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A New Nonlinear Excitation Controller for Synchronous Power Generator

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Abstract: - This paper presents a new and simple controller for transient stabilization with voltage regulation of a synchronous power generator connected to an infinite bus. The overall stability of the system is shown using Lyapunov technique. The design of the proposed controller takes into account the important non linearities of the power system model and it is independent of the equilibrium point. Simulation results have been shown to demonstrate the effectiveness of the proposed controller for the enhancement of the transient stability and voltage regulation of the power system under a large sudden fault and a wide range of operating conditions.

Key-Words: - Excitation control, Lyapunov technique, non linear control, synchronous generator, transient stability, voltage regulation

1 Introduction

The high complexity and nonlinearity of power systems, together with their almost continuously time varying nature, have deal of challenge of power system control engineers for decades. A particular issue encountered at the generating plant level is to maintain stability under various operating conditions. In order to obtain high quality for synchronous generator controllers, many researches has been established and numerous paper are published. Conventional excitation controllers such as the automatic voltage regulator (AVR) and power system stabilizer (PSS) are mainly designed by using linear control theory [1], [2]. These excitation controllers can be used effectively to damp oscillation and insure asymptotic stability of the equilibrium following small perturbation. In case of a large fault, the operating point of the system may vary considerably; non linearities begin to have then significant effects and a linear controllers may not be able to maintain asymptotic stability [3].

Recently, advanced nonlinear controller technique, which are independent of the equilibrium point and take into account the important non-linearities of the power system model have been used in the excitation control of power systems [4], [5], [6]. Most of these controllers are based on feedback linearization technique [3], [7], [8]. It was shown in the literatures that the dynamics of the power system could be exactly linearized by employing nonlinear state feedback. The essence of this technique is to first transform a nonlinear system into a linear on by a nonlinear feedback, and then uses the well-known linear design techniques to complete the controller design. Consequently one can use conventional linear control to give acceptable performance [9], [10] and [11]. Nevertheless in many cases the feedback linearization method requires precise parameters plant and often cancels some useful non-linearities. It is well known that power systems contain some parametric uncertainties in practice. In this case, it is difficult to exactly linearize the system with nominal parameters. Adaptive versions of the feedback linearizing controls are then developed in [12], [13]. Feedback linearization is recently enhanced by using robust control designs such as $H\propto$ control and $L2$ disturbance attenuation [14], [15].

Lyapunov theory has for a long time been an important tool in linear as well as nonlinear control [16]. However, its use within nonlinear control has been hampered by the difficulties to find a Lyapunov function for a given system. If one can be found, the system is known to be stable, but the task of finding such a function has often been left to the imagination and experience of the designer.The aim of this paper is the design of a control law for a nonlinear excitation controller to enhance the transient stability and to ensure good post-fault voltage regulation for synchronous generator connected to an infinite bus through a transmission line, as shown in Fig. 1. The model of the synchronous machine used is a 7^{th} order model, 5 for the electrical dynamics and 2 for the mechanical dynamics, which takes into account the stator dynamics as well as the damper winding effects and practical limitation on control. The feedback system is globally asymptotically stable in the sense of the Lyapunov stability theory.

The rest of this paper is organized as follows. In section 2, we describe the single-machine-infinite-bus power system model in a state space form suitable for

Lyapunov-based control design. In section 3, the nonlinear excitation controller is derived. The stability of this controller is proven. Some illustrative simulation results are presented and compared to the performance of a standard regulator voltage AVR and PSS in section 4 to validate the proposed controller and some concluding remarks are mentioned in the final section.

2 Mathematical model of power system

The generator to be controlled, studied in this work, is shown in Fig. 1. It consists of synchronous generator connected to an infinite bus via a transmission line (SMIB). The synchronous machine equations in terms of Park's d-q axis are expressed as follows [17], [18]:

Armature windings

$$v_d = -R_s i_d - \omega\lambda_q + \dot{\lambda}_d \quad (1)$$

$$v_q = -R_s i_q + \omega\lambda_d + \dot{\lambda}_q \quad (2)$$

where

$$\lambda_d = -L_d i_d + L_{md}(i_{fd} + i_{kd}) \quad (3)$$

$$\lambda_q = -L_q i_q + L_{mq} i_{kq} \quad (4)$$

Field winding

$$v_{fd} = R_s i_{fd} - L_{md}\dot{i}_d + L_{fd}\dot{i}_{fd} + L_{md}\dot{i}_{kd} \quad (5)$$

