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Transient and Dynamic Stability Improvement of a Single Machine Infinite Bus Power System using Adaptive Fractional Order Proportional Integral Derivative Power System Stabilizer

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Abstract: This paper presents a study of the transient and dynamic stability enhancement and control of a synchronous generator connected to an infinite bus (single machine infinite bus system) via two parallel transmission lines when the power system working under different operating conditions and subjected to different disturbances. An effective mean of damping the oscillations resulting from these disturbances is to provide the synchronous generator with power system stabilizer. An adaptive fractional order proportional integral derivative controller is suggested to play the role of power system stabilizer in this paper. The results obtained from simulation study are presented and discussed.

Keywords: Transient Stability, Dynamic Stability, Single Machine Infinite Bus System, Power System Stabilizer, Adaptive Fractional Order Proportional – Integral – Derivative Controller.

Abbreviations

AVR	Automatic Voltage Regulator	PSS	Power System Stabilizer
FO	Fractional Order	RL	Riemann – Liouville
GL	Grunwald – Letnikov	SG	Synchronous Generator
IB	Infinite Bus	SMIB	Single Machine Infinite Bus System
IO	Integral Order	T.L.	Transmission Line
PID	Proportional – Integral – Derivative		

Nomenclature

A_k	Weighting factor of feedback voltage signal	i_F	Field current
D	Damping constant	i_q	q-axis current
E_{fD}	Exciter output voltage	i_Q	q-axis current of damper winding
E_{oA}	Initial value of E_{fD}	k_A	Regulator amplifier gain
i_d	d-axis current	K_D	Derivative gain
i_D	d-axis current of damper winding	k_f	Regulator stabilizing circuit gain

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K_I	Integral gain	V_{max}	The maximum voltage values
K_P	Proportional gain	V_{min}	The minimum voltage values
P	Active power	V_{PSS}	PSS output signal
Q	Reactive power	V_{ref}	Regulator reference voltage setting
S	Laplace operator	V_t	Terminal voltage
T_A	Regulator amplifier time constant	δ	Power angle
T_d	Damping torque	λ	Integrator order
T_e	Electrical torque	μ	Differentiator order
T_f	Regulator stabilizing circuit time constant	τj	Inertia time constant
T_m	Mechanical torque	ω	Rotor speed
V_3	Voltage feedback signal	$\Delta\omega$	Rotor speed error
V_4	Voltage error signal		

1. Introduction

The problem of control and stability of SGs has received and will receive a great deal of attention. The recent trends in power system design are toward the application of a large size generating units to feed higher expected loads. Therefore, a robust, strong, adequate and fast action control system is required to provide the compensation with which the reduction in stability margin is offset [1].

Stability analysis always differentiates between transient and dynamic stability, and it is hard to find a single control can enhance both of them. Also, stability analysis of large electric power systems depends almost entirely on digital computer simulation of system dynamic behavior. Simulation implies the existence of mathematical models for a variety of apparatus, data files which contain model parameters for specific power systems and computer programs [2].

In this paper, the application of an adaptive fractional order PID controller to act as a PSS to a prepared nonlinear mathematical model for SMIB is considered. The influence of the proposed PSS on both of the transient and dynamic performance of the synchronous generator is investigated when the system is subjected to different disturbances and operating at different conditions as stated in the results and discussions.

2. Power System Model

The power system under consideration is shown in Fig. 1. It consists of a SG connected to an IB through a power transformer and two parallel T.L.s [3].

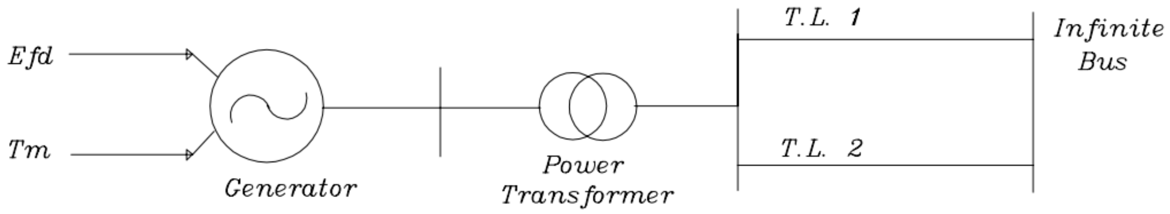


Fig. 1. The Single Machine Infinite Bus System (SMIB)

