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Ganesh K. Venayagamoorthy
Missouri University of Science and Technology

E. C. Anene

U. O. Aliyu

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[1]E.C. Anene, [2]G. K. Venayagamoorthy, *Senior Member, IEEE*, and [1]U.O. Aliyu, *Member, IEEE*
[1]Electrical Engineering Programme, Abubakar Tafawa Balewa University, PMB 0248, Bauchi, Nigeria
[2]Real-Time Power and Intelligent Systems Laboratory
Missouri University of Science and Technology, Rolla, MO, USA

Abstract- **An optimal transient controller for a synchronous generator in a multi-machine power system is designed using the concept of flatness-based feedback linearization in this paper. The computation of the flat output and corresponding controller for reduced order model of the synchronous generator is presented. The required feedback gains used to close the linearization loop is optimized using particle swarm optimization for maximum damping. Typical results obtained for transient disturbances on a two-area, four-generator power system equipped with the proposed controller on one generator and conventional power system stabilizers on the remaining generators are presented. The effectiveness of the flatness-based controller for multi-machine power systems is discussed.**

***Keywords* - Flatness, feedback linearization, multi-machine systems, particle swarm optimization, transient stability.**

I. INTRODUCTION

STABILITY has been described generally as a system and an economic problem in the sense that the need to install larger and larger generating units to meet economic needs of growth, bring about higher system reactance and lower inertias [1]. To keep the system stability within a reasonable limit, it is necessary to keep the overall reactance within bound. Control actions, for example, of excitation systems and turbine valves, and by reductions in circuit breaker opening and reclosing times can be used to increase this limiting permissible reactance. Much work has been done in the use of such control strategies for stability studies of synchronous generators employed in multi-machine systems.

Notable among them include feedback linearization schemes, optimal control, neural networks etc. Many authors [2]-[4] have applied input-state feedback linearization schemes for SISO and MIMO systems to the synchronous machine model with good results. Research on flatness-based feedback linearization has generated considerable literature [5]-[7]. Work on the theoretical basis for the scheme is ongoing. Reference [7], reports the application of flatness based controller to a reduced order model of the synchronous generator.

In a conventional multi-machine system, controller design to stabilize the generator rotor angle to the reference and other generators requires the knowledge of the state vector of all the generators. This is difficult to achieve, more so as it complicates the necessary computations required for generating the control law. The authors in [6] applied a decentralized decoupled feedback strategy in a multi-machine study, where a nonlinear transformation is used to map the state space vector into an observation decoupled state space. The decoupled system states are computed based on local measurements of the system variables. Since feedback linearization requires, the full knowledge of the system variables for feedback, it will not be practically feasible to compute in real time a changing rotor angle knowing that a full-scale load flow will be done for each cycle. Therefore assumptions are made to calculate rotor angles using only local information and with respect to any convenient reference.

The associated feedback gains in feedback linearization schemes are usually computed via pole placement [8]. Since the synchronous generator dynamics and the associated power system interconnections are inherently nonlinear, the need to operate the system in an optimal operating point is necessary. This brings about the need to establish a set of gains that will permit the system to operate at an optimal operating point from the region of system operating points.

Particle swarm optimization (PSO) is a population based algorithm modeled after the behavior of a flock of birds or a school of fish [9]. Very similar to evolutionary algorithms, the PSO begins its search with random candidate solutions. It has matured over the years as a heuristic optimization tool that uses the system information or response to evaluate its solution accuracy, the so-called fitness. PSO algorithm has been used to obtain the optimal proportional, integral and derivative (PID) gains and power system stabilizer (PSS) parameters in studies of synchronous generator control techniques [10].

The feedback gains generated by the PSO are used to evaluate the performance of the flatness-based controller when placed on one out of the four generators in the two area power system [11] model studied, while the remaining generators are equipped with conventional power system stabilizers. Typical simulation results for the above mentioned power system controller setup experiencing large transient disturbances (three phase faults) are presented and compared with results of

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the system having all the generators equipped with the conventional PSSs.

