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SUMMER 2025

SAKDINUN THEWANA

AUTOMATIC VOLTAGE REGULATOR

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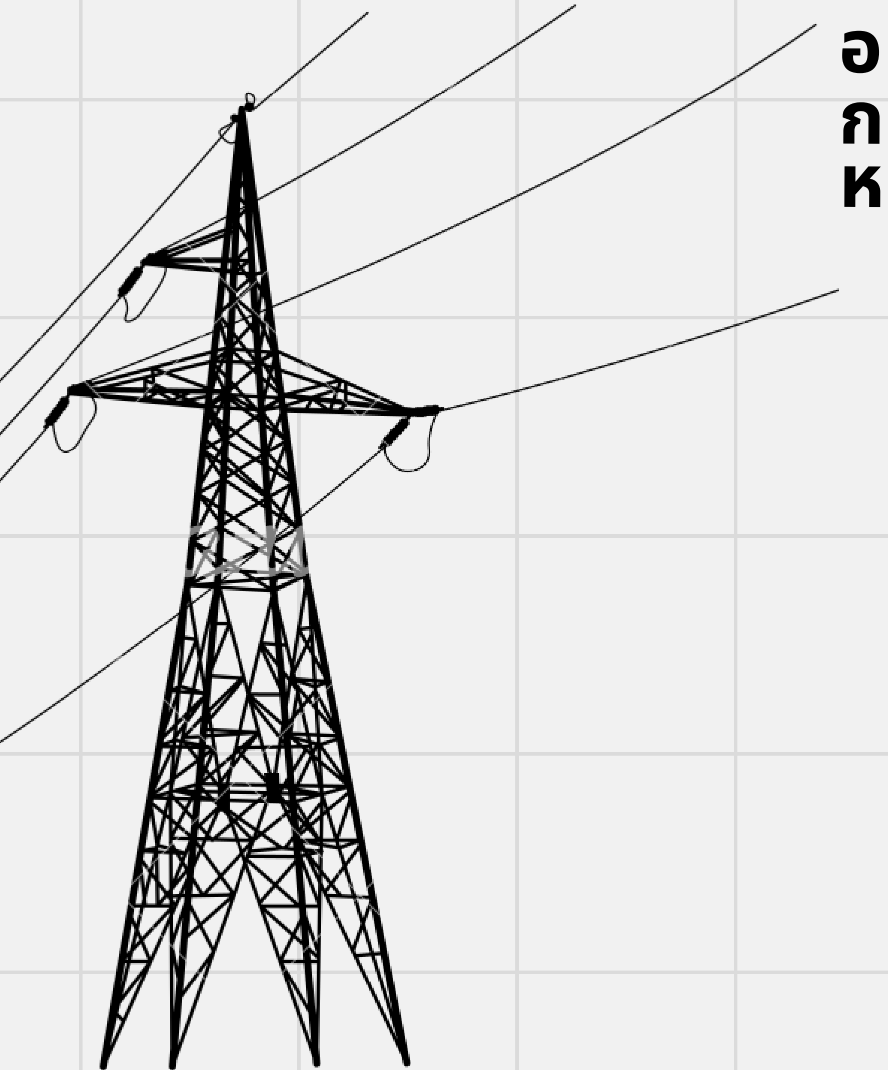
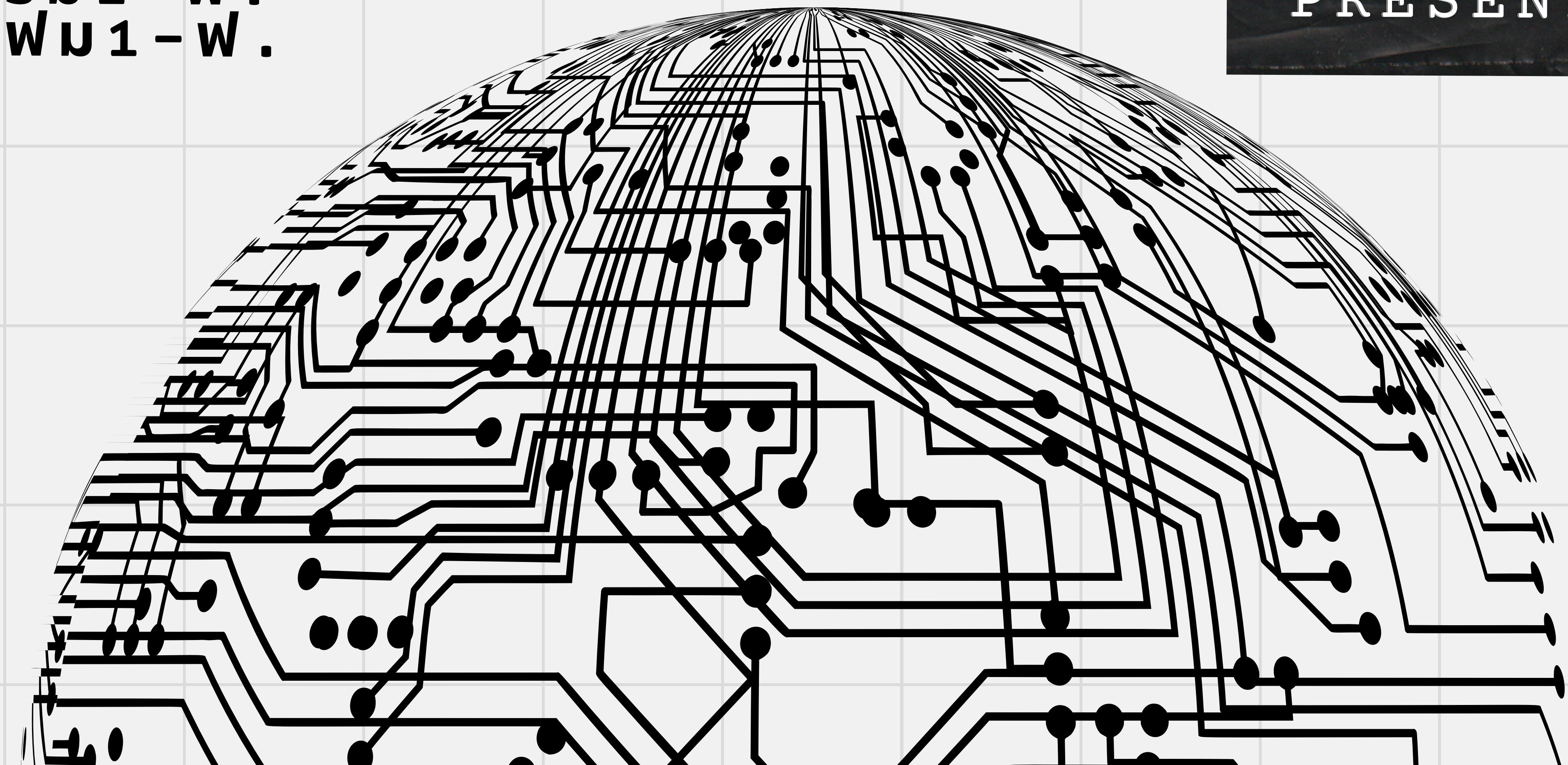
PRESENTATION