The mathematical model of the power system shown in Fig. 1. is based on the state-space formulation. In this model, the state-space variables are chosen to be the currents. This can be expressed in the matrix form as:

$$[I]^{\bullet} = [A]\cdot[I] + [B]\cdot[U] \tag{1}$$

where:

$$[I]^{t} = \begin{bmatrix} i_d & i_F & i_D & i_q & i_Q \end{bmatrix} \tag{2}$$

The torque equation can be expressed in the form of:

$$\tau_j \cdot \omega^{\bullet} = T_m - T_e - T_d \tag{3}$$

where:

$$T_d = D \cdot \omega \tag{4}$$

Also, the relation between δ and ω can be defined as:

$$\Delta\omega = \delta^{\bullet} = \omega - 1 \tag{5}$$

The excitation system with which the SG is equipped is an IEEE static type 1-S exciter and by feeding-back the terminal voltage signal and comparing this signal with a reference value, the excitation system is related to be an AVR and its block diagram is shown in Fig. 2. [4].

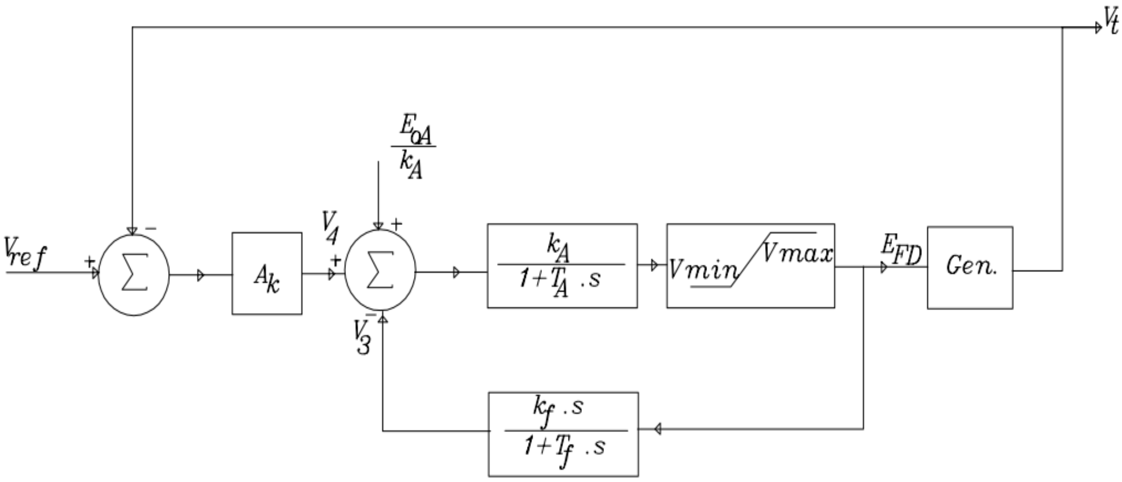


Fig. 2. Block diagram of AVR

The equations of the excitation system only can be written in the state-space form as following:

$$\begin{bmatrix} E_{fd} \\ V_3 \end{bmatrix}^{\bullet} = \begin{bmatrix} \dfrac{-1}{T_A} & \dfrac{k_A}{T_A} \\ \dfrac{-k_f}{T_A \cdot T_f} & -\left(\dfrac{k_f \cdot k_A}{T_f \cdot T_A} + \dfrac{1}{T_f}\right) \end{bmatrix} \cdot \begin{bmatrix} E_{fd} \\ V_3 \end{bmatrix} + \begin{bmatrix} \dfrac{k_A}{T_A} \cdot \left(V_4 + \dfrac{E_{oA}}{k_A}\right) \\ \dfrac{k_f \cdot k_A}{T_f \cdot T_A} \cdot \left(V_4 + \dfrac{E_{oA}}{k_A}\right) \end{bmatrix} \tag{6}$$

Combining equations (1), (3), (5) and (6), the complete system model will be constructed.

