

On a Novel Simulation of a Control Technique for Power Oscillation Damping and Applications

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ABSTRACT

This research presents a novel simulation model of adaptive control to implement a control process using the MIT-rule adjustment mechanism for power oscillation damping in the single-machine infinite-bus (SMIB) system, and to measure its possible effects on the response of the damper by changing its parameters according to an external disturbance using Simulink. The results show that the use of the model-reference adaptive control (MRAC) technique maintains the response of the damper when the transfer function changes because of an external disturbance.

Keywords: Matlab ▪ Control ▪ Simulation ▪ POD

1. INTRODUCTION

A control system is defined as a device that dynamically regulates or controls any facility or process. The controller is the most important element in this system, and its performance depends mainly on adjusting the gain value in accordance with the mathematical model of the controlled system. This model is designed for specific operating conditions (normal working conditions), but it changes because of various disturbances and changes in the operating environment. This necessitates resetting the controller's gain to comply with new or emergency operating conditions so that the controller maintains the desired performance, which is the main goal of the control process [1]. Many techniques have been used to achieve this goal [2].

Although there are many techniques for achieving optimization, adaptive control techniques are still required to obtain a fully adaptive response. Adaptive control changes the parameters of the control algorithm in real time to compensate for changes in the environment or in the system itself. It also changes the transfer function of the system depending on the situation. In special cases, a model-reference adaptive

control system is generally best implemented using a digital computer because of the complexity of the controller [3]. In this way, the response of the system is forced to track the response of the reference model regardless of changes in the plant parameters.

The controller parameters are adjusted to achieve the desired closed-loop performance. The controller parameters are evaluated to produce the required change in the plant transfer function so that its performance becomes similar to that of the reference model. In addition to the MIT rule, the model-reference adaptive control system (MRACS) is a direct adaptive strategy with adjustable parameters and an adjustment mechanism for tuning these parameters. Although research on adaptive control has continued for a long time, in 1960 it was used to design an autopilot for aircraft operating over a wide range of altitudes and speeds; gain scheduling was therefore conditioned on auxiliary measurements of wind speed [3].

Nowadays, adaptive control schemes are replacing traditional control systems that are unable to cope with situations such as:

- a. uncertainty and inertia;
- b. the possibility of sudden and unexpected breakdowns; and
- c. the possibility of frequent and unexpected disturbances.

Adaptive control has recently been used to modify the PI gain in FACTS-system controllers to ensure that the requirements for connecting wind turbines to the electrical grid are met under various disturbances, and the MRAC method has been compared with the genetic algorithm [4]. It has also been used to control induction motors [5], DC motors [6], and maximum-power-point tracking [7]. Conventional fixed-gain PID controllers are unable to cope with the above problems. Many techniques are used to design MRACS, such as Lya-punov theory and built-in-error theory; this research focuses on the MIT rule.

2. IMPORTANCE OF THE RESEARCH AND ITS GOALS

The importance of this research lies in its treatment of one of the most recently used methods for gain optimization in conventional systems, based on tracking the performance of a proposed reference model. The plant output must track this performance by using the output of the adaptation loop as an additional control signal whose task is to force the output of the controlled plant to track the output of the reference model under all operating conditions. This achieves the goal of the control system: obtaining the desired response, especially in systems that contain many parameters of a probabilistic nature, as is the case in electric power systems.

This research focuses on developing a computer model in MATLAB–Simulink for an electric power system consisting of a single machine connected to an infinite bus and containing a power oscillation damping (POD) controller with MRAC technology. Its potential effect on reducing rotor-speed oscillations is studied using an adjustment mechanism based on the MIT rule.

3. RESEARCH METHODS AND MATERIALS

The research is based on developing a computer model of the model-reference adaptive control method according to the MIT rule for a POD controller and testing its performance on a single-machine infinite-bus power system. Its effect on damping rotor-speed oscillations is compared with that of a conventional POD controller when a disturbance changes the controller transfer function. MATLAB–Simulink is used for the simulations.

3.1 Model-Reference Adaptive Control

Adaptive control covers a set of technologies that provide an organized method for the automatic, real-time adjustment of controllers. The aim is to achieve or maintain a desired level of control-system performance when the parameters of the dynamic model of the controlled plant are unknown or change with time. The system has three main elements: the reference model, the plant model, and the adjustment mechanism, as shown in Figure 1.

3.1.1 Reference Model

This part of the control system represents the desired performance of the closed-loop system; that is, it expresses the performance of the plant for the given reference input. In this research, the reference behavior is modeled as the steady-state transfer function of a vibration damper, as shown in Figure 2.