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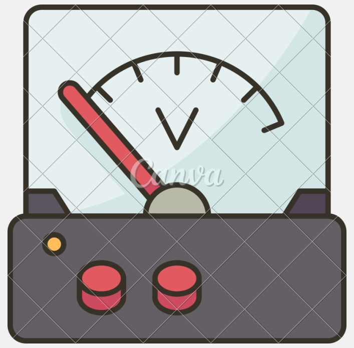
HOW IT WORK?

The AVR is a closed-loop control system that automatically adjusts the generator's excitation to maintain the terminal voltage at a desired setpoint.



VOLTAGE SENSING

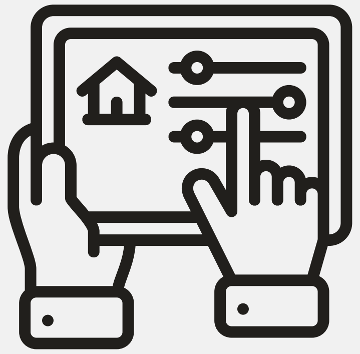
The AVR continuously monitors the generator's terminal voltage.

COMPARISON

The sensed voltage is compared to a pre-set reference voltage.

ERROR DETECTION

Any difference between the sensed voltage and the reference voltage creates an error signal.



EXCITATION ADJUSTMENT

The AVR uses this error signal to adjust the current in the field winding of the generator's exciter.

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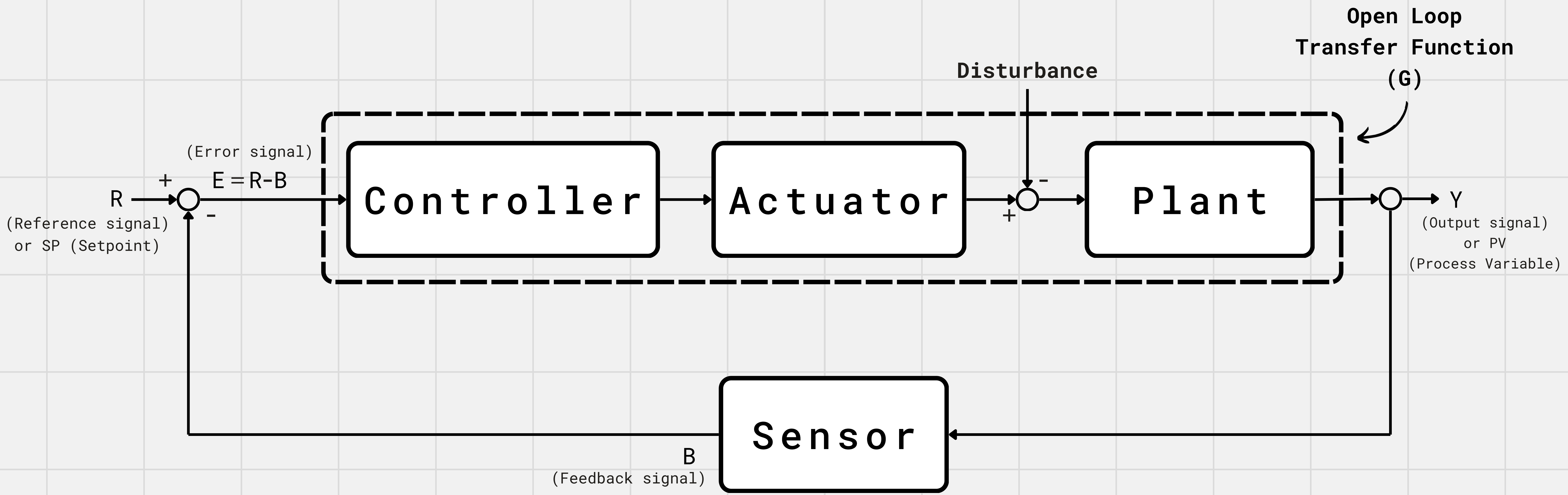
CLOSED-LOOP CONTROL SYSTEM



* There are many particular controller configurations but this configuration is **Series (cascade) compensation**.

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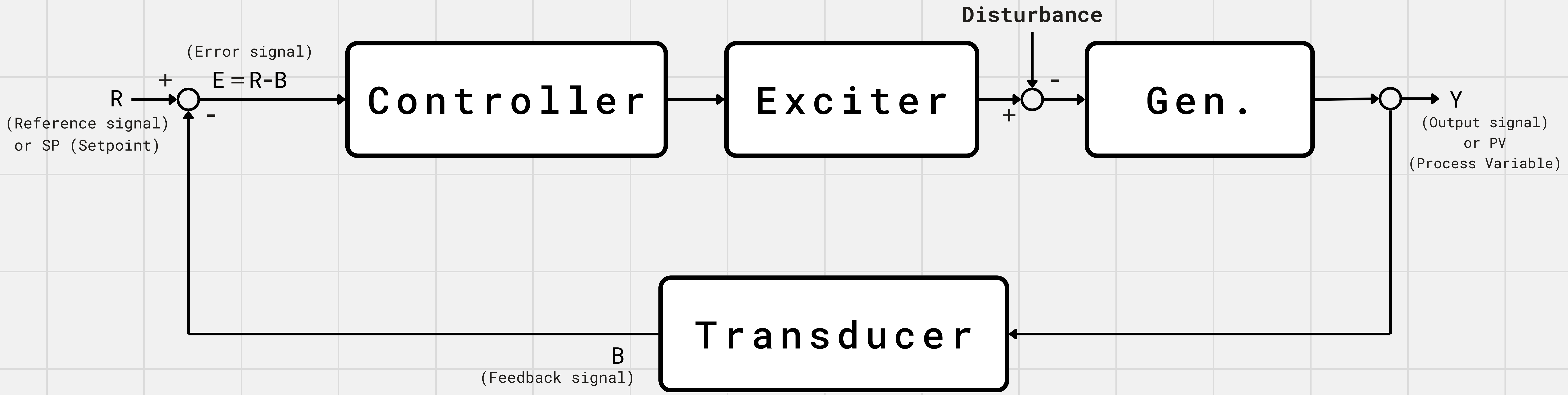
EXICITATION SYSTEM (AVR)