3. FO Controller

Traditional calculus is based on integer order differentiation and integration. The concept of fractional calculus has tremendous potential to change the way that model and control nature around can be seen. FO-PID controllers are introduced which may make FO controllers ubiquitous in industry. Additionally, several typical known FO controllers are introduced and commented. Numerical methods for simulating FO systems are given in detail. The continuous integro-differential operator is defined as [5]:

$$ {}_aD_t^r = \begin{cases} \dfrac{d^r}{dt^r} & R(r) > 0 \\ 1 & R(r) = 0 \\ \int_a^t (d\tau)^{-r} & R(r) < 0 \end{cases} \tag{7} $$

where r is the order of the operation, generally r ϵ R but r could also be a complex number. Of the several definitions of fractional derivatives, there are commonly two definitions used for which are the RL definition and the GL definition. The RL definition is given as:

$$ {}_aD_t^\alpha f(t) = \frac{1}{\Gamma(m-\alpha)} \cdot \frac{d^m}{dt^m} \int_a^t \frac{f(\tau)}{(t-\tau)^{\alpha-m+1}} \cdot d\tau \tag{8} $$

for $m-1 < \alpha < m$ where $\Gamma(\bullet)$ is the well-known Euler's gamma function, where [•] means the integer part. The GL definition is given as:

$$ {}_aD_t^\alpha f(t) = \lim_{h\to 0} h^{-\alpha} \cdot \sum_{m=0}^{\frac{t-a}{h}} (-1)^m \cdot \binom{\alpha}{m} \cdot f(t-mh) \tag{9} $$

The generalized form of the GL fractional derivative by using the Gamma Function is given by:

$$ {}_aD_t^\alpha f(t) = \lim_{h\to 0} h^{-\alpha} \cdot \sum_{m=0}^{\left[\frac{t-a}{h}\right]} (-1)^m \cdot \frac{\Gamma(\alpha+1)}{m! \cdot \Gamma(\alpha-m+1)} \cdot f(t-mh) \tag{10} $$

Intuitively, with FO controllers for IO plants, there is more flexibility in adjusting the gain and phase characteristics than using IO controllers. These flexibilities make FO control a powerful tool in designing robust control system with less controller parameters to tune. The key point is that using few tuning knobs, FO controller achieves similar robustness achievable by using very high-order IO controllers. In general form, the transfer function of $PI^\lambda D^\mu$ is given by [6]:

$$ C(S) = \frac{U(S)}{E(s)} = K_P + K_I S^{-\lambda} + K_D S^\mu \tag{11} $$

Involving an integrator of order λ and a differentiator of order μ, where λ and μ are positive real numbers; K_P is the proportional gain, K_I is the integral gain and K_D is the derivative gain. Clearly, taking $\lambda = 1$ and $\mu = 1$, we obtain a classical PID controller. If $\lambda = 0$ ($K_I = 0$) we obtain a PD^μ controller, etc. All these types of controllers are particular cases of the $PI^\lambda D^\mu$ controller. The time domain formula is:

$$ u(t) = K_P e(t) + K_I D_t^{-\lambda} e(t) + K_D D_t^\mu e(t) \tag{12} $$

It can be expected that $PI^{\lambda}D^{\mu}$ controller (as in Equation (12)), may enhance the systems control performance due to more tuning knobs introduced. One of the most important advantages of the $PI^{\lambda}D^{\mu}$ controller is the better control of dynamical systems, which are described by fractional order mathematical models. Another advantage lies in the fact that the $PI^{\lambda}D^{\mu}$ controllers are less sensitive to changes of parameters of a controlled system. This is due to the two extra degrees of freedom to better adjust the dynamical properties of a FO control system. It was shown that the best FO-PID works better than IO-PID. For actually implementation, we introduced a modified approximation method to realize the designed FO-PID controller.

With the rapid development of computer performances, the realization of FO control systems also became possible and much easier than before. Despite FO control's promising aspects in modeling and control design, FO control research is still at its primary stage. The notable future research is to develop tuning rules for FO-PID and in particular on tuning the FOs.

The FO-PID controller generalizes the IO-PID controller and expands it from point to plane. As shown in Fig. 3., extending the four control points of the classical PID to the range of control points of the quarter-plane defined by selecting the values of λ and μ. This expansion adds more flexibility to controller design.

