

Comparing the Power System Stabilizer Based on Sliding Mode Control with the Fuzzy Power System Stabilizer for Single Machine Infinite Bus System (SMIB)

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Abstract: This study compares the power system stabilizer based on sliding mode control with the fuzzy power system stabilizer for Single Machine Infinite Bus System (SMIB). Using the sliding mode control, a range is obtained for the changes in system parameters; and a stabilizer is designed to have a proper performance in this wide range. The purpose of designing the sliding mode stabilizer and fuzzy stabilizer is the increased stability and improving the dynamic response of the single machine system connected to the infinite bus in different working conditions. In this study, simulation results are compared in case of conventional PSS, no PSS, PSS based on sliding mode control and PSS based fuzzy logic. The results of simulations performed on the model of nonlinear system shows good performance of sliding mode controller and the Fuzzy controller. SMIB system was selected because of its simple structure, which is very useful in understanding the effects and implications of the PSS.

Keywords: Chattering, fuzzy logic, Power System Stabilizer (PSS), Sliding Mode Control (SMC), SMIB system

INTRODUCTION

Electromechanical oscillations with small amplitude, in the frequency range of 0.2 to 3 Hz, are inherent characteristics of power systems. Oscillations often appear in long periods of time and in some cases can create restrictions on the transmission capacity of power systems. Therefore, in recent years, damping oscillations of the electric system to improve the stability of small signal in power systems has been an important issue for control engineers. Many papers have been published on this issue (Boukarim *et al.*, 2000; DeMello and Concordia, 1969; El-Zonkoly, 2006; Kothari *et al.*, 1996; Kundur, 1994; Larsen and Swann, 1981; Loukianov *et al.*, 2004; Mohagheghi *et al.*, 2007; Mukherjee and Ghoshal, 2007; Rao and Sen, 1999; Sherbiny *et al.*, 2003; Yan *et al.*, 2004).

Use can be made of Voltage Regulators (VR) and excitation system with increasing torque of synchronous to improve transient stability of the system, but it may pose a negative effect on the damping of rotor oscillations. To reduce this undesirable effect and improve the dynamic performance of the system, complementary signals are proposed to increase the damping.

One cost effective solution to this problem is fitting the generators with a feedback controller to inject a supplementary signal at the voltage reference input of the automatic voltage regulator to damp the oscillations. This device, known as the Power System Stabilizer (PSS), is

now widely used in electrical industry. Regulating PSS in order to stabilize oscillations has been the subject of research during the past four decades. Conventional PSS structure consists of the circuit of the dc remover and cascade lead-lag networks.

Some of the input signals are the rotor speed (slip), accelerating power, electric power and a linear combination of them, which have been widely studied and the ways to use them in PSS design have been published in various studies.

To compensate for the phase retardation, conventional stabilizer (CPSS) makes use of phase compensation method, which is caused by the excitation of generator and power system (such as torque production) and is of the same phase with the changes in speed. This is the simplest method to comprehend and implement and thus is widely used in industry. For the design of PSS, it is necessary to evaluate (or regulate) several parameters for each device, such as the total dc interest, time constant of dc eliminating circuit and constant types of the lead-lag networks. Many sequential and simultaneous methods have been reported in the literature for adjusting these parameters. In conventional method of PSS regulation, only a small number of parameters (instead of all) are regulated by a series of intuitive assumptions. Then, a trial and error method is used to determine the best possible combination of these parameters, according to the performance criteria proposed. This approach gives satisfactory results on oscillation damping of local modes. However, as the PSS

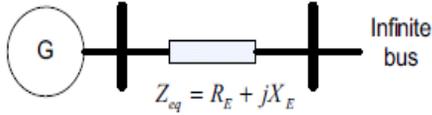


Fig. 1: A single machine connected to a large system, through a transmission line

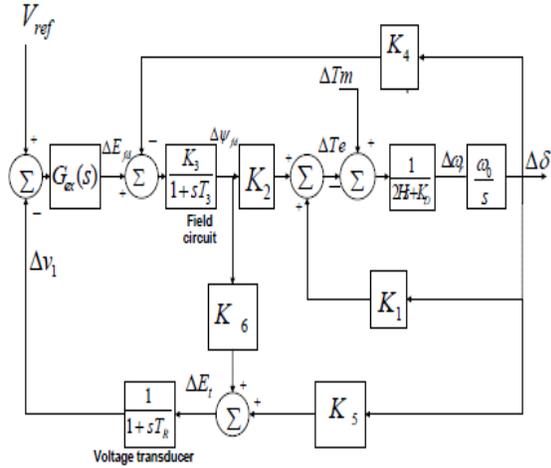


Fig. 2: Block diagram of the SMIB system with exciter and AVR

design is very sensitive, this result cannot be regarded as the best possible way, due to the assumptions made and the inherent nature of the design process.