GENERATOR MATHEMATICAL MODEL

Although the theory of synchronous generator has been known since the beginning of its application, the research of modelling and analysis of synchronous generators is still very much ongoing. Mathematical description of electromechanical systems operation such as synchronous generator generally leads to a system of differential equations which is regularly nonlinear due to the multiplication of state variables. With the increase of computing power, the capabilities for modelling and analysis are increased as well. This has resulted in a large number of models that differ depending on the type of research they are intended for and on the degree of desired accuracy.

There are different approaches when developing a mathematical model and the corresponding simulation model of a synchronous generator. The most common approach is based on general two-reaction theory upon which a three-phase winding of a generator is substituted by one equivalent, fictitious two-phase winding projected onto the direct (d) and quadrature (q) rotor axis. The field winding is represented as a d-axis winding and the reaction of damper winding caused by the eddy currents in the cylindrical rotor is substituted by fictitious windings in d-axis and q-axis.

3. PARK'S TRANSFORMATION

Mathematical description of a synchronous generator can be significantly simplified with proper variable transformation. One of the possible stator variables (currents, voltages, fluxes) transformation is known as Park's or d-q transformation. The number of variables after a transformation generally remains the same and in general case, substitution with new variables should be observed as a completely mathematical operation, thus no physical interpretation of fictitious is necessary. In this case, according to [1], the applied transformation can be physically interpreted because the new variables are obtained by projecting the real variables onto the three axes (direct, quadrature and stationary):

$$\mathbf{i}_{0dq} = \mathbf{P}\,\mathbf{i}_{abc} \tag{1}$$

$$\mathbf{i}_{0dq} = \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} \quad \mathbf{i}_{abc} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

$$\mathbf{P} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos\vartheta & \cos\left(\vartheta - \frac{2\pi}{3}\right) & \cos\left(\vartheta + \frac{2\pi}{3}\right) \\ \sin\vartheta & \sin\left(\vartheta - \frac{2\pi}{3}\right) & \sin\left(\vartheta + \frac{2\pi}{3}\right) \end{bmatrix} \tag{3}$$

10. BLOCK DIAGRAM OF A SYNCHRONOUS GENERATOR

To develop a corresponding block element based simulation model from a certain mathematical mode, the mathematical model must be represented by a block diagram. Detailed nonlinear model of a synchronous generator in a block form is shown in figures 5 through 8.

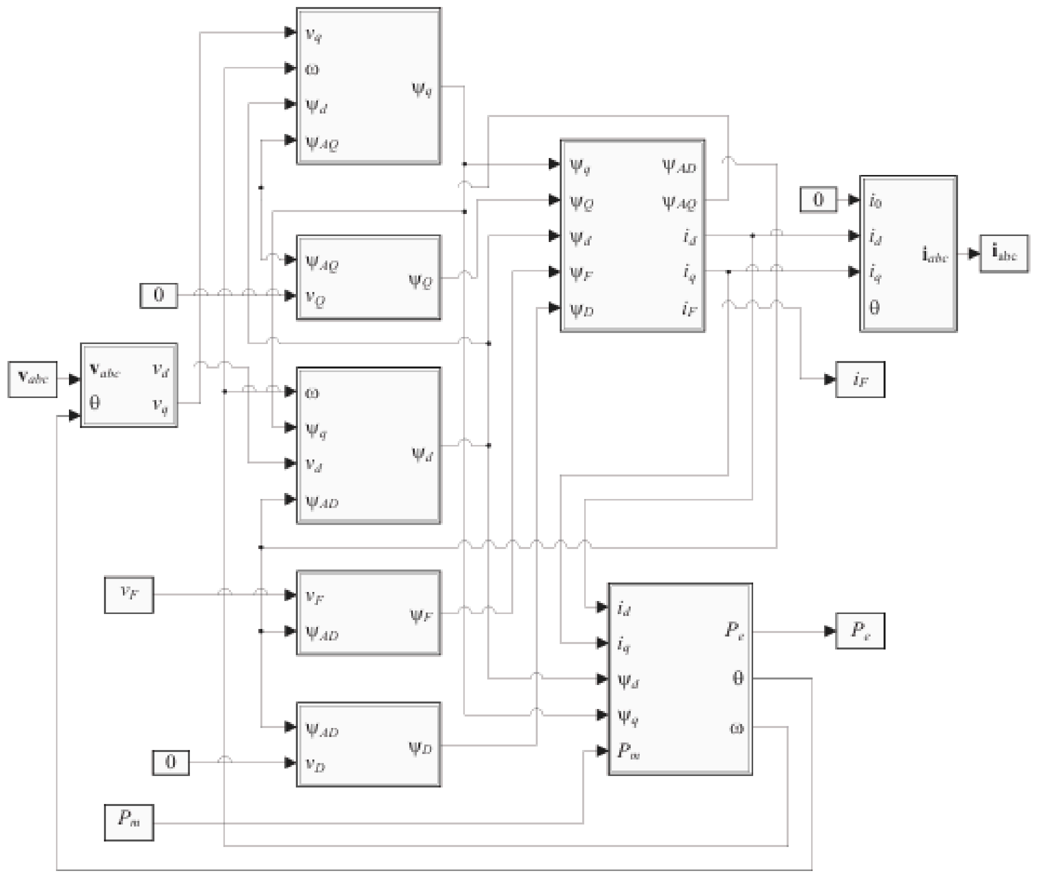


Figure 5. Complete generator system block diagram

The mathematical model of a non-salient pole synchronous generator in the dq0 reference frame is a set of coupled non-linear differential equations representing the stator and rotor circuits. Due to the complexity of the full non-linear model, especially for obtaining an analytical transfer function from V_f to V_t, a linearized and simplified model is used.