Section II describes the multi-machine power system used in this paper. Flat output definitions and feedback law constructed via the flat output is given in Section III. Section IV describes the implementation of the optimal flatness based controller; while in Section V, typical simulation results are presented. Conclusion is made in Section VI followed by an Appendix which summarizing the derivations of the flat output.

II. Multi-machine Power System

Fig. 1 shows the two-area four generator power system used in this study. Each area is equipped with two identical round rotor generators rated 20kV/900 MVA. The synchronous generators G1-G4 have identical parameters, except for inertias which are H = 6.5s in Area 1 and H = 6.175s in Area 2. Thermal plants having identical speed regulators are added at all locations, in addition to fast static exciters with a gain of 200. The load is represented as constant impedances and split between the areas in such a way that Area 1 is exporting 413MW to Area 2. The reference load-flow with G2 considered the slack generator is such that all generators are producing about 700 MW each. The power system model given in [11] is used.

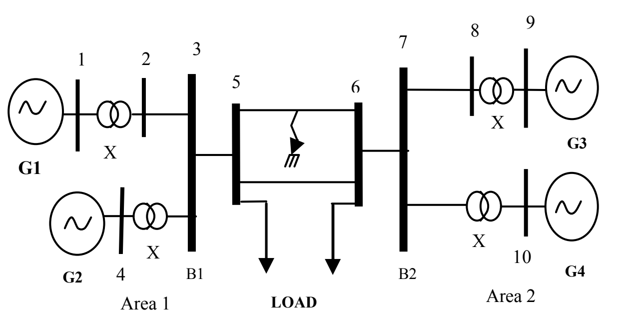

Figure 1. Two-area four generator power system

The one-axis system equations for the i^{th} generator are given by:

$$\tau_{d0}\dot{e}'_{qi} = e_{fdi} - e'_{qi} - (x_{di} - x'_{di})i_{di} \quad (1)$$

$$\frac{2H_i}{w_{Ri}}\frac{d^2\delta_i}{dt^2} = P_{mi} - D_i(\omega_i - \omega_0) - e'_{di}(i_d)_i - e'_{qi}(i_q)_i \quad (2)$$

$$\dot{\delta}_i = \omega_i - \omega_0 \quad (3)$$

for $i = 1,2,......,n$ generators in the network,
where the current in the network is given by

$$I = \begin{bmatrix} i_{q1} + j\,i_{d1} \\ : \\ i_{qn} + j\,i_{dn} \end{bmatrix} \quad (4)$$

and also

$$\bar{I} = \bar{Y}\,\bar{V} \quad (5)$$

In the case where the generators are not within the immediate influence of each other, the control law can be generated and applied to the i^{th} generator by assuming that its equivalent impedance is looking into the network. The terminal voltage is also assumed constant. The authors in [2] used a simple and direct approach to derive the control law for each generator in a three generator power system using reference signals tied to steady state power flow conditions. The step uses the assumption that the generators can be controlled with such signals before and after a fault but readjusted to new optimal conditions when the system conditions changes. The method adopted here is to compute the control law for each generator using the transformer equivalent impedance approximated to the distant end of the transmission line that is directly connected to the generator under the assumption that the optimal power flow conditions are not changed. Justifications for this assumption use the fact that since feedback linearization is model dependent, the computational requirement to obtain the control law of a full scale multi-machine model is prohibitive. It is noteworthy however that feedback law computed on the basis of a single generator reduced order model in a multi-machine environment requires a lot of approximation that will result in trade-offs to achieve linearization accuracy.

