supplies constant power load systems. Thus we propose to assume that the electrostatic energy is the candidate flat output the unstable dynamic zeroes which cannot be guaranteed for other types of dynamical systems. Equations (12-17) explaining Flatness Technique quite.

$$\begin{cases} \dot{x}(t) = f\left(x(t), u(t)\right) \\ y(t) = h\left(x(t), u(t)\right) \end{cases} \tag{12}$$

$$u = \left[u_1, u_2, \ldots, u_{\mathrm{m}}\right]^T \tag{13}$$

$$x = \left[x_1, x_2, \ldots, x_{\mathrm{n}}\right]^T \quad , n \geq m \tag{14}$$

$$y = \phi\left[x, u, \dot{u}, \ldots, u^{(\alpha)}\right] \quad , \quad rank\left\{\phi\right\} = m \tag{15}$$

$$x = \varphi\left[y, \dot{y}, \ldots, y^{(\beta)}\right] \quad , \quad rank\left\{\varphi\right\} = n \tag{16}$$

$$u = \psi\left[y, \dot{y}, \ldots, y^{(\beta+1)}\right] \quad , \quad rank\left\{\psi\right\} = m \tag{17}$$

The unique feature of allowing a parameterization of all system variables makes of flatness a tool for analysis revealing the nature of each system variable in its isolated relation with a centrally important set of variables from view point of controllability and observability. The invertible parameterization, involved in the flat outputs definition, thus creates a local bijection between system state solutions and arbitrary trajectories in the flat output space. There is no uniqueness of the flat output even if there is usually a favorite flat output expressing physical properties. The concept of fatness scan be seen as a nonlinear generalization of the Kalman's controllability and of the Brunovsky decomposition. Hence every linear controllable system is flat. More recently, flatness has been defined in a more geometric context, where tools for nonlinear control are more commonly available. There are two different geometric frameworks for studying flatness and provide constructive methods for deciding the flatness of certain classes of nonlinear systems and for finding these flat outputs if they exist. One approach is to use exterior differential systems and regard a nonlinear control system as an affine system on an appropriate space [10]. In this context, flatness can be described in terms of the notion of absolute equivalence defined by Cartan [11]. Another geometric approach to study flatness is by using "JetBundles" . In this paper a somewhat different geometric point of view is adopted, relying on a Lie-Backlund framework as the underlying mathematical structure. It offers a compact framework in which to describe basic results and is also closely related to the basic techniques that are used to compute the functions that are required to characterize the solutions of flat systems (the so-called flat outputs). In jet bundle approach a mapping from an infinite dimensional manifold whose coordinates are not only made up of original variables but also of jets of infinite order is dealt. Figure 2 show special concept of flatness.

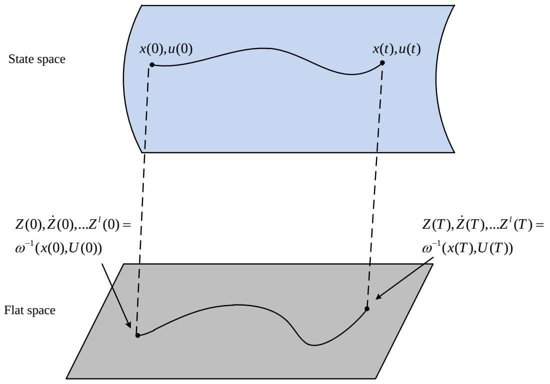

Fig. 2. Special concept of flatness

4. Interest of the Flatness-Based Approach

Some properties of the flat systems are suitable for their control. From [21], we can list the main advantages for power applications. The fact that the flat controllers use the reference reactions instead of disturbance reactions reduces the noise impact. Indeed, the derivative terms in control laws are less affected by noise. For the control of differentially flat systems, one concentrates on generating feasible trajectories rather than trying to force the system trajectory to converge toward a given operating point. With the flat approach, transient states can be analytically foreseen which is not the case with classical approaches for flat systems, the application of the I/O exact feedback linearization technique does not lead to the occurrence of the unstable dynamic zeroes which cannot be guaranteed for other types of dynamical systems. Another interesting point to underline is that the use of reference trajectories of the flat outputs allows ensuring a safe operation during the start-up Moreover, in our particular application, the number of sensors is reduced. The implementation of the control law does not use inductive current measurements. Only load current sensors are used for generating the control law. Figure5 show block diagram control based flatness.

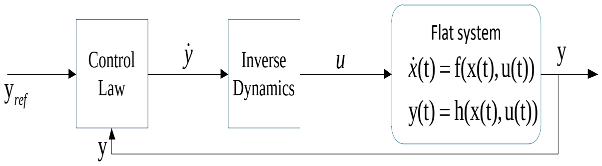

Fig. 3. Block diagram control based flatness

5. System Simulation

Figure 4 summarizes the simulation block diagram implemented in the Matlab version 6.5. In all simulations, the constraints on equations that is, the admissible values of the field voltage and steam valve position are included. It is assumed the generator terminals were connected to the infinite bus via a transformer and a tie line consisting of a resistance Re and inductance Xe.