The transfer function $G(s) = \frac{\Delta V_t(s)}{\Delta V_f(s)}$ is commonly represented as a first-order system:

$$G(s) = \frac{K_g}{1 + T'_d s}$$

Where K_g is the generator gain and T'_d is the effective d-axis transient time constant, both depending on the generator parameters and the operating point.

General Form of a Second-Order Transfer Function

A common form for a second-order system is:

$$G(s) = \frac{K(1+T_z s)}{(1+T_1 s)(1+T_2 s)} = \frac{K(1+T_z s)}{1+(T_1+T_2)s+T_1T_2 s^2}$$

Or, in the standard form:

$$G(s) = \frac{K_{num} s^2 + K_{num1} s + K_{num0}}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

For the synchronous generator, this often simplifies to:

$$G(s) = \frac{K_g(1+T_3 s)}{(1+T'_d s)(1+T''_d s)}$$

3.	Time constants (unsaturated at 95°C)	Sym.	Value	Dim.
3.1	Direct-axis transient short-circuit time constant	T'd	0.73	s
3.2	Direct-axis subtransient short-circuit time constant	T"d	0.016	s

Based on typical behavior and parameters, the transfer function might look something like:

$$G(s) = \frac{0.85(1+0.15s)}{(1+0.73s)(1+0.16s)}$$

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EXCITER MATHEMATICAL MODEL

Mathematical Model of an Exciter (General Functional Blocks)

A typical exciter model (e.g., IEEE Type 1 or Type AC1A, etc.) consists of several cascaded blocks, each representing a physical or functional component. The core components are:

1. **Voltage Regulator (Amplifier):** Compares the actual terminal voltage (or a rectified and filtered version) to a reference voltage and generates an error signal. It then amplifies this error signal to provide a control voltage for the exciter.
2. **Exciter (Power Stage):** This is the main power conversion stage that takes the amplified signal from the voltage regulator and produces the DC field voltage (V_f or E_fd) for the generator's field winding. This can be a DC exciter, AC exciter with rectifiers, or a static exciter.
3. **Stabilizer (Optional but Common):** Often a Power System Stabilizer (PSS) is included to damp oscillations in the power system. It feeds a stabilizing signal back into the voltage regulator.
4. **Feedback/Measurement Blocks:** Represent the sensors, transducers, and filters that measure the generator terminal voltage and provide a feedback signal to the voltage regulator.
5. **Limits and Saturation:** Exciter output is limited by maximum and minimum voltages, and the exciter itself might have saturation characteristics.

Standard Exciter Models (IEEE Standards)

The IEEE provides detailed block diagrams and typical parameters for various types of excitation systems. These models are widely used in power system simulation software. Some common types include:

- **Type DC1A:** DC commutator exciter with a continuously acting voltage regulator.
- **Type AC1A:** AC alternator exciter with non-controlled rectifiers.
- **Type ST1A:** Static exciter (using power electronics).
- **Type ST2A/ST3A/ST4B:** More advanced static excitation systems.

Each type has its own specific block diagram, including elements like lead-lag compensators, time constants, gains, limits, and sometimes saturation functions.

2. Exciter Block (Power Stage)

This block represents the actual exciter, which converts the regulator output (V_A) into the field voltage (V_f or E_fd) for the generator. It often includes a time constant and a saturation function.

- **Input:** V_A (Voltage Regulator Output)
- **Output:** E_fd (Generator Field Voltage, also commonly denoted as V_f)
- **Transfer Function:** Often a simple first-order lag.

$$G_{exc}(s) = \frac{K_E}{1 + T_E s}$$

Where:

- K_E: Exciter gain.
- T_E: Exciter time constant.
- **Saturation:** The exciter output E_fd is subject to saturation. This is typically modeled by a non-linear function based on two saturation points, $S\_E(E\_fd1)$ and $S\_E(E\_fd2)$. The effect of saturation is often incorporated by modifying K_E dynamically or by adding a feedback term. For linearization, saturation is usually ignored or linearized around an operating point.

IEEE ST1A Exciter

IEEE ST1A exciter model

General | Advanced | Init. conditions

Tr:	0.020	s
Lead time constant Tc1:	0.01	s
Lag time constant Tb1:	0.1	s
Lead time constant Tc2:	0.01	s
Lag time constant Tb2:	0.1	s
Major regulator gain Ka:	200.0	
Major regulator time constant Ta:	0.001	s
Feedback stabilization gain Kf:	0.001	
Feedback stabilization time constant Tf:	1.0	s
Field current limit ILr:	2.0	pu
Field current limiter gain KLr:	1.0	
Regulator output upper limit Vamax:	100	pu
Regulator output lower limit Vamin:	-100	pu
Rectifier loading factor Kc:	0.038	
Execution rate:	inherit	