The reference model can also be determined from the closed-loop system specifications, as shown in Figure 3, with a desired rise time of 0.413 s, a settling time of 0.706 s, and a steady-state error of zero.

3.1.2 Plant Model

In this research, a second-order transfer function is used to express the desired performance of the damper, and this function is changed by an external disturbance. The actual output of the controlled process is Y_p , so the controller must change or adjust its parameter values to achieve the desired performance, such that $Y_p - Y_m = e = 0$, where Y_m is the output of the reference model and Y_p is the output of the controlled process.

3.1.3 Controller

The controller is usually described by a set of adjustable parameters. In this research, the transfer function of the controller is combined with that of the system to obtain a transfer function representing the controlled system and its controller.

3.1.4 Adjustment Mechanism

This component adjusts the controller parameters so that the actual output of the plant tracks the reference model. Its purpose is to change its output, θ , according to the error, e , between the output of the reference model, Y_m , and the output of the plant, Y_p . The adaptation speed depends on the learning rate or adaptation gain, γ . With high values of γ , the controller adapts more rapidly to a change in the plant, although side effects may occur. The controller output is calculated from $U = U_c \theta$, where U_c is the reference input, U is the control signal, and θ is the output of the adaptation loop.

The basic block diagram of the MRACS is shown in Figure 1. The difference between the reference-model output, $y_m(t)$, and the actual plant output, $y(t)$, is called the error:

$$e(t) = y(t) - y_m(t). \quad (1)$$

3.2 The MIT Rule

The MIT rule was first developed in 1960 by researchers at the Massachusetts Institute of Technology to design an aircraft autopilot system. It is also used to design adaptive controllers with an MRACS scheme. According to this rule, the cost function is defined as

$$J(\theta) = \frac{e^2}{2}, \quad (2)$$

where e is the error signal between the actual-model output and the reference-model output, and θ is the adjustable parameter that is tuned so that the cost function is as small as possible.

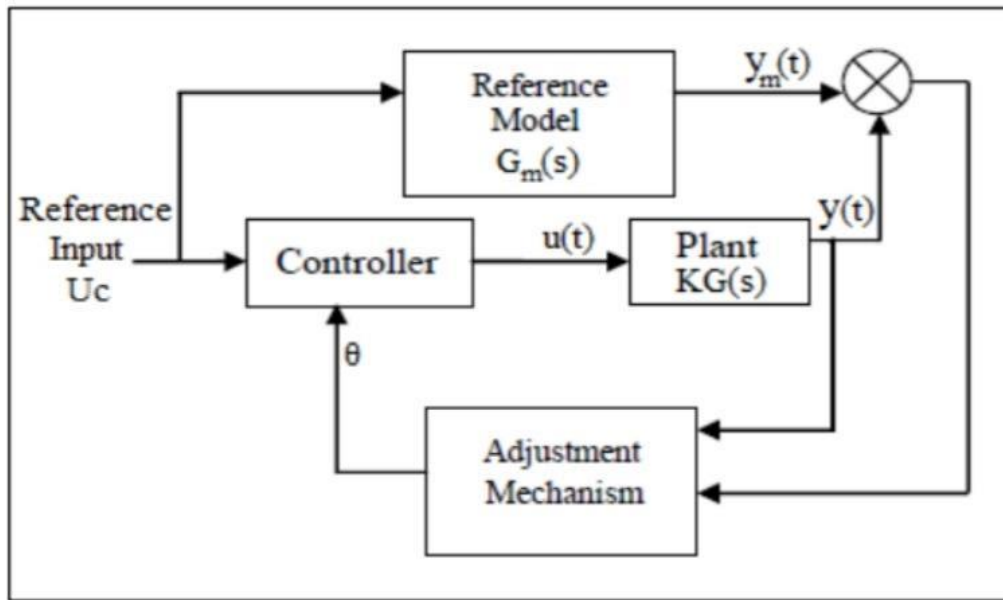


Figure 1. Adaptive control system with an MRA reference model.

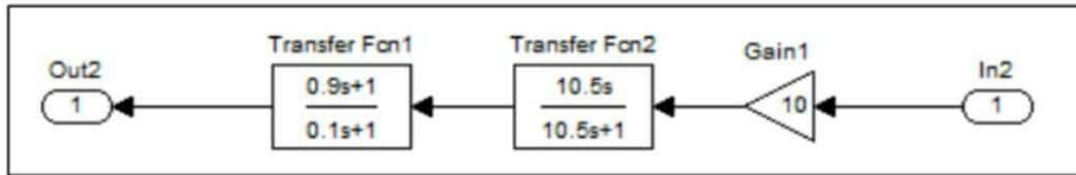


Figure 2. Reference model.