Strength of PSS is an important issue. PSS must work well under changes in the operating point. In recent years, several efforts have been made in PSS design using modern control techniques, some of these methods are sliding mode control (Slotine and Li, 1991), fuzzy control, robust control and Artificial Neural Network (ANN).

In this study, the system equations are linear in the first step. Then in the next step, once a sliding mode controller and another time the fuzzy controller is implemented; and the simulation output of MATLAB Simulink are compared for both controllers.

SINGLR MACHIE MODEL CONNECTED TO THE INFINITE BUS

Infinite bus is a source of constant frequency and voltage in amplitude and angle. A diagram of this system is indicated in Fig. 1.

To analyze the stability of the small signal of the system with a synchronous machine, DeMello and Concordia (1969) have obtained a method by expanding the elements of the state matrix as the simple and explicit function of system parameters. Figure 2 shows the block diagram modeled by Concordia, which includes the effect of excitation system.

In Fig. 2, constants K_2 , K_3 and K_4 are generally positive, while coefficient K_6 is always positive; constant K_5 can be positive or negative depending on working conditions; and the external network impedance is $R_E + jX_E$. The value of K_5 has an important role in effectiveness of AVR on the damping of the system's oscillations. Linear state-space model of the system, which is shown in Fig. 2, is as follows:

$$\dot{x} = Ax + bu \quad (1)$$

where,

$$x = [\Delta\omega \quad \Delta\delta \quad \Delta\psi_{fd} \quad \Delta v_1]^T \quad (2)$$

$$A = \begin{bmatrix} 0 & -\frac{K_1}{2H} & -\frac{K_2}{2H} & 0 \\ 2\pi f & 0 & 0 & 0 \\ 0 & a_{32}^* & a_{33}^{**} & a_{34}^{***} \\ 0 & \frac{K_5}{T_R} & \frac{K_6}{T_R} & -\frac{1}{T_R} \end{bmatrix} \quad (3)$$

$$b = \left[\frac{1}{2H} \quad 0 \quad 0 \quad 0 \right]^T \quad (4)$$

(Relations (a_{32}^*) , (a_{33}^{**}) and (a_{34}^{***}) are given in Appendix B)

POWER SYSTEM STABILIZER BASED ON THE SLIDING MODE CONTROL

Power system stabilizer is used to improve the performance of synchronous generator. However, when conventional PSS is employed, it will result in poor performance under various load conditions. Therefore, while using a stabilizer, it is necessary to make a good performance in such conditions (here, a power system stabilizer based on sliding mode control is used).

Sliding mode control method is one of the most important non-linear control ones, whose prominent feature is the lack of sensitivity to changing parameters and complete disturbance rejection and also dealing with uncertainty. Sliding mode control method has been used for over two decades to achieve robust stability in power electronics and drives. This controller brings the system from the initial state to a defined sliding surface, which has Lyapunov asymptotic stability, using the law; and then leads to equilibrium via the law of sliding. Sliding surface is a plane that the system dynamics on its both sides is such that the path of the state is guided over it and provides a stable and desirable behavior.

Designing variable structure systems includes the following two steps:

- Determining the key levels, so that the intended stability and behavior can be provided.
- Determining the control subsystems, so that the system can rise to a good sliding surface and can provide the necessary conditions.