III. Flatness-based Feedback Controller

The system

$$f(\dot{x}, x, u) = 0 \quad (6)$$

with $x \in R^n$ and $u \in R^m$ is differentially flat if one can find a set of variables called flat output;

$$y = h(x, u, \dot{u}, \ddot{u}, ..., u^{(r)}) \quad (7)$$

$y \in R^m$ and system variables,

$$x = \alpha(y, \dot{y}, \ddot{y}, ..., y^{(q)}) \quad (8)$$

and control,

$$u = \beta(y, \dot{y}, \ddot{y}, ..., y^{(q+1)}) \,. \quad (9)$$

Lévine's necessary and sufficient conditions for differential flatness [7] are used on the system model (1-3) of order $n = 3$ and input $m = 1$, to derive generators' flat output, found to be the load angle $y = \delta$. The states of the model are verified to be a function of the flat output and its derivatives up to order $\alpha = 2$, while the endogenous feedback to the closed loop system is of order $\alpha + 1 = 3$. The state transformations are invertible and exist throughout the domain of stable operation $0 < \delta < 180^o$. The flat output, gives us the framework to construct the flatness-based feedback law. For the equivalent linear system, the new input v is equivalent to

$$\dddot{y} = \dddot{\delta} = v = \ddot{\omega} \quad (10)$$

The nonlinear control law is computed by inverting the expressions from $\ddot{\omega}$ and e_{fd} using the network parameters. It is given by:

$$e_{fd} = \frac{\tau_{d0}}{E}\left(\frac{2Hu}{\Lambda\omega_0} + \frac{D\dot{\omega}}{\Lambda} + A\dot{e}'_d + B\dot{e}'_d - C\dot{e}'_q\right) + e'_q + (x_d - x'_d)i_d \quad (11)$$

where, $\Lambda = (r_a + R_e)^2 (x_d^{'} + x_e)(x_q^{'} + x_e)$

$$A = 2R_{eT}\,\dot{e}_d^{'} - R_{eT}\sin(\delta) - x_{qt}\cos(\delta)$$

$$B = x_{qt}\sin(\delta)\dot{\delta} - R_{eT}\cos(\delta)\dot{\delta}$$

$$C = (x_{dt} - x_{qt})\,e_d^{'} - R_{eT}\sin(\delta)\dot{\delta} - x_{dt}\cos(\delta)\dot{\delta}$$

$$E = (x_q - x_d^{'})\,e_d^{'} - x_{dt}\sin(\delta) - 2R_{eT}e_q^{'} - R_{eT}\cos(\delta)$$

$$\dot{e}_d^{'} = \frac{1}{\Lambda}((x_q - x_d) + x_{dt})(x_{dt}\cos(\delta) + R_{eT}\sin(\delta)\dot{\delta}) + R_{eT}\,e_q^{'}$$

$$R_{eT} = (r_a + R_e); x_{dt} = (x_d^{'} + x_e);\ x_{qt} = (x_q^{'} + x_e)$$

And the linear control is given by

$$u = -k_1(\delta - \delta^*) - k_2(\dot{\delta} - \dot{\delta}^*) - k_3(\ddot{\delta} - \ddot{\delta}^*) \qquad (12)$$

The gains k_i are chosen such that the linear time invariant error dynamics

$$e^{(3)} = -k_1 e - k_2 \dot{e} - k_3 \ddot{e} \qquad (13)$$

where $e^{(j)} = \delta^{(j)} - (\delta^*)^{(j)}$ are stable. To compute the gains, (13) can be rewritten as a Hurwitz polynomial by

$$s^3 + k_3 s^2 + k_2 s + k_1 = 0\,.$$

(14)

The closed loop characteristic polynomial of a third order equivalent system is given in terms of the natural frequency and damping ratio by

$$(s^2 + 2\xi\omega_n s + \omega_n^2)(s + \beta) \qquad (15)$$

such that comparing (14) and (15) gives

$$k_1 = \beta\omega_n,\ k_2 = 2\xi\omega_n\beta + \omega_n^2\ ,\ k_3 = \beta + 2\xi\omega_n$$