Consequently, the parameter θ changes in the direction of the negative gradient of J :

$$\frac{d\theta}{dt} = -\gamma \frac{dJ}{d\theta}, \quad (3)$$

where $J(\theta)$ is the cost function, $d\theta/dt$ is the rate of change of the adaptation-loop output, $dJ/d\theta$ is the rate of change of the cost function with respect to the output of the adjustment mechanism, and γ is the adaptive gain of the controller.

From Equation (2),

$$\frac{d\theta}{dt} = -\gamma e \frac{de}{d\theta}, \quad (4)$$

where the partial derivative $de/d\theta$ is called the system sensitivity derivative and indicates how much the error changes with θ .

Equation (3) describes the change of θ with time required to reduce the cost function $J(\theta)$ to zero. The quantity γ is positive and represents the adjustment gain of the controller. Suppose that the controlled process is linear and has the transfer function $KG(s)$, where K is an unknown parameter and $G(s)$ is a defined second-order transfer function. The goal is to design a controller that enables the controlled process to track a reference model with transfer function $G_m(s) = K_0 G(s)$, as shown in Figure 1.

From Equation (1),

$$E(s) = KG(s)U(s) - K_0 G(s)U_c(s), \quad (5)$$

where K_0 is the initial value of the parameter affected by the

disturbance, K is its new value after the disturbance, U is the control signal, and U_c is the reference input. The control law is

$$U(t) = \theta U_c. \quad (6)$$

From Equations (5) and (6), taking the partial derivative gives

$$\frac{dE(s)}{d\theta} = KG(s)U_c(s) = \frac{k}{k_0} y_m(s). \quad (7)$$

Equations (4) and (7) therefore give

$$\frac{d\theta}{dt} = -\gamma e \frac{k}{k_0} y_m = -\gamma' e y_m, \quad (8)$$

where γ' represents the adaptation gain. Equation (8) gives the adjustment law for θ . The simulation model is shown in Figure 4. The simulation results indicate that the plant response depends on γ' . In some industrial plants, large values of γ' cause system instability, so selecting this value is very important.

3.3 Power Oscillation Dampers

A power oscillation damper (POD) provides an additional control loop to the automatic voltage regulator (AVR) circuit and/or to the turbine and speed-governor system of the generating unit. Using a vibration damper is one of the most important and effective ways to improve power-system stability. The basic idea is that, in steady state, the speed deviation should approach zero and the voltage regulator should be driven only by the voltage error ΔV .

During a transient, the generator speed is not constant, the

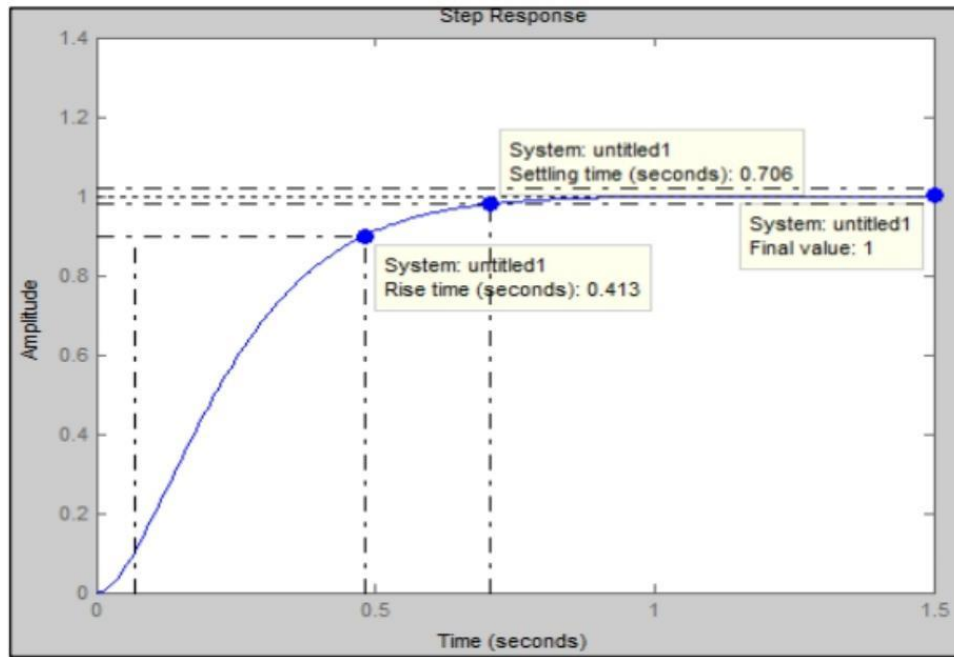


Figure 3. Determination of the reference model from the closed-loop specification.