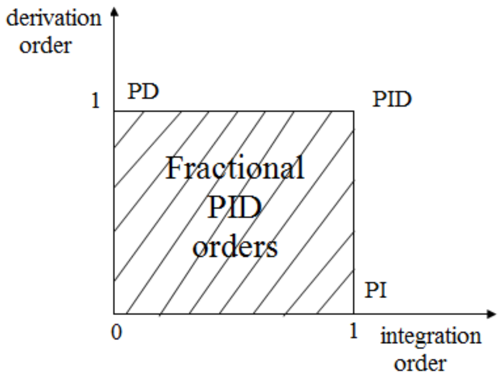


Fig. 3. FO-PID Controllers

Using FO-PID controllers, we have significantly reduced percentage overshoot and rise and settling times compared to integral PID controllers.

4. Proposed Adaptive FO-PID-PSS

In this paper, a proposed adaptive FO-PID-PSS is designed. The parameters of this controller are not constant but they are computed according to the variation of the system operating conditions. Figure (4) shows the block diagram of the controlled process, AVR, and the proposed PSS. The figure shows the method on which the design is depend [7].

For a wide range of system operating conditions (active power (P) and reactive power (Q)), the obtained controller parameters are stored in look-up table against the system operating conditions. During on-line operation, the controller monitors the P and Q values of the system and picks up the corresponding controller parameters at each sampling instant. The system of equations is:

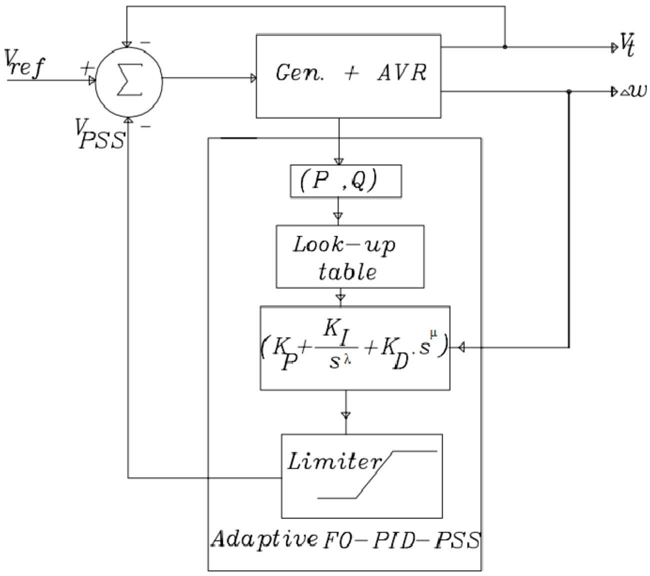


Fig. 4. Adaptive FO-PID Controllers

$$\begin{aligned} \dot{X} &= A \cdot X + B \cdot U \\ Y &= C \cdot X \end{aligned} \tag{13}$$

where:

$$[I]^t = [i_d \quad i_F \quad i_D \quad i_q \quad i_Q \quad \omega \quad \delta \quad E_{fd} \quad V_3] \tag{14}$$

Taking the Laplace transform for system of equations (13):

$$\begin{aligned} S \cdot X(S) &= A \cdot X(S) + B \cdot U(S) \\ Y(S) &= C \cdot X(S) \end{aligned} \tag{15}$$

which can be rewritten as:

$$X(S) = (S \cdot I - A)^{-1} \cdot B \cdot U(S) \tag{16}$$

The control signal will be:

$$U(S) = H(S) \cdot Y(S) \tag{17}$$

$$U(S) = \frac{S.T_W}{1 + S.T_W} \cdot \left[K_P + \frac{K_I}{S^{\lambda}} + K_D \cdot S^{\mu} \right] \cdot Y(S) \tag{18}$$