Damper windings

$$0 = R_{kd} i_{kd} - L_{md}\dot{i}_d + L_{md}\dot{i}_{fd} + L_{kd}\dot{i}_{kd} \quad (6)$$

$$0 = R_{kq} i_{kq} - L_{mq}\dot{i}_d + L_{kq}\dot{i}_{kq} \quad (7)$$

where v_d, v_q are direct and quadrature axis stator terminal voltage components, respectively; v_{fd} is the excitation control input; i_d, i_q direct and quadrature axis stator current components, respectively; i_{fd} the field winding current; i_{kd}, i_{kq} direct and quadrature axis damper winding current components, respectively; λ_d, λ_q direct and quadrature axis flux linkages, respectively; R_s the sator resistance; R_{fd} the field resistance; R_{kd}, R_{kq} the damper winding resistances; L_d, L_q the direct and quadrature self inductances, respectively; L_{fd} the rotor self inductance; L_{kd}, L_{kq} direct and quadrature damper winding self inductances, respectively and L_{md}, L_{mq} *d*irect and quadrature magnetizing inductances, respectively.

Mechanical equation

$$\dot{\delta} = \omega - 1 \quad (8)$$

$$2H\dot{\omega} = T_m - T_e - D\omega \quad (9)$$

where ω is the angular speed of the generator; δ the rotor angle of the generator; T_m the mechanical torque; T_e the electromagnetic torque; D the damping constant and H the inertia constant.

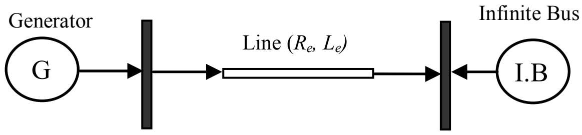

Fig. 1. Single machine infinite bus.

The equation for transmission network with external resistance R_e and inductance L_e, in the Park transformed coordinates are

$$v_d = R_e i_d + L_e\dot{i}_d - \omega L_e i_q + V^\infty \cos(\delta - a) \quad (10)$$

$$v_q = R_e i_q + L_e\dot{i}_q + \omega L_e i_d - V^\infty \sin(\delta - a) \quad (11)$$

where V^∞ is the infinite bus voltage and a is its phase angle.

By combining equations (1) to (11), the resultant generator system model, in per unit, has the following form

$$\dot{i}_d = a_{11}i_d + a_{12}i_{fd} + a_{13}\omega i_q + a_{14}i_{kd} + a_{15}i_{kq}\omega + a_{16}\cos(-\delta + a) + b_1 v_{fd} \quad (12)$$

$$\dot{i}_{fd} = a_{21}i_d + a_{22}i_{fd} + a_{23}\omega i_q + a_{24}i_{kd} + a_{25}i_{kq}\omega + a_{26}\cos(-\delta + a) + b_2 v_{fd} \quad (13)$$

$$\dot{i}_q = a_{31}i_d\omega + a_{32}i_{fd}\omega + a_{33}i_q + a_{34}i_{kd}\omega + a_{35}i_{kq} + a_{36}\sin(-\delta + a) \quad (14)$$

$$\dot{i}_{kd} = a_{41}i_d + a_{42}i_{fd} + a_{43}i_q\omega + a_{44}i_{kd} + a_{45}i_{kq}\omega + a_{46}\cos(-\delta + a) + b_3 v_{fd} \quad (15)$$

$$\dot{i}_{kq} = a_{51}i_d\omega + a_{52}i_{fd}\omega + a_{53}i_q + a_{54}i_{kd}\omega + a_{55}i_{kq} + a_{56}\sin(-\delta + a) \quad (16)$$

$$\dot{\omega} = a_{61}i_d i_q + a_{62}i_{fd}i_q + a_{63}i_q i_{kd} + a_{64}i_d i_{kq} + a_{65}\omega + a_{66}T_m \quad (17)$$

$$\dot{\delta} = \omega_R(\omega - 1) \quad (18)$$

where ω_R is the electrical frequency; a_{ij} and b_i are constants which depend on the generator and on the load parameters [3].