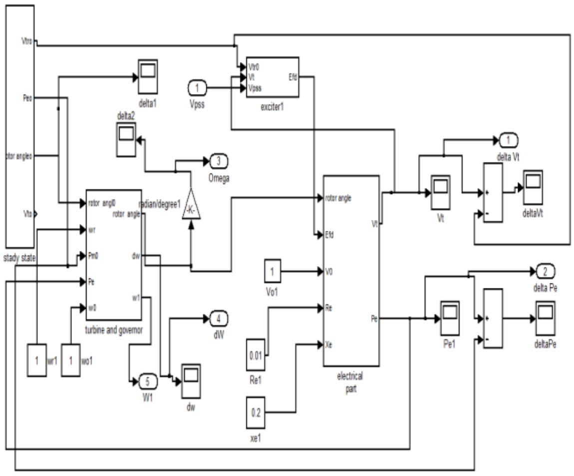

Fig. 4. The Complete Model of The Nonlinear Power System SMIB

Three-phase short circuit fault was simulated for the study in three time periods:

- The steady state operation from 0.0 to 1.0 seconds.
- Three phase fault at transformer terminals from 1.0 sec to 1.06 seconds.
- Post fault stabilization from 1.06 to 6seconds.

It is also assumed that the parameters Xe & Re and others used to compute the controllers remained constant during the fault transient period. Data used to initialize the system is given in the appendix.

The simulation results for the feedback linearized synchronous machine equipped with turbine dynamics (or multivariable dynamics feedback controller (MDFC)) under a bolted three-phase fault for a period of three cycles are presented in Figs. 5 to 8. Comparisons are offered between the proposed technique and conventional fast-valving (FV) / forced excitation (FE) control as well as conventional Automatic Voltage Regulator (AVR) and speed regulation.

Cases reported by [22] using model predictive controller scheme, shows longer damping time of about 4 seconds. Figure 7 compares the system with MDFC and the system with FV/FE and AVR/Speed Reg. It shows that the controller not only assures stabilization of system variables but also stabilizes system output voltage. It restores all the variables as well as the voltage to pre fault equilibrium voltage under fault and post fault trajectory stabilization is shown in figure 8 for 3-cycle fault duration. It is noteworthy in the study that voltage ceiling or used limits, influences the dynamics of the control effort. Operating the system at high limits speeds up the system post fault stabilization but that will result in physically high dynamical stresses in the exciter and this requires a compromise solution. The field voltage control highly dominates the response trajectories of the synchronous machine during faults but the effect of turbine control is to help damp those minor oscillations that are capable of building up in the event of major disturbances. Figure 9 shows the MDFC Load Angle with and without turbine valve controller for fault duration of 9 cycles. Detailed inspection shows the trajectory without turbine control as a having sustained swings. Figure (9) , (10) shows application this technique for Machine load angle response to 11- cycle fault.

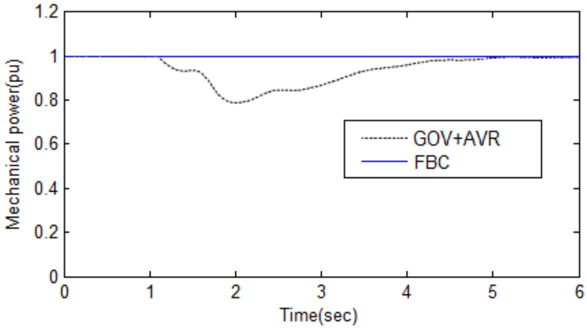

Fig. 5. Machine mechanical power response to 3-cycle fault for FBC and FV/FE and AVR/Speed Reg.

Fig. 6. Conclusions

The corresponding diffeomorphism led to the compensator. A nonlinear controller was subsequently designed and Simulation studies carried out showed that the nonlinear controller achieved asymptotic stabilization of the sample power system when subjected to fault conditions. The multivariable scheme based on combined stabilizing actions of excitation and fast turbine control returned better transient performance than the single variable excitation scheme usually considered in the existing literature.