Help | OK | Cancel

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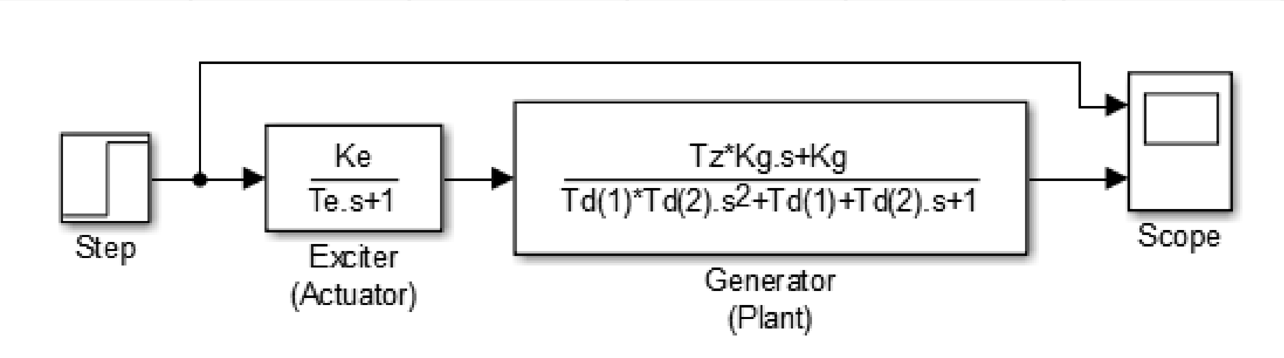
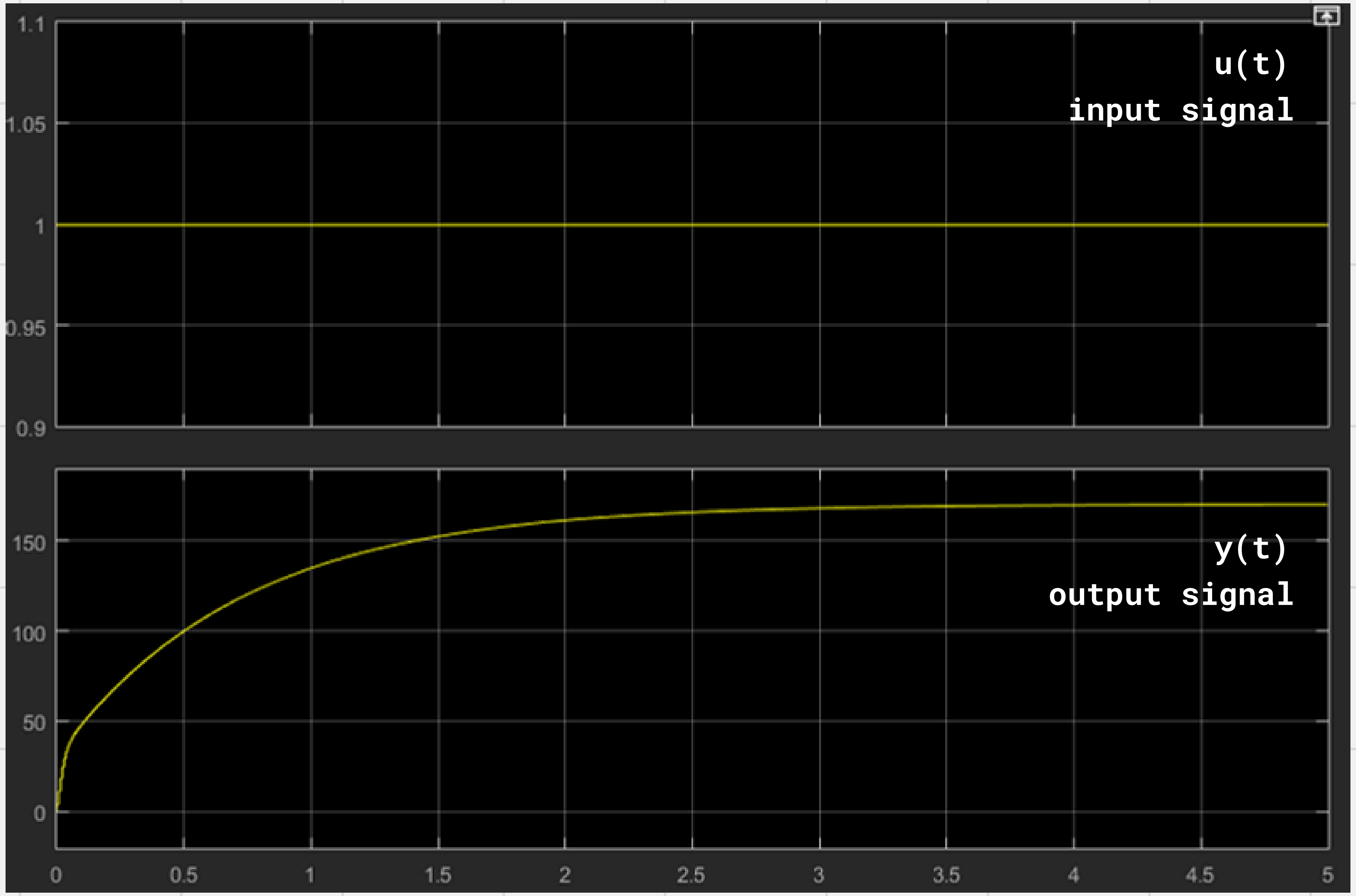
PLANT WITHOUT FEEDBACK





You can see that the output is look like the input but **the final value is lower than the input**. We call this error as "**steady state error**". which can be calculated by take limit of the different between output and input when time is infinite.

$$e_{ss} = \lim_{t\to\infty} e(t) = \lim_{t\to\infty} (u(t) - y(t))$$

(steady state error)

We can calculated this error by self but the system can't so we need to **negative feedback** the output to get **the error signal**. We will use this signal to **control the system**.