Consider the following dynamic single-input system:

$$\dot{X}^n = f(x) + b(x)u \quad (5)$$

The issue of control is that we find mode X so that it can follow a variable state with the specified time X_d , notwithstanding the error in $f(x)$ and $b(x)$. For the task of tracking to be done using a finite control u , the desired initial mode $X_d(0)$ must be such that:

$$X_d(0) = X(0) \quad (6)$$

Let the tracking error in variable x be \tilde{X} and suppose that:

$$\tilde{X} = X - X_d \quad (7)$$

is the tracking error vector. Furthermore, let us define a time-varying surface $S(t)$ in state space $R^{(n)}$ with the scalar equation $s(X, t)$ as:

$$s(X, t) = \left(\frac{d}{dt} + \lambda \right)^{n-1} \tilde{x} \quad (8)$$

where, λ is a strictly positive constant. In addition, restrictions on s can be directly moved to the restrictions of the tracking error vector X , so the scalar s is the true measure of tracking performance. As a result, following some calculations, the problem of first order to keep scalar s at zero can be obtained with the control law u of Eq. (1) so that outside $S(t)$:

$$\frac{1}{2} \left(\frac{d}{dt} s^2 \right) \leq -\eta |s| \quad (9)$$

In this equation, which is called the sliding condition, η is a strictly positive constant. Now for the above system, we can choose the control law as follows:

$$u = u_{eq} - k \text{sign}(s) \quad (10)$$

where, u_{eq} is the control estimate.

Although it is possible to determine the range of changes in k , determining the best value will be done through trial and error. If the number of controllers and input is high, this amount will be accompanied by a large error. Due to its nonlinear nature, the use of this controller

for power system is associated with some restrictions: if the degree of system is low, the nonlinear controller can be designed using the above method. But as the degree of system increases, in practice it is impossible to optimize it due to the high error in the determination of k .

A major disadvantage of this method is the problem of chattering, which has discrete signals. This problem is extended by the delays existing in the system itself. If the disturbance entering the system has a certain sign, the effect of disturbance can be removed at any time with a given control law. Sign function is a discontinuous function, which causes chattering. Discontinuity in control causes high, frequent on/off switching in the control, leading to high energy consumption, causing noise, mechanical depreciation and excitation of non-modeled high-frequencies of system.

In most systems, chattering is an undesirable phenomenon; and a continuous function (e.g., saturation function) must be used to remove it. Accordingly, our control law is changed as follows:

$$u = u_{eq} - k \text{sat}\left(\frac{s}{\phi}\right) \quad (11)$$

where, Φ is the thickness of the boundary layer.

The most important properties that cause this method to be developed are high accuracy, fast dynamic response, good stability, ease of implementation and good, robust stability.

POWER SYSTEM STABILIZER BASED ON FUZZY LOGIC

The theory of fuzzy sets has been around since 1965 when first proposed by Prof. Zadeh. Due to its simplicity and its excellent control of linear and nonlinear devices, a fuzzy logic has been found as a widespread tool for engineers in many facets of everyday life (Nallathambi and Neelakantan, 2004; Rajabi *et al.*, 2010; Roosta *et al.*, 2010; Shah Majid *et al.*, 2002).

Fuzzy control systems are rule-based systems in which a set of so-called fuzzy rules represent a control decision mechanism to adjust the effects of certain system stimuli. The aim of fuzzy control systems is normally to replace a skilled human operator with a fuzzy rule-based system. The fuzzy logic controller provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. The heart of Fuzzy Systems is a knowledge base, which is formed by the if-then rules of fuzziness. The basic configuration of a fuzzy logic controller consists of a fuzzification interface, a knowledge base, a fuzzy inference engine and a defuzzification interface. Sensors'

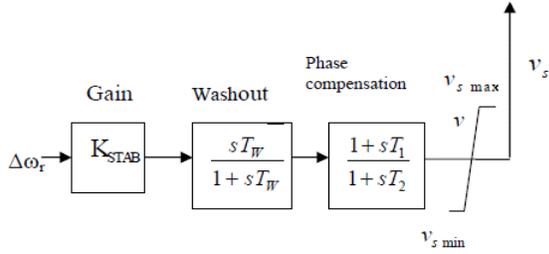


Fig. 3: Block diagram of CPSS

Table 1: Rules used in the fuzzy method

$\Delta\omega$	Acceleration						
	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NM	NS
NM	NL	NM	NM	NM	NS	NS	Z
NS	NM	NM	NS	NS	Z	Z	PS
Z	NM	NS	NS	Z	PS	PS	PM
PS	NS	Z	Z	PS	PS	PM	PM
PM	Z	PS	PS	PM	PM	PM	PL
PL	PS	PM	PL	PL	PL	PL	PL