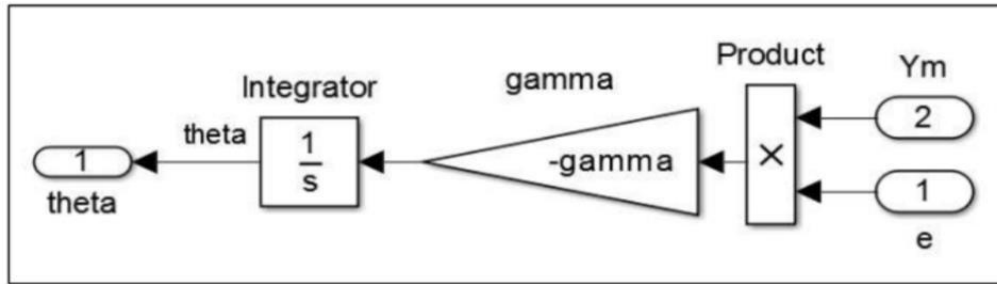


Figure 4. MIT-rule simulation model.

rotor oscillates, and ΔV is subjected to oscillations because of changes in the rotor angle. The task of the POD is to provide an additional signal that compensates for the oscillations in ΔV and produces a torque component in phase with the speed deviation $\Delta\omega$. The damper contains the washout block $T_w s / (T_w s + 1)$, which reduces the dynamic response to damping during major faults and has a time constant T_w , and the phase-lead block $(T_1 + s) / (T_2 + s)$, which compensates for the delay between the controller output and the application of electric torque. It also includes the damper gain K_{dd} , which determines the amount of damping. Figure 5 shows the block diagram of the POD transfer function connected to the electrical power system.

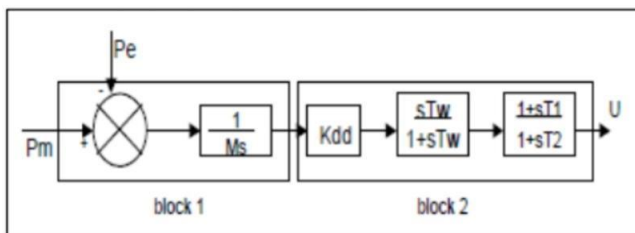


Figure 5. Block diagram of the transfer function of the POD.

3.4 POD with MRAC Technology

The MRAC simulation model based on the MIT rule controls a POD structure whose transfer function represents the de-

sired steady-state response. Its parameter values are selected according to the specifications of the electrical system. The general form of the damper is

$$G_p = K \frac{T_w s}{T_w s + 1} \frac{T_1 + s}{T_2 + s}.$$

In this research, the appropriate damper parameters were selected for the standard Philip–Heffron system. Its transfer function is

$$G_m = 10 \frac{10.5s}{10.5s + 1} \frac{0.9 + s}{0.1 + s}.$$

When the damper parameters change because of a disturbance, the transfer function changes in proportion to the new unknown parameters, producing a performance different from the design or reference performance. The new transfer function representing the damper becomes

$$G_p = 15 \frac{15s}{15s + 1} \frac{0.9 + s}{0.1 + s}.$$

The MIT-rule adjustment mechanism was selected with an adaptation gain of -3 . Its value depends on the type of system and significantly affects the extent to which the plant output follows the desired reference-model output. Beyond a certain value of this gain, however, the system becomes unstable.

4. RESULTS AND DISCUSSION

Figure 7 in the source study shows the simulation model of the tested system, represented by an SMIB electric-power system with system constants obtained using the computer program in the appendix. When the model is run with the original plant values without applying MRACS, the damper does not provide the desired performance after its parameters change from the design values to the actual values listed in Table 1. The simulation results referred to as Figure 8 in the source study show that, at 4 s, the oscillation range decreases from $[0.223, -0.447]$ by 0.223 p.u., or 50%.

Table 1. Design and actual values of the POD parameters.

Parameter	Design value	Actual value
K	10	5
T_w	10.5	10

5. CONCLUSION

The simulation results show that the plant model tracks the output of the reference model despite a change in the transfer function (the mathematical model of the controlled process) caused by a malfunction at $t = 1$ s. Applying this technique to the speed and angle deviations of the SMIB system when an electric-torque disturbance occurs proves its effectiveness in reducing the steady-state settling time. This distinguishes the method from other conventional control methods that rely on tracking a 1 p.u. reference input.

The output of the controlled process depends on its transfer function, which may change because of disturbances and changes in the operating environment. The control technique applied in this research is effective and is consistent with the results reported in relevant previous research. It improves the response of systems with unknown parameters that change over time and helps ensure that the desired performance is maintained when operating conditions change.

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