Hence,

$$Y(S) = C \cdot (S \cdot I - A)^{-1} \cdot B \cdot U(S) \tag{19}$$

and

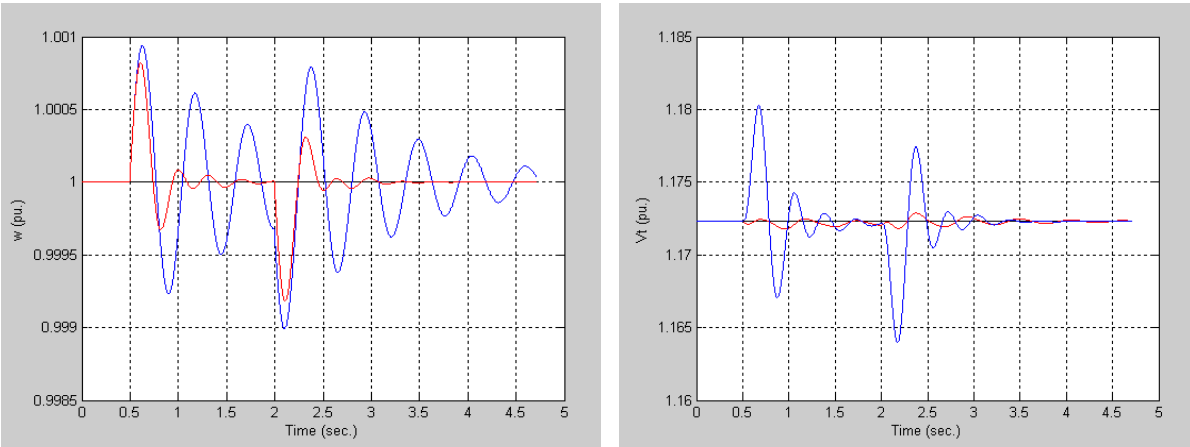
$$\begin{aligned} H(S) &= \frac{1}{C \cdot (S \cdot I - A)^{-1} \cdot B \cdot U(S)} \\ &= \frac{S.T_W}{1 + S.T_W} \cdot \left[K_P + \frac{K_I}{S^{\lambda}} + K_D \cdot S^{\mu} \right] \end{aligned} \tag{20}$$

The gains KP, KI and KD may be computed by finding the given values of the open loop system, prespecifying the eigen values of the closed loop system, and substituting the three eigen values of Equation (20), we can get three equations when solved together, we get KP, KI and KD. The input signal to the PSS may be expressed as:

$$V_{PSS} = W.\Delta\omega \tag{21}$$

5. Results and Discussions

To test the validity of the proposed control strategy explained in previous sections, a simple fault of 5% sudden increase in the input mechanical torque of SG is supposed after 0.5 seconds and the fault is cleared after 2 seconds. The simulation results are shown in Fig. 5.



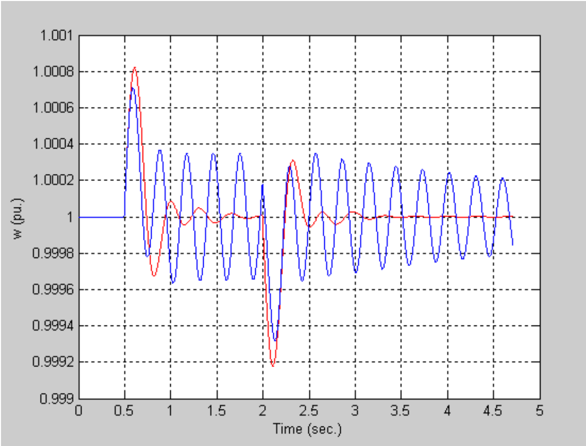
(a) Rotor speed – time curve (b) Terminal voltage – time curve

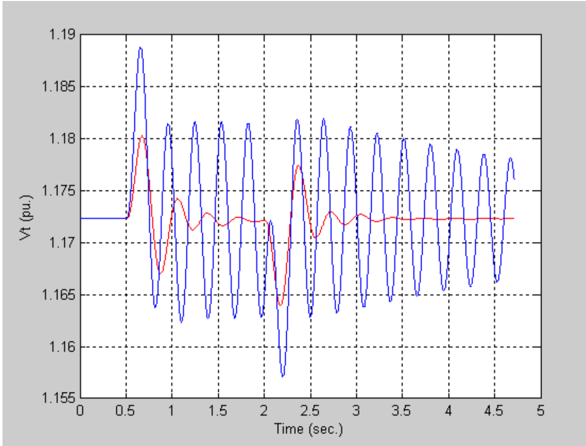
Fig. 5. Power system response to 5% sudden increase in the input mechanical torque

Fig. (5-a) represents rotor speed – time curve. Fig. (5-b) represents terminal voltage – time curve. In both figures, the curve in black represents the system when working at steady-state, the curve in blue represents the system when working under fault and without the proposed control strategy, and the curve in red represents the system when working under fault and with the proposed control strategy.