NL: Negative Large; NM: Negative Medium; NS: Negative Small; Z: Zero; PS: Positive Small; PM: Positive Medium; PL: Positive Large

Table 2: Parameters of the conventional stabilizer

Parameters	Numerical values
T_1	0.154
T_2	0.033
T_w	1.4
K_{STAB}	9.5

outputs are absolute numbers. To make fuzzy inference, we converted them to fuzzy through fuzzification. The fuzzy inference engine converts if-then rules to a mapping from fuzzy sets in input space to fuzzy sets in output space. The required knowledge for the performance of fuzzy system is provided from fuzzy rules base. Fuzzy inference engine outputs, are fuzzy sets, which we converted to absolute numbers with defuzzification interface.

Generator speed deviation and acceleration are used as the inputs of the fuzzy logic based PSS proposed in this study. These variables have significant effects on the system oscillations. Stabilizer signals through fuzzy membership functions are calculated that are dependent on these variables. In this study, Membership functions for input and output in the fuzzy system is in the form of a triangle. Rules used in this method are given in Table 1.

CONVENTIONAL POWER SYSTEM STABILIZER (CPSS)

Figure 3 shows a block diagram of CPSS used in this study:

The parameters of this stabilizer are given in Table 2.

SIMULATION RESULTS

Simulation results were obtained using Simulink of software MATLAB 7.6. System data and system operating point are provided in Appendix A.

First, we consider the single machine model connected to the infinite bus with exciter and AVR.

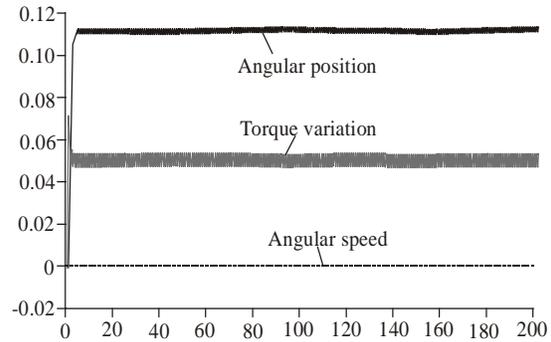


Fig. 4: System response to PSS based on the SMC for a change of 5% in mechanical input for positive K_5

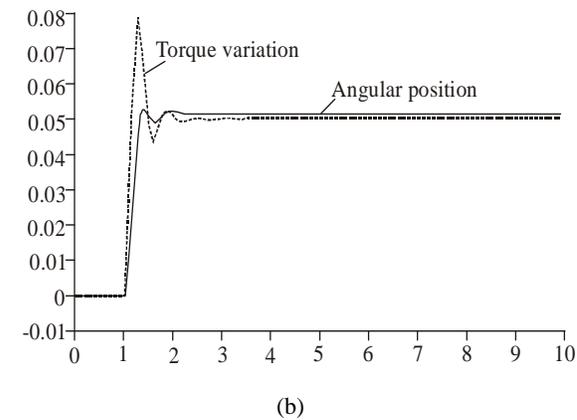
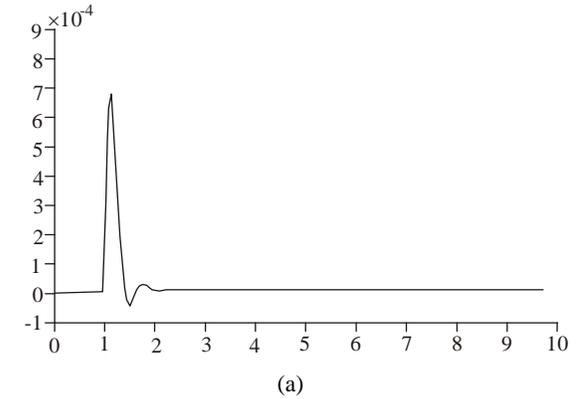


Fig. 5: (a) Changes in the angular speed with the PSS based on the SMC for a K_5 , (b) Changes in the angular position and torque with the PSS based on the SMC for a change of 5% in mechanical input for negative K_5