IV. Implementation of PSO Tuning of Flatness-based Excitation Controller (FEC)

The PSO is a pseudorandom algorithm to search the solution space of an optimization problem. First proposed by Kennedy and Eberhart, it makes use of the inference that the social behavior of birds requires them to flock together and migrate from place to place without a consistent leader but rather by rotational leadership of individual members who display exceptional directional knowledge and skills towards the perceived direction they should go. It therefore makes use of a collection of possible solutions called particles whose individual velocity and position are updated according to two basic expressions. The current position of each solution particle is constantly compared with the previous ones and the best is used along with the groups' best solution particle to determine the next direction of search, thereby narrowing the search space using the following relations.

$$\begin{aligned} v_i(t+1) = w\,v_i(t) + c_1\,rand * (x_{pi}(t) - x_i(t)) \\ + c_2\,rand * (x_{Gb} - x_i(t)) \end{aligned} \qquad (16)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \qquad (17)$$

(16) and (17) are used to update the particles velocity and position at each iteration. Where x_{pi}, x_{Gb} represent each particle's personal best solution and the populations' best solution respectively; and w, c_1, c_2 are the inertia constant, and two positive numbers referred to as the cognitive and social acceleration constants respectively. These PSO parameters have to be chosen to ensure fast and accurate convergence of the PSO. *Rand* is a random number with uniform distribution in the interval [0, 1]. Since the terminal voltage is not a feedback variable in this scheme, voltage stabilization will have to depend on the stabilization of the load angle which is also the flat output. The loose connection between the terminal voltage and the load angle necessitates the design of the fitness function for the PSO optimization to select feedback gains that will give a balanced tradeoff between speed and terminal voltage equilibrium.

The fitness function which is used to update the particles' velocity and position is the square of the area under the terminal voltage deviation and speed deviation curves given by the following:

$$J = \int_{t_1}^{t_2} \left| e_1(\tau) + e_2(\tau) \right|^2 d\tau < \varepsilon \qquad (18)$$

where $e_1 = \alpha_1(V_t - V_{ref})$, and $e_2 = \alpha_2(\omega - \omega_0)$ representing the weighted average of the terminal voltage plus the speed. α_1 and α_2 are pre-determined weights chosen to equalize the contribution of both parameters in fitness computation. The block diagram of the FEC implementation on generator G1 is shown in Fig. 2. The controller gains are tuned using the PSO algorithm with 10 particles, each of three dimensions corresponding to the feedback gains k_1, k_2, k_3. Tables I and II give the PSO parameters and computed gains after 50 iterations for n particles.

TABLE I
PSO Parameters

n	w	c_1	c_2	v_{min}	v_{max}	$iteration$
20	0.8	1	3	-30	30	50

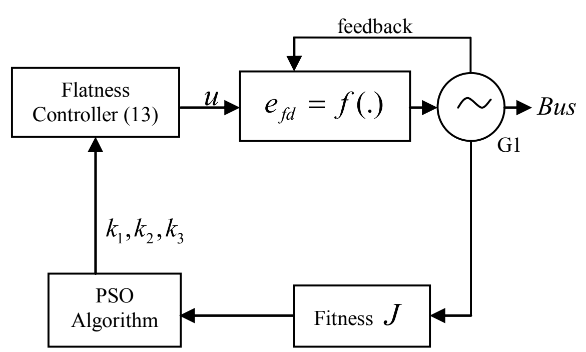

Figure 2 Block diagram of PSO gain optimization implementation for Flatness-Based excitation controller.

V. Results

To tune the controller gains using the PSO algorithm, an 8-cycle three phase short circuit is applied at the mid-point of buses 5 and 6 and the transmission line is removed for the duration of the simulation. The convergence of the PSO algorithm is indicated by the average fitness plot over ten trials shown in Fig. 3 for 50 iterations. The optimized gains are shown in Table II which resulted in system transient performance shown in Figs. 4 to 12.