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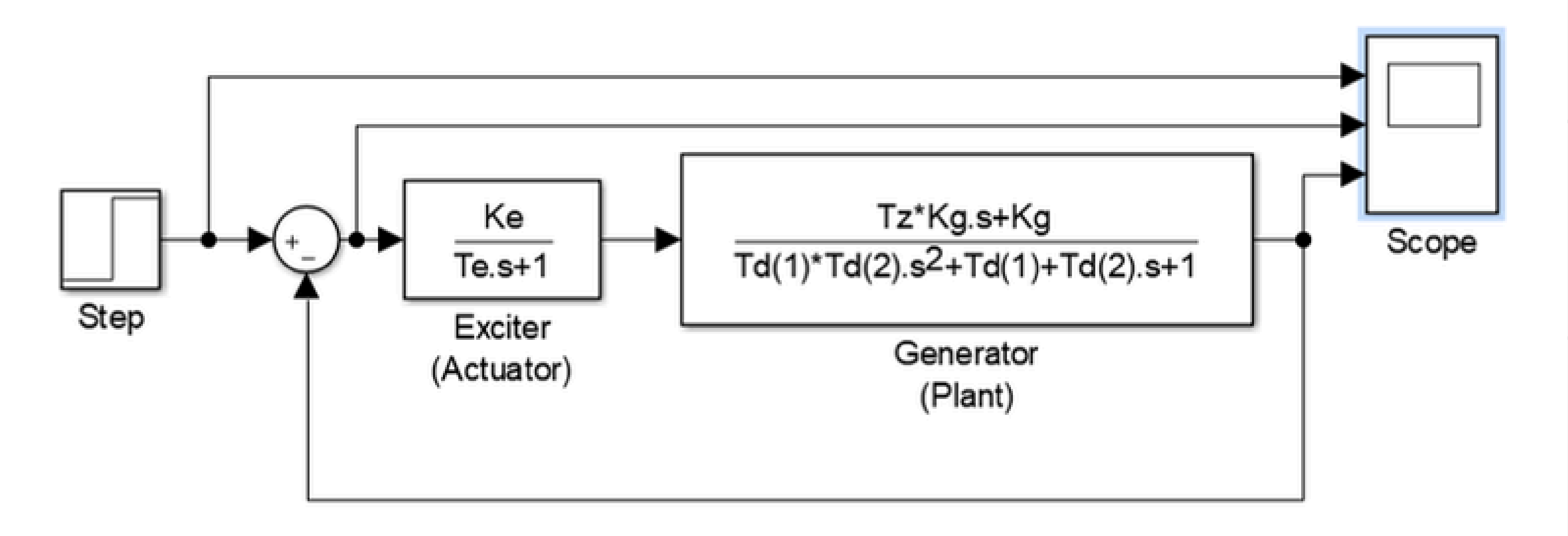
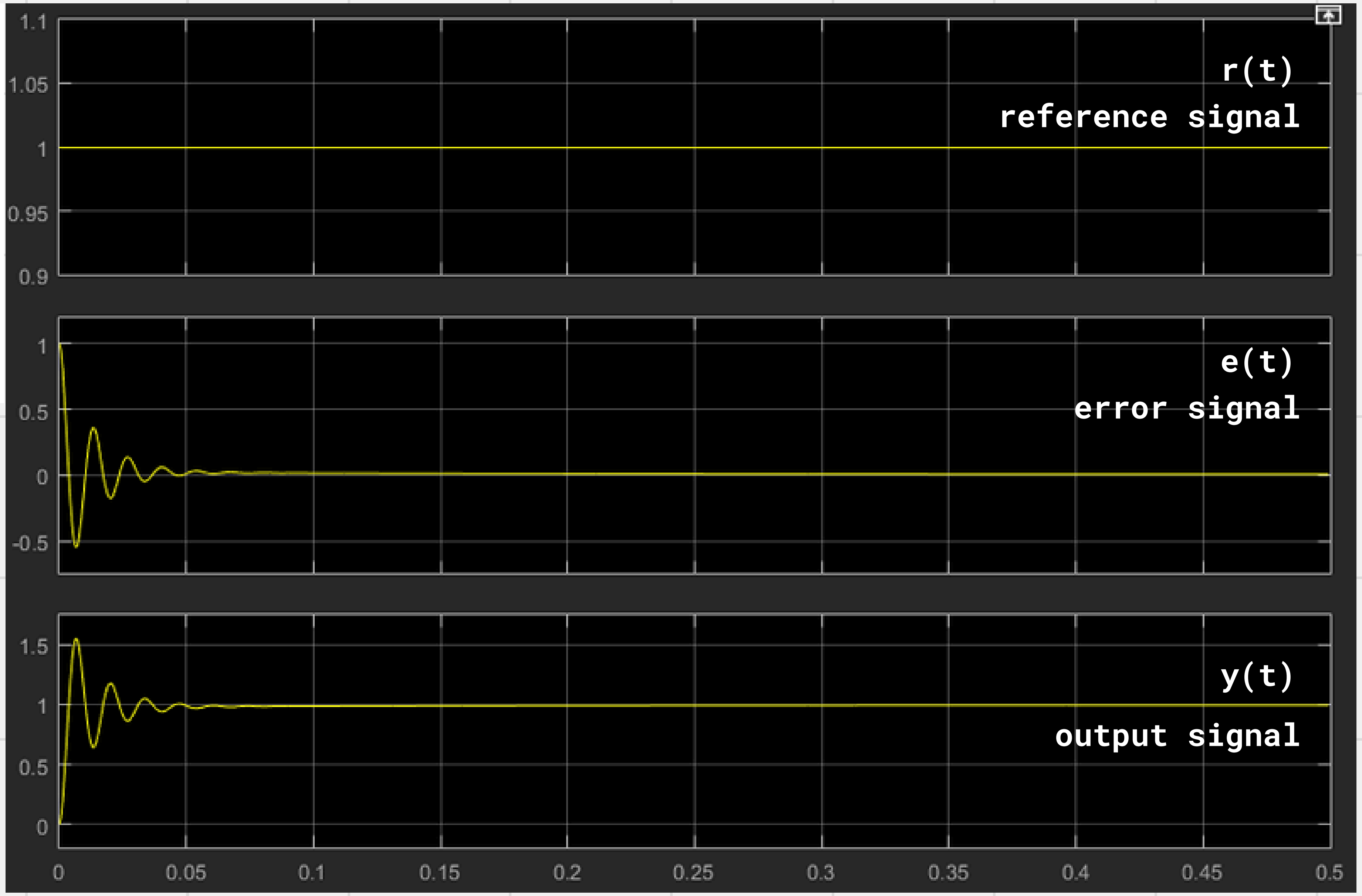
PLANT WITH UNITY FEEDBACK





$$e_{ss} = \lim_{t\to\infty} e(t) = \lim_{s\to 0} sE = \lim_{s\to 0} \frac{sR}{1+G}$$

$$R = \frac{1}{s}; \quad e_{ss} = \frac{1}{1+\lim\limits_{s\to 0} G} = \frac{1}{1+170} = 0.005848$$