3 Design of a nonlinear excitation controller

Lyapunov's second or direct method is a very powerful tool of assessing stability of a nonlinear system [16], [19]. In this paper, the concept of Lyapunov's stability criterion is used to select the control strategy of the Single Machine Infinite Bus (SMIB), in order to ensure good steady and transient stability. To reach this objective, we define the terminal voltage error as

$$e = v_t - v_t^* \tag{19}$$

where $v_t^* = 1$ is the desired trajectory and

$$v_t = \sqrt{v_d^2 + v_q^2} \tag{20}$$

The expressions of v_d and v_q as a function of the state variables can be expressed as follow

$$\begin{aligned} v_d &= c_{11} i_d + c_{12} i_{fd} + c_{13}\omega i_q + c_{14} i_{kd} + c_{15} i_{kq}\omega \\ &\quad + c_{16}\cos(-\delta + a) + c_{17} v_{fd} \end{aligned} \tag{21}$$

$$\begin{aligned} v_q &= c_{21} i_d \omega + c_{22} i_{fd}\omega + c_{23} i_q + c_{24} i_{kd}\omega + c_{25} i_{kq} \\ &\quad + c_{26}\sin(-\delta + a) \end{aligned} \tag{22}$$

where c_{ij} are constants which depend on the constants a_{ij} and on the load parameters [3].

A positive definite Lyapunov function of the SMIB can be considered as

$$V = \frac{1}{2} e^2 \tag{23}$$

The time derivative of the $V(e)$ can be written as

$$\dot{V} = e\dot{e} \tag{24}$$

From the derivative of the terminal voltage error and by using (12)-(16) and (20)-(22), we obtains the following expression

$$\begin{aligned} \dot{e} = \dot{v} &= \frac{1}{v_t}\left(v_d \dot{v}_d + v_q \dot{v}_q \right) \\ &= c_{17}\frac{v_d}{v_t}\dot{v}_{fd} + b_3 c_{14}\frac{v_d}{v_t} v_{fd} + \frac{v_d}{v_t} g_1 + c_{14}\frac{v_d}{v_t} g_2 + \frac{v_q}{v_t}\dot{v}_q \end{aligned} \tag{25}$$

where

$$\begin{aligned} g_1 &= c_{11}\dot{i}_d + c_{12}\dot{i}_{fd} + c_{13}\left(\omega \dot{i}_q + i_q \dot{\omega} \right) \\ &\quad + c_{15}\left(\omega \dot{i}_{kq} + i_{kq}\dot{\omega} \right) + c_{16}\sin(-\delta + a) \end{aligned} \tag{26}$$

and

$$\begin{aligned} g_2 &= a_{41} i_d + a_{42} i_{fd} + a_{43} i_q \omega + a_{44} i_{kd} + a_{45} i_{kq}\omega \\ &\quad + a_{46}\cos(-\delta + a) \end{aligned} \tag{27}$$

Then the derivative of the Lyapunov function is computed as

$$\begin{aligned} \dot{V} &= c_{17}\frac{v_d}{v_t}\dot{v}_{fd}\, e + b_3 c_{14}\frac{v_d}{v_t} v_{fd} e + \frac{v_d}{v_t} g_1 e \\ &\quad + g_2 c_{14}\frac{v_d}{v_t} e + \frac{v_q}{v_t}\dot{v}_q\, e \end{aligned} \tag{28}$$

Thus, the Lyapunov's stability criterion can be satisfied by making term on the right hand side of (28) negative semi definite in order to guarantee the global asymptotic stability of the system. The candidates of v_{fd} that

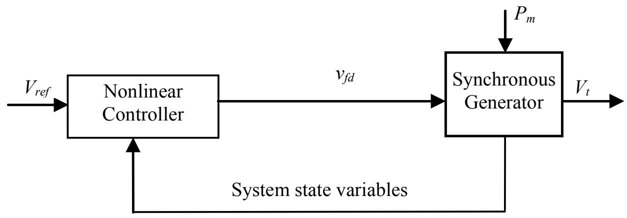

Fig. 2 Bloc diagram of the proposed nonlinear scheme

guarantees the semi negative definiteness criterion of equation (28) can be considered as

$$\dot{v}_{fd} = -\frac{v_t}{c_{17} v_d}\left[\begin{aligned} & Ke + b_3 c_{14}\frac{v_d}{v_t} v_{fd} + \frac{v_d}{v_t} g_1 \\ & + c_{14}\frac{v_d}{v_t} g_2 + \frac{v_q}{v_t}\dot{v}_q \end{aligned} \right] \tag{29}$$

where K is a positive constant feedback gain.