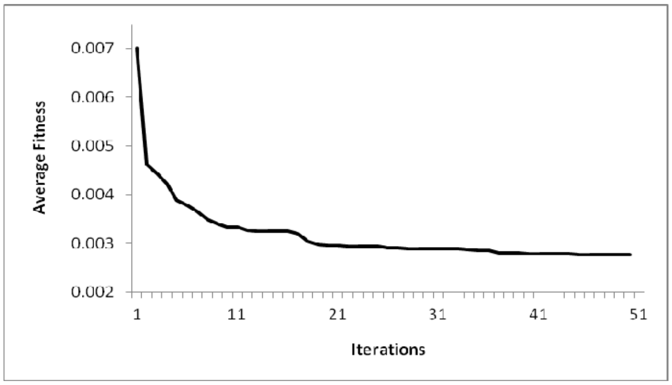

Figure 3 Average PSO fitness plot for 50 iterations.

TABLE II
CONTROLLER GAINS USED

	$50 < k_1 < 800$	$50 < k_2 < 150$	$10 < k_3 < 150$
PSO tuned	114.2397	58.3972	90.2023
No tuning	400.00	55.1400	15.8600

The field voltage responses of generator G1 with the different controllers are shown in Fig. 4. The speed response for generator G1 in Area 1 is shown in Figs. 5 and 6 as the system is subjected to a three phase 6 and 8 cycle's short circuit respectively. These figures show that the PSS scheme, the PSO-tuned and un-tuned flatness-based controllers in generator G1 damped the fault oscillations. But the flatness-based schemes out performs the PSS in damping the speed deviations. Fig. 7 shows the speed for generator G3 in Area 2 for a 8 cycle fault.

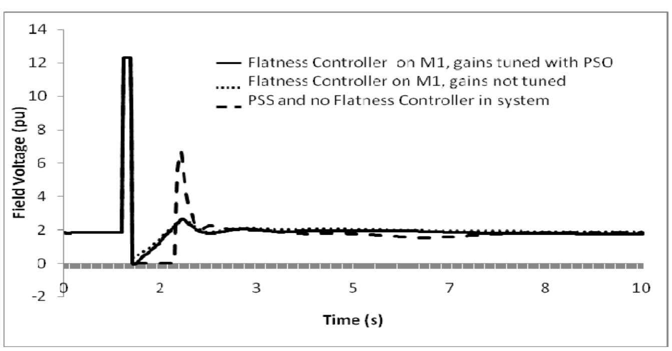

Fig.ure 4 Comparison of field voltage of generator G1 for PSO tuned, not tuned and PSS case schemes for a three phase 8-cycle short circuit.

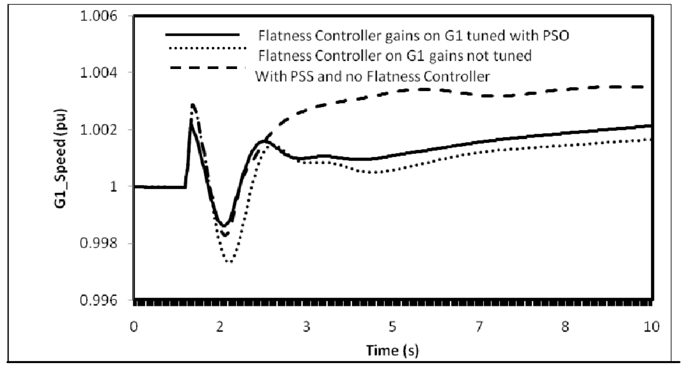

Figure 5. Speed of generator G1 for PSO tuned, not tuned and PSS case schemes for a three phase 6-cycle short circuit.