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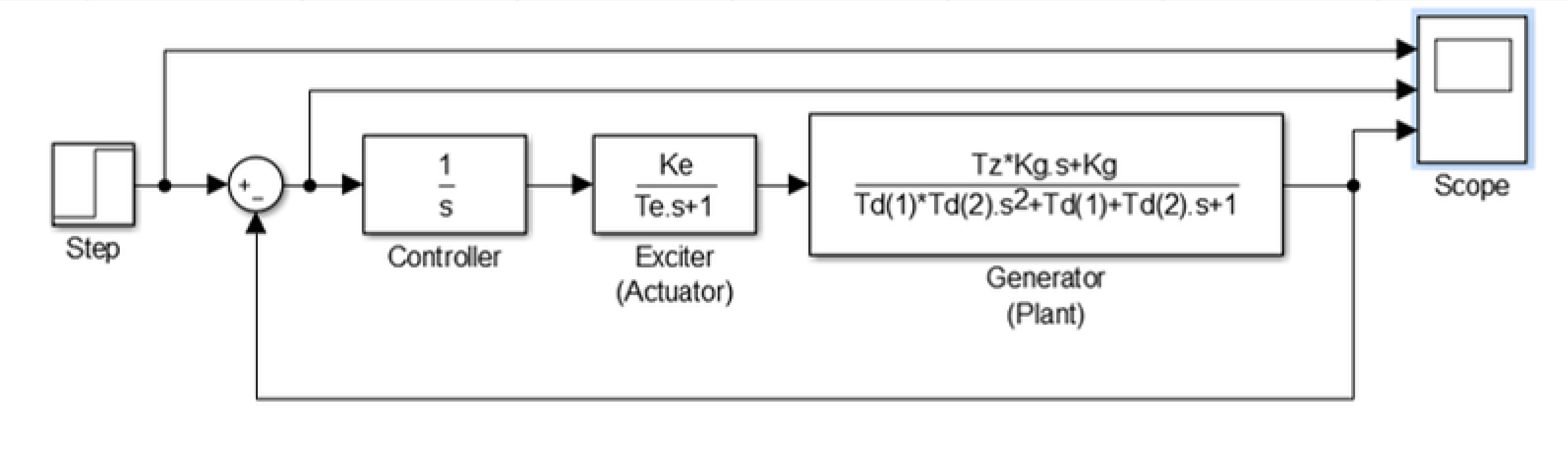
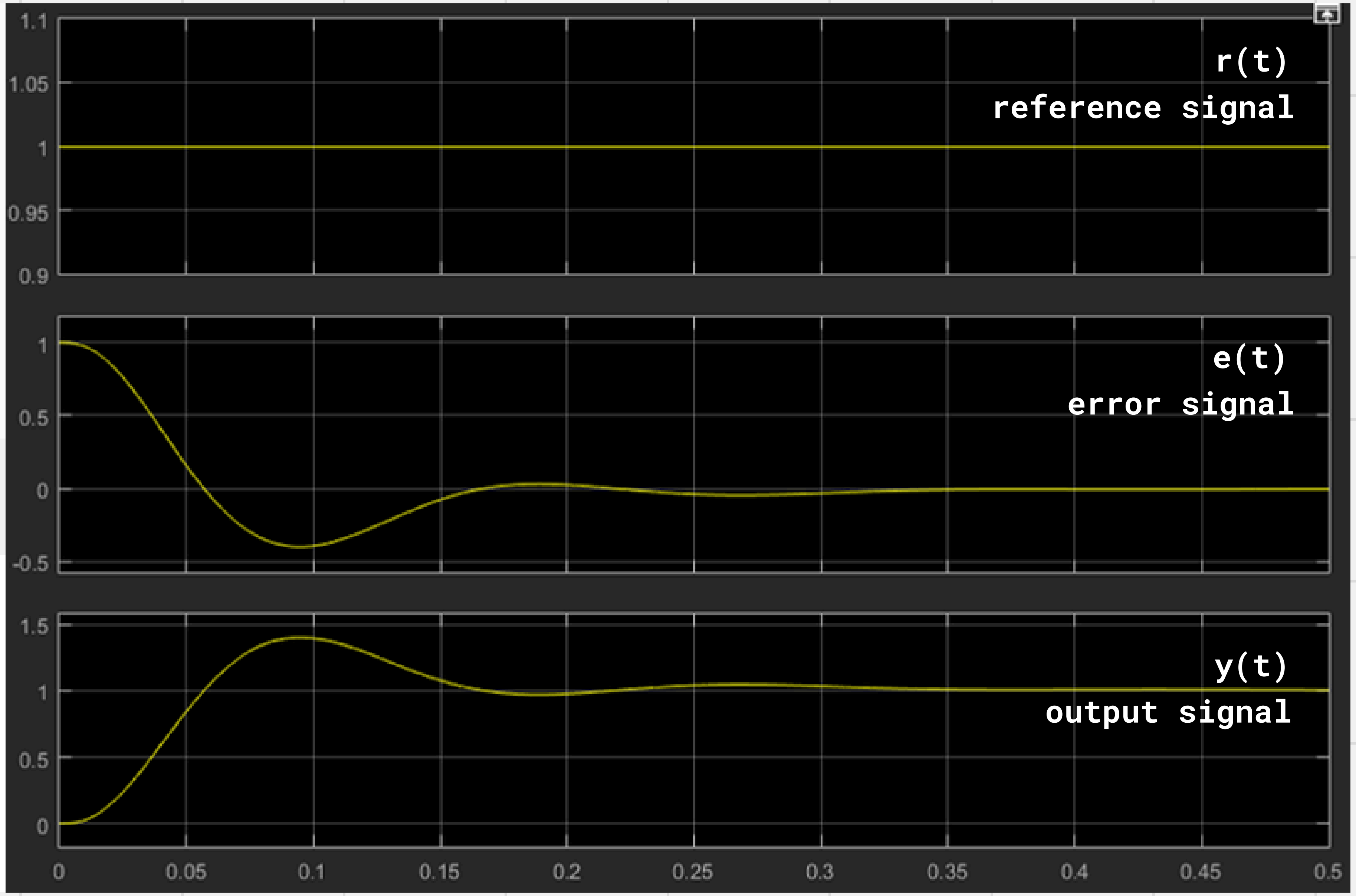
REMOVE STEADY STATE ERROR

TABLE 5-1 Summary of the Steady-State Errors Due to Step-, Ramp-, and Parabolic-Function Inputs for Unity-Feedback Systems

Type of System	Error Constants			Steady-State Error e_{ss}		
				Step Input	Ramp Input	Parabolic
j	K_p	K_v	K_a	$\frac{R}{1+K_p}$	$\frac{R}{K_v}$	$\frac{R}{K_a}$
0	K	0	0	$\frac{R}{1+K}$	∞	∞
1	∞	K	0	0	$\frac{R}{K}$	∞
2	∞	∞	K	0	0	$\frac{R}{K}$
3	∞	∞	∞	0	0	0