Substituting (29) into (28) the derivative of the Lyapunov function becomes

$$\dot{V} = -Ke^2 \tag{30}$$

Define the following equation

$$W(t) = Ke^2 \geq 0 \tag{31}$$

Furthermore, by using LaSalle Yoshizawa's theorem [16], its can be shown that $W(t)$ tend to zero as $t \to \infty$. Therefore, e will converge to zero as.

4 Simulation results and discussion

In order to validate the mathematical analysis and, hence, to establish the effectiveness of the proposed nonlinear control scheme, Simulations works are carried out for the Single Machine Infinite Bus System. The system configuration is presented as shown in Fig.2.The performance of the nonlinear controller was tested on the complete 7th order model of the generator system with the physical limit of the excitation voltage of the generator. The parameter values used in the ensuing simulation are given in the appendix. The fault considered in this paper is a symmetrical three-phase short circuit. The fault location is indexed by a constant λ which is the fraction of the line to the right of the fault. If $\lambda = 1$ the fault is at the infinite bus bar.

The simulated results are given in Fig. 3. It is shown terminal voltage, rotor speed, rotor angle and excitation voltage, respectively. The operating point considered is $P_{mo} = 0.6$ p.u. The fault occurs closer to the infinite bus bar at t = 5s and removed by opening the barkers of the faulted line at t = 5.1s. As can be seen the post fault terminal voltage is regulated to its prefault value very quickly. It is quite evident that the proposed