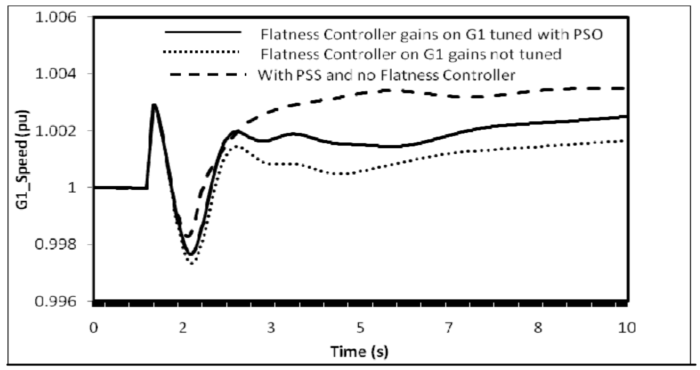

Figure 6. Speed of generator G1 for PSO tuned, not tuned and PSS case schemes for a three phase 8-cycle short circuit.

Using (18), the performance of the flatness-based controller vis a vis the the others are evaluated by simulations for the 6 and 8 cycle's three phase short circuit. Table III gives perfomance index J of the controllers. The PSS shows better perfomance for small cycle faults but becomes poor as fault cycles increase.

TABLE III
CONTROLLER FAULT PERFORMANCE INDEX J

	PSS	PSO Tuned	Not Tuned
6 Cycles	0.0027	0.0032	0.0035
8 Cycles	0.0046	0.0042	0.0045

Figs. 8-10 give the system terminal voltage response for generator G1 as the system is subjected to a three phase 6 and 8 cycle's short circuit respectively. The post fault terminal voltage is generally better for the flatness based controller response than for the PSS response save for a slight higher voltage response for generator G1. This indicates that the flat controller exerts a strong control effort on the generator it is attached to, and because the voltage is not directly damped there seems to be a drag to return it to steady state on its terminals. From Fig. 10 the area 2 voltage from the flatness-based controller are seen to return to steady state better than the PSS voltage.

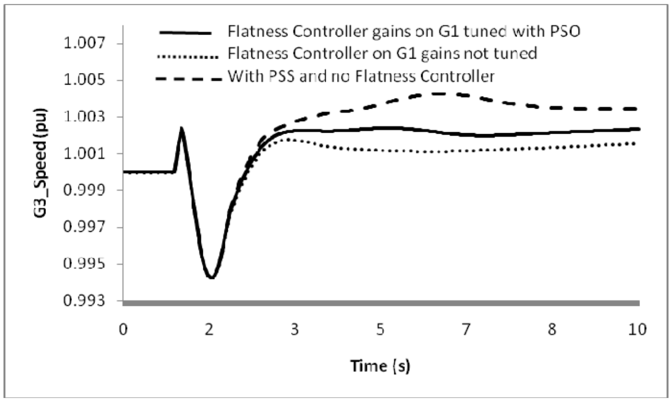

Figure 7. Speed of generator G3 (Area 2) for PSO tuned, not tuned and PSS case schemes for a three phase 8-cycle short circuit.

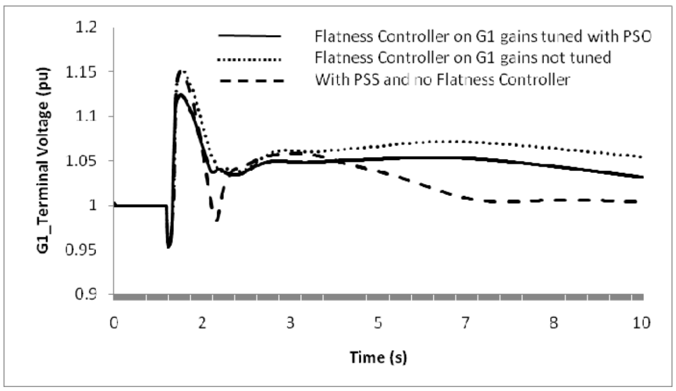

Figure 8. Terminal voltage generator G1 for PSO tuned, not tuned and PSS case schemes for a three phase 6-cycle short circuit.