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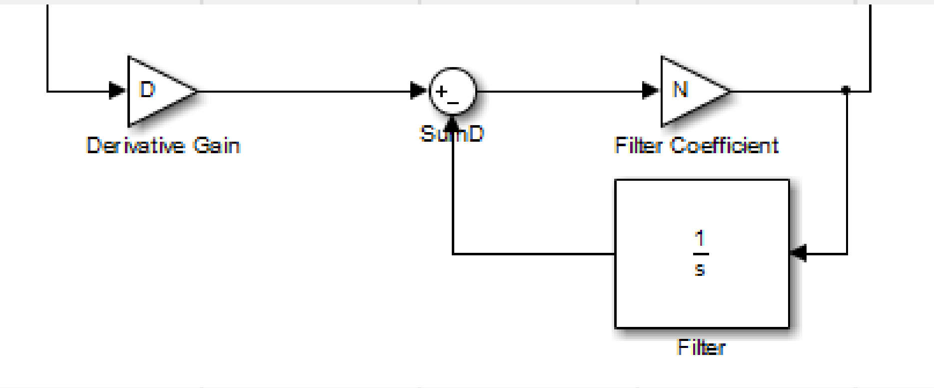
PID CONTROLLER

$$G_C = K_P + \frac{K_I}{s} + K_D s$$

$$= \frac{K_D s^2 + K_P s + K_I}{s}$$

(Ideal transfer function)



$$G_A = \frac{K_E}{T_E s + 1} \qquad G_P = \frac{K_g(T_z s + 1)}{T_d' T_d'' s^2 + (T_d' + T_d'')s + 1}$$

$$G_A \cdot G_P = \frac{170(0.15s+1)}{(0.001s+1)(0.01168s^2+0.746s+1)}$$

$$G_C = K_P + \frac{K_I}{s} + \frac{K_D N s}{(s+N)}$$

$$= \frac{(K_P + K_D N)s^2 + (K_I + K_P N)s + K_I N}{(s+N)}$$

$$= \frac{n_2 s^2 + n_1 s + n_0}{s(s+N)}$$

(Modified transfer function)

$$\begin{bmatrix} K_I \\ K_P \\ K_D \end{bmatrix} = \begin{bmatrix} 0 & 0 & N^{-1} \\ 0 & N^{-1} & -N^{-2} \\ N^{-1} & -N^{-2} & N^{-3} \end{bmatrix} \begin{bmatrix} n_2 \\ n_1 \\ n_0 \end{bmatrix}$$

$$\mathbf{K = Cn \longleftrightarrow n = C^{-1}K}$$

$$\begin{bmatrix} K_I \\ K_P \\ K_D \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0.15^1 \\ 0 & 0.15^1 & -0.15^2 \\ 0.15 & -0.15^2 & 0.15^3 \end{bmatrix} \begin{bmatrix} 0.01168 \\ 0.746 \\ 1 \end{bmatrix}$$

$$N = \frac{1}{0.15} \qquad \begin{bmatrix} K_I \\ K_P \\ K_D \end{bmatrix} = \begin{bmatrix} 0.15 \\ 0.0894 \\ -0.0117 \end{bmatrix}$$

$$G = G_A \cdot G_P \cdot G_C = \frac{170(0.15)}{s(0.001s+1)}$$

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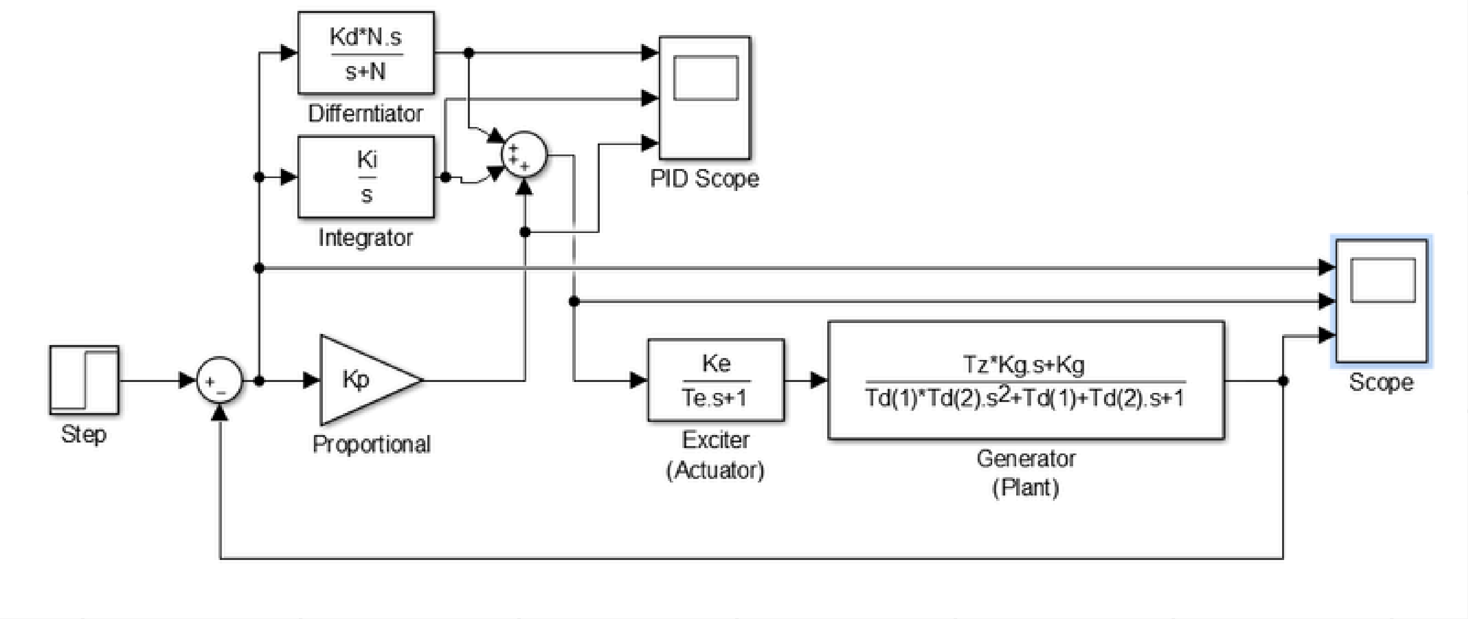
PLANT WITH PID CONTROLLER