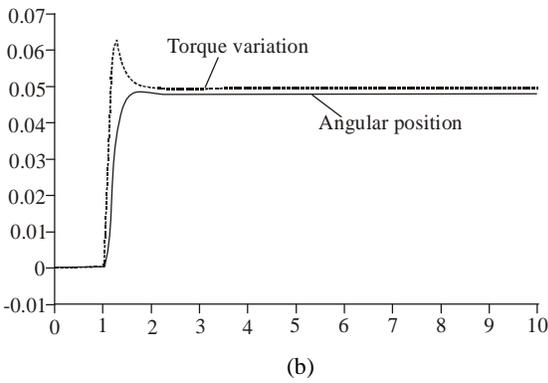
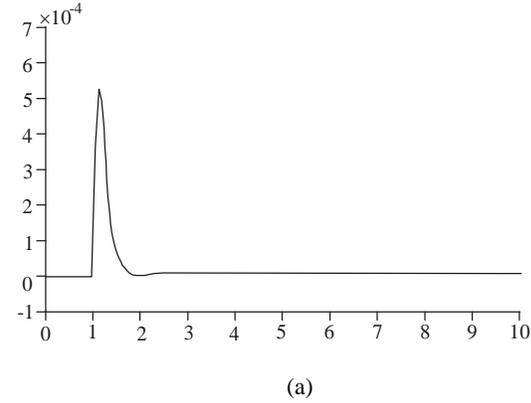


Fig. 6: (a) Changes in the angular speed with the fuzzy PSS for a change of 5% in mechanical input for negative K_5 (b) Changes in the angular position and torque with the fuzzy PSS for a change of 5% in mechanical input for negative K_5

According to what was said, it is clear that the system does not enjoy acceptable stability at this operating point. Then, performances of conventional controller, sliding mode controller and fuzzy controller on the sample system are discussed using the simulation.

In order to evaluate the performance of sliding mode controller on the SMIB system in Fig. 1, we apply control law (10), as expressed in the comments. Since the sign function is a discontinuous one, we will expect to see the chattering in the output. If we increase the simulation time, chattering becomes quite evident (Fig. 4). According to what was said, we can use the control law (11) to resolve this problem and the results of this simulation for negative K_5 are shown in Fig. 5. Then, according to Section 4, we apply the stabilizer based on fuzzy logic. The results of the simulation of fuzzy controller for negative K_5 are shown in Fig. 6.

CONCLUSION

PSS performance was simulated with different controllers using MATLAB Simulink. This study

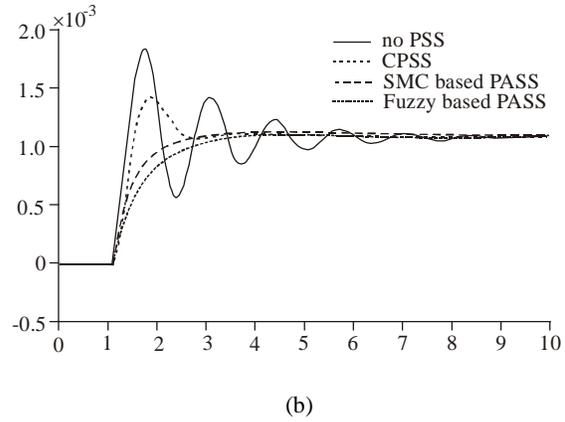
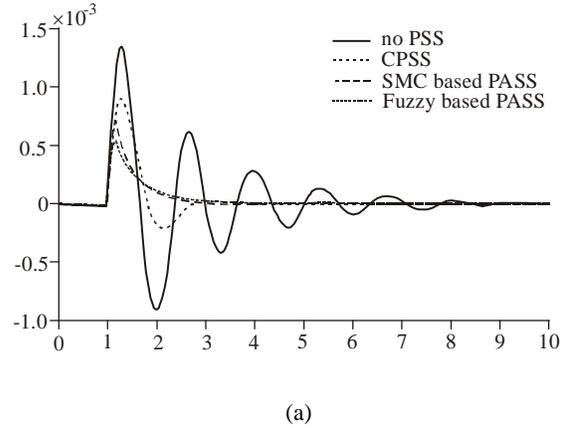
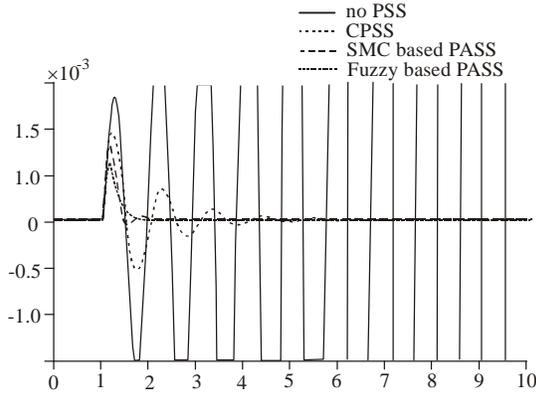
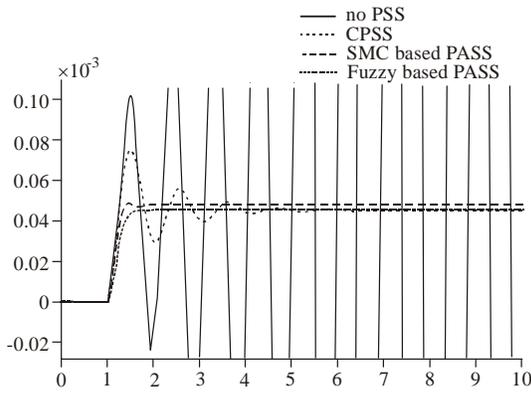