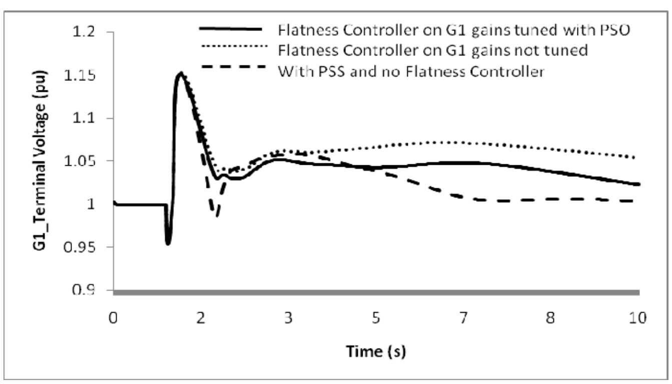

Figure 9. Terminal voltage of generator G1 for PSO tuned, not tuned and PSS case schemes for a three phase 8-cycle short circuit.

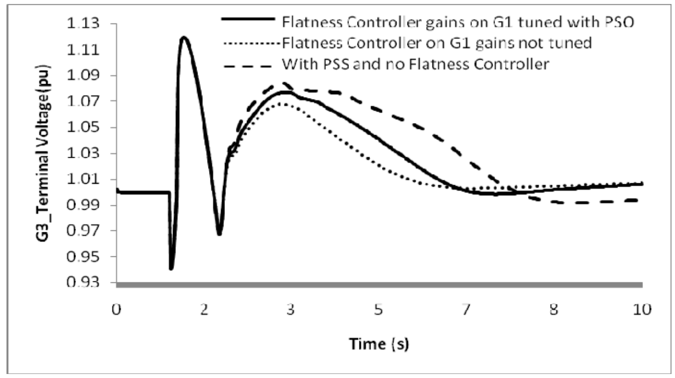

Figure 10. Terminal voltage generator G3 (area 2) for PSO tuned, not tuned and PSS case schemes for a three phase 8-cycle short circuit.

Notice from Figs. 5 and 8 that the speed response of the flatness-based controller without tuning seemed comparable or better than that with tuning, but the voltage response is worse as seen in Fig. 9. This is the motivation for this study. The need to satisfy stability conditions as well as steady state requirements after a disturbance necessitated the tuning of the gains to achieve an overall optimal response for the system which is the essence of this work.

VI. Conclusion

Flatness based feedback controller has been shown to effectively damp transient oscillations in a multi-machine power system when connected to generator G1 in a two area multi-machine power system. A general comparison of the results showed that the controller performed optimally when the gains are tuned with particle swarm optimization algorithm. It can be reasoned that one major way of employing the flatness-based controller in a multi-machine environment will be for an immediate post fault control action following a disturbance. Overall, the scheme shows good promise in stabilizing post fault transients and restoring system voltages to post fault values.

VII. Appendix

Given the one-axis model of (1)-(3), the system currents for the i[th] generator are given by

$$i_d = \frac{1}{\Lambda}(-(r_a + R_e)(e_d^{'} - V\sin(\delta)) + (x_q^{'} + x_e)(e_q^{'} - V\cos(\delta)$$
$$i_d = \frac{1}{\Lambda}(-(x_q^{'} + x_e)(e_d^{'} - V\sin(\delta)) + (r_a + R_e)(e_q^{'} - V\cos(\delta) \quad (19)$$

Where the generator is assumed remote with respect to the rest of the generators such that the remote voltage V is 1 pu.