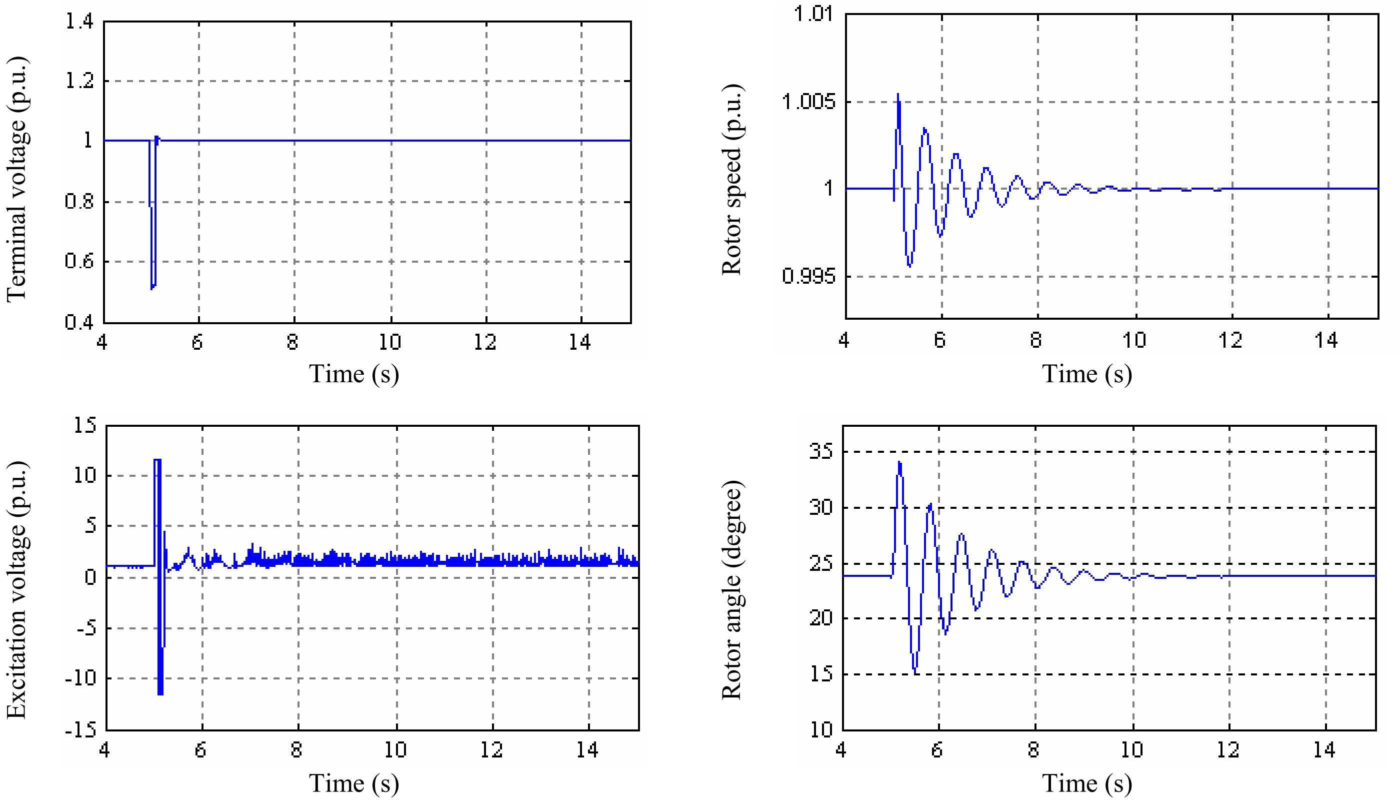

Fig. 3 Simulated result of the proposed nonlinear excitation controller.

controller achieves good transient stability, and dampens out the power angle oscillations.

In order to prove the robustness of the proposed controller, the results are compared with those of the linear controllers (conventional IEEE type 1 AVR and PSS). Fig. 4 and Fig. 5 show the responses of the terminal voltage under P_{mo} = 0.9 p.u , λ = 0.01 and P_{mo} = 0.3 p.u, λ = 1, respectively. It is seen how dynamics of the terminal voltage exhibit large overshoots during post fault state before he settle to its steady state value with the standard linear scheme than with the nonlinear controller. The proposed controller can quickly and accurately track the desired terminal voltage despite the different fault locations and operating points.

Another simulated terminal voltage responses for a sudden increase in the mechanical power is shown in Fig.6. The power system is started at mechanical power of P_{mo} = 0.3 p.u. Around t = 6s, the mechanical power is set at P_{mo} = 0.75 p.u. It is shown that the terminal voltage of the linear controller shows remarkable transient before to steles to desired value, while the terminal voltage of the proposed controller is unaffected by this variation. From the results presented earlier, again the superiority of the nonlinear controller is observed.

5 Conclusion

This paper has successfully demonstrated the design, and stability analysis of Lyapunov technique approach for the transient stability and voltage regulation of a SMIB power system based on the complete 7^{th} order model of the generator system. First, the dynamic model of a SMIB was introduced. Then, a nonlinear control system was designed in the sense of Lyapunov control technique. The feedback system is globally asymptotically stable. The design of the controller is independent of the operating point.

Simulation results demonstrate that with the proposed controller, the generator excitation controller can effectively improve the voltage stability damp oscillation and enhance the transient stability of power system under a large sudden fault. With the derived control high and accuracy stability can be achieved compared to the conventional AVR and PSS controllers.

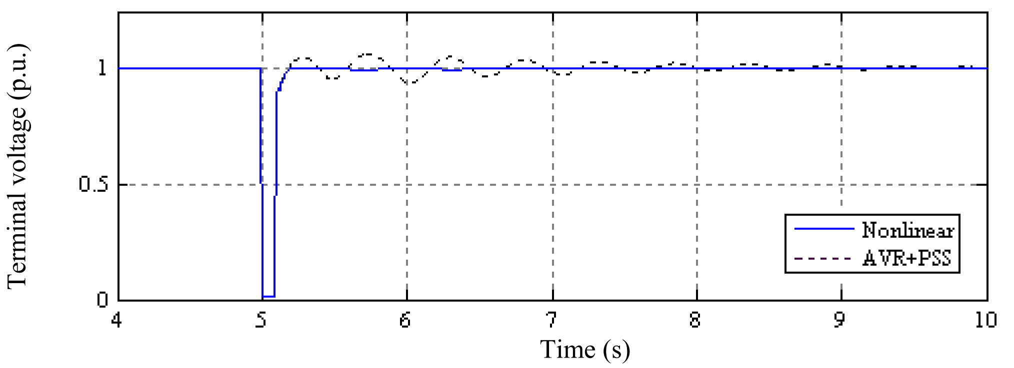

Fig. 4 Responses of the terminal voltage under P_{mo} = 0.9 p.u and λ = 0.01; (solid) proposed controller; (dot) linear controllers.