Fig. 7: (a) Comparison of the angular speed for a change of 5% in mechanical input for positive K_5 without PSS, with CPSS, PSS based on SMC and PSS based on fuzzy, (b) Comparison of the angular position for a change of 5% in mechanical input for positive K_5 without PSS, with CPSS, PSS based on SMC and PSS based on fuzzy

suggests a new method for designing the stabilizer for SMIB using sliding mode control and fuzzy logic. In Fig. 7 and 8, the performance of the system without PSS, with CPSS, PSS based on sliding mode control was compared for positive and negative K_5 with PSS based on fuzzy logic, respectively. In Fig. 7 is observed that the fuzzy controller has minimum overshoot, but the sliding controller reaches about 2.5 sec after the disturbance to its final answer, which is less time than other controllers. In Fig. 8 is observed that the fuzzy controller has minimum overshoot and also reaches about 0.8 sec after the disturbance to its final response, which is less time than other controllers. In Fig. 7 (a) and 8 (a) is the response peak value in the fuzzy controller about 0.5 milli, but the peak response in the sliding controller is about 0.68 milli. The results of the simulation show that the fuzzy will produce the best response. However, the sliding mode controller for positive K_5 reaches to its final response quicker. Also, the implementation cost of the sliding mode control is less than fuzzy control in practice.



(a)



(b)

Fig. 8: (a) Comparison of the angular speed for a change of 5% in mechanical input for negative K_5 without PSS, with CPSS, PSS based on SMC and PSS based on fuzzy, (b) Comparison of the angular position for a change of 5% in mechanical input for negative K_5 without PSS, with CPSS, PSS based on SMC and PSS based on fuzzy

APPENDIX A

Nominal values of the system and working conditions for the above system are given in Table 1a.

Here, the dynamic specifications of the system are expressed in expressions called the constant K.

Table 1a: Nominal values of the system and working conditions

$R_s = 0.003$	$P = 0.02$	$T_R = 0.02$
$X_c = 0.65$	$Q = 0.03$	$E_{Tmag} = 1.0$
$T_{d01} = 8.0$	$E_f = 1.0$	$L_{adu} = 1.65$
$A_{SAT} = 0.031$	$F = 50$	$L_{aqu} = 1.60$
$B_{SAT} = 6.93$	$X_d = 1.81$	$R_{fd} = 0.0006$
$H = 3.5$	$X_q = 1.76$	$L_{fd} = 0.153$
$\Psi_1 = 0.8$	$X_{d1} = 0.3$	$K_{sd} = 0.8491$
$\omega_0 = 14$	$X_l = 0$	$K_{sq} = 0.8491$
$K_D = 0$	$K_{su1} = 0.434$	$K_{sd1} = 0.434$

$K_1 = 0.7636; K_2 = 0.8644; K_3 = 0.3231; K_4 = 1.4189; K_5 = \pm 0.1463; K_6 = 0.4167$

APPENDIX B

$$a_{32} = -\frac{\omega_0 R_{fd}}{L_{adu}} K_4$$

$$a_{33} = -\frac{\omega_0 R_{fd}}{L_{adu}} K_3$$

$$a_{34} = -\frac{\omega_0 R_{fd}}{L_{adu}} K_A$$

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