The system equations are first transformed to the implicit equivalent, obtained by eliminating the dynamics that contains the system input e_{fd}, giving:

$$\frac{2H}{w_R}\frac{d^2\delta}{dt^2} - P_m + D(\omega - \omega_0) + e_d^{'} i_d + e_q^{'} i_q = 0 \quad (20)$$
$$\dot{\delta} - \omega + \omega_0 = 0$$

The cotangent approximation to the implicit equation is computed from:

$$P(F) = \left(\frac{\partial F}{\partial \delta} + \frac{\partial F}{\partial \dot{\delta}}\frac{d}{dt},\ \frac{\partial F}{\partial \omega} + \frac{\partial F}{\partial \dot{\omega}}\frac{d}{dt},\ \frac{\partial F}{\partial e_q^{'}} + \frac{\partial F}{\partial \dot{e}_q^{'}}\frac{d}{dt} \right) \qquad (21)$$

$$P(f) = \begin{pmatrix} \frac{d}{dt} & -1 & 0 \\ a_{21} & a_{22} & a_{23} \end{pmatrix} \begin{pmatrix} d\delta & d\omega & de_q^{'} \end{pmatrix}^T \qquad (22)$$

where:

$$a_{21} = \frac{\omega_0 V}{2H\Lambda}\left(e_d^{'} - (R_e \cos(\delta) + x_{qt}\sin(\delta))\dot{\delta} + e_q^{'}(x_{dt}\cos(\delta)\dot{\delta} + R_e\cos(\delta)\right)$$

$$a_{22} = \left(\frac{d}{dt} + \frac{\omega_0}{2H}D\right)$$

$$a_{23} = \frac{\omega_0 e_d^{'}}{2H\Lambda}(x_{qt} - x_{dt}) + V(x_{dt}\sin(\delta) + R_e\cos(\delta)) + 2R_e V e_q^{'} \dot{e}_q^{'}$$

It is noteworthy according to propositions 2 and 3 [7], that the resulting polynomial matrix of (20) is hyper-regular if and only if it is controllable. And if it is locally flat around $\overline{x}_0$, its linear cotangent approximation around $\overline{x}_0$ is controllable. Therefore there must exist

$V \in L - Smith\ (P(F))$ and (or)

$U \in R - Smith\ \ (P(F))$ such that

$$VP(F)U = (I_m, 0_{n-m,m}) \qquad (23)$$

The Smith decomposition algorithm applied to (20) in successive polynomial matrix manipulations using unimodular matrices of rank n until $P(f)$ is of rank $n-m$. Reducing it to lower or upper triangular polynomial matrix proves its hyper-regularity. Right multiplying the unimodular matrices used to generate $P(f)$, generates the U matrix:

Thus $$\hat{U} = U\begin{pmatrix} 0_{2,1} \\ I_1 \end{pmatrix} \qquad (24)$$

Using the definition $Q\,\hat{U} = \begin{pmatrix}1 & 0 & 0\end{pmatrix}^T$ (25)

further matrix manipulations on $Q \in L - Smith(\hat{U})$ yields

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ -\frac{d}{dt} & 1 & 0 \\ -A_{33} & 0 & 1 \end{pmatrix} \qquad (26)$$

Where $A_{33} = -\frac{1}{a_{23}}(\frac{d}{dt} + \frac{\omega_0}{2H}D)\frac{d}{dt} + a_{21}$

Multiplying Q by the vector $(d\delta, d\omega, de_q^{'})^T$ the last two lines gives $-\frac{d}{dt}d\delta + d\omega$; $\left(\frac{1}{a_{23}}(\frac{d}{dt} + \frac{\omega_0}{2H}D)\frac{d}{dt} + a_{21}\right)d\delta + de_q^{'}$ which by (22) identically vanishes on $\overline{X}_0$ while the first line is expressed as:

$$\begin{pmatrix}1 & 0 & 0\end{pmatrix}\left(d\delta, d\omega, de_q^{'}\right)^T = dy \qquad (27)$$

is trivially strongly closed such that

$$d\delta = dy \qquad (28)$$

and so gives the flat output $y = \delta$ (29)

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