The SG response curves are shown in Fig. 5, show that the proposed adaptive FO-PID-PSS has high capability in improving the performance of the SG in comparison with that of conventional AVR. Also, it is clear that both of the transient stability and dynamic were enhanced which represents a new achievement of this type of controllers.

To prove the robustness of adaptive FO-PID-PSS over conventional PID-PSS, more check for this contribution can be verified by the comparison between the effectiveness of both the adaptive FO-PID-PSS and the conventional PID-PSS $(\lambda = \mu = 1)$ at the same fault conditions. The simulation results are shown in Fig. 6.



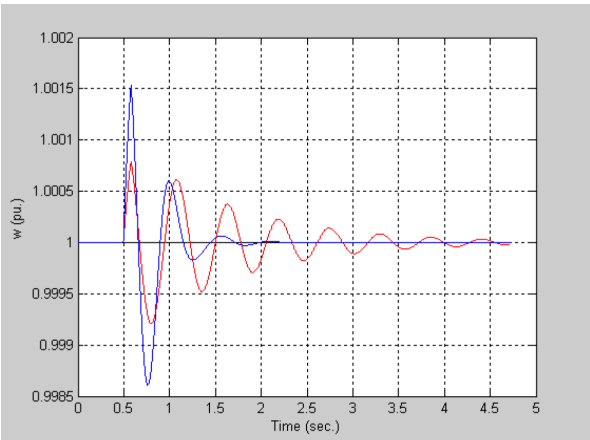


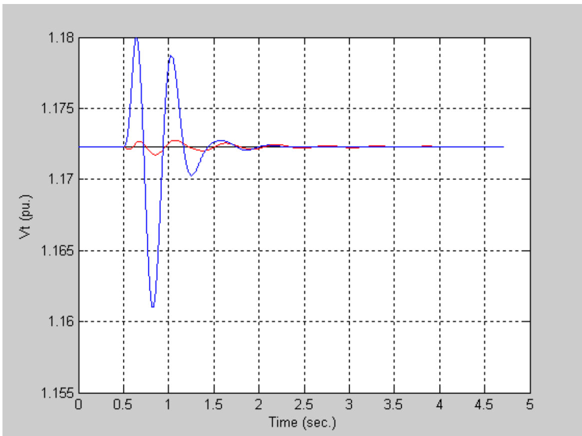
(a) Rotor speed – time curve (b) Terminal voltage – time curve

Fig. 6. Comparison between adaptive FO-PID-PSS and the conventional PID-PSS

In Fig. 6, the curve in blue represents the system when working under fault and with the proposed control strategy and the controller is conventional PID-PSS ($\lambda = \mu = 1$), and the curve in red represents the system when working under the same fault conditions and with the proposed control strategy and the controller is adaptive FO-PID-PSS.

For more check of the validity of the proposed control strategy, a severe disturbance is considered and simulated as a short circuit in one T.L. after 0.5 seconds at its midpoint with a successful enclosure of the circuit breakers. We assume that the short circuit remains for 0.08 second and the breakers are reclosed after 0.16 second. The simulation results is shown in Figure 7.





(a) Rotor speed – time curve (b) Terminal voltage – time curve

Fig. 7. Power system response to a short circuit in one T.L.

6. Conclusions

In this paper, the transient and dynamic performance of a synchronous generator when equipped with a continuous acting AVR and adaptive FO-PID-PSS is described. The effect of rotor speed error feedback stabilizing signal on the generator response is also examined. The proposed adaptive FO-PID-PSS is proved to be an efficient mean for improving the synchronous generator transient and dynamic stability when the generator operate under light and at severe disturbance conditions.

7. References

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