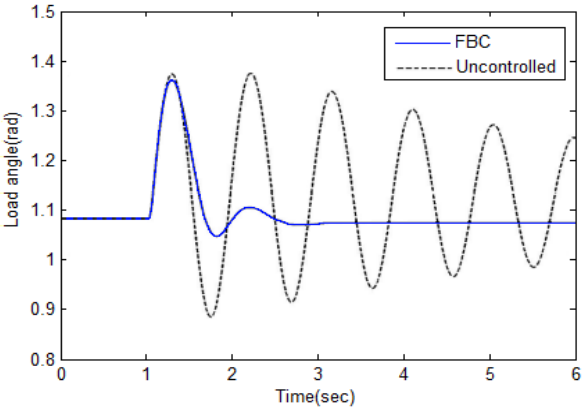

Fig. 7. FBC Machine load angle response to 3- cycle fault

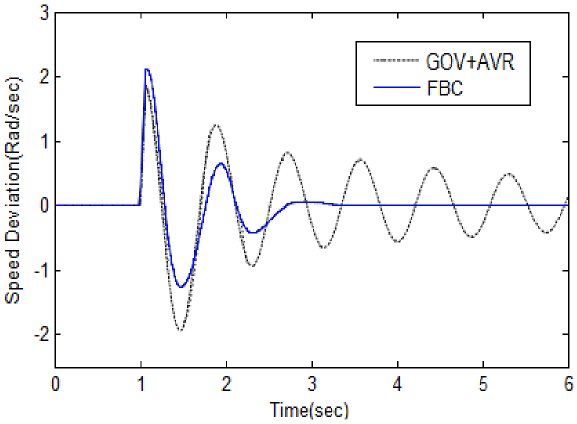

Fig. 8. Machine speed deviation response to 3-cycle fault for FBC and AVR/Speed Reg.

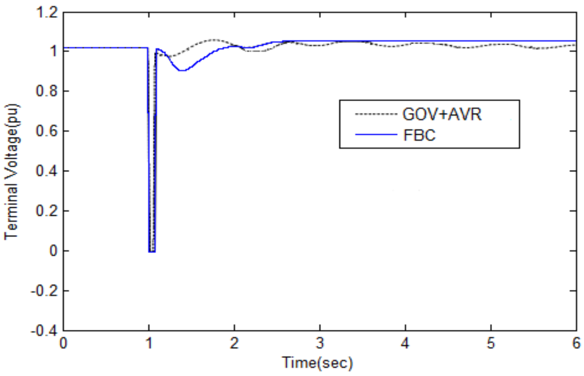

Fig. 9. Machine Terminal Voltage response to 3-cycle fault for FBC and AVR/Speed Reg.

It was also found to be robust to fault durations and parameter variations. The ultimate goal being pursued is to extend the control design approach to multi-machine system based on decentralized control actions for system-wide transient stabilization.

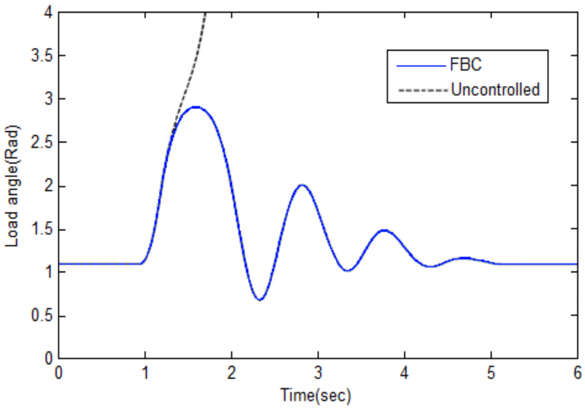

Fig. 10. FBC Machine load angle response to 11- cycle fault.

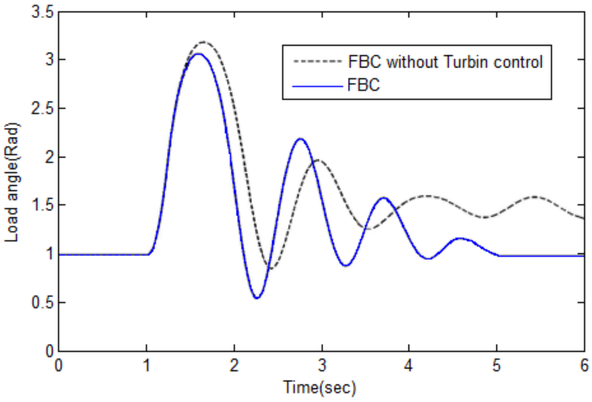

Fig. 11. FBC Machine load angle response to 11- cycle fault.

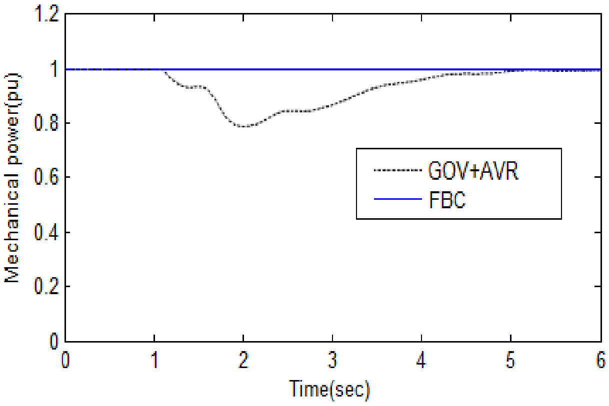

Fig. 12. Time domain response generator mechanical power

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