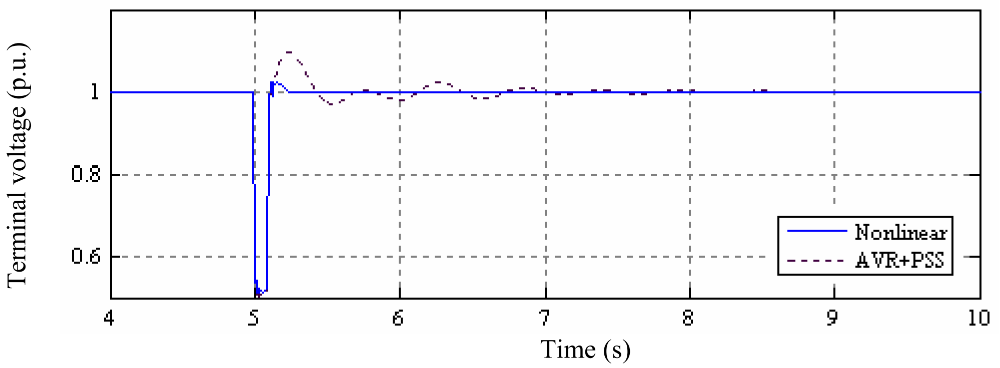

Fig. 5 Responses of the terminal voltage under P_{mo} = 0.3 p.u and λ = 1; (solid) proposed controller; (dot) linear controllers.

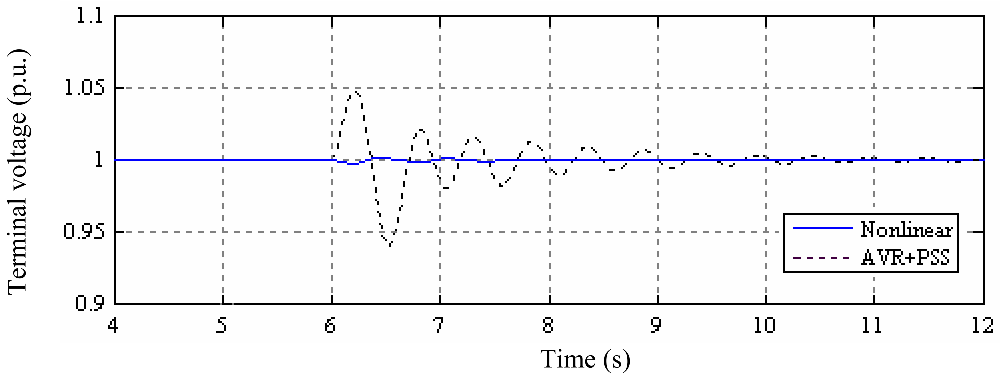

Fig. 6 Responses of the terminal voltage for a sudden increase in mechanical power, ΔP_{mo}=0.45 at t = 6 s; (solid) proposed controller; (dot) linear controllers.

Appendix

Table 1
Parameters of the Transmission Line in p.u.

Parameter	Value
L_e, inductance of the transmission line.	$11.16\ 10^{-3}$
R_e, resistance of the transmission line.	$60\ 10^{-3}$

Table 2
Parameters of the Power Synchronous Generator in p.u.

Parameter	Value
R_s , stator resistance.	$3\ 10^{-3}$
R_{fd}, field resistance.	$6.3581\ 10^{-4}$
R_{kd}, direct damper winding resistance.	$4.6454\ 10^{-3}$
R_{kq}, quadrature damper winding resistance.	$6.8460\ 10^{-3}$
L_d, direct self-inductance.	1.116
L_q quadrature self-inductances.	0.416
L_{fd}, rotor self inductance.	1.083
L_{kd}, direct damper winding self inductance.	0.9568
L_{kq}, quadrature damper winding self inductance.	0.2321
L_{md}, *d*irect magnetizing inductance.	$9.1763\ 10^{-1}$
L_{mq}, quadrature magnetizing inductance.	$2.1763\ 10^{-1}$
V^{∞}, infinite bus voltage	1
D, damping constant.	0
H, inertia constant.	3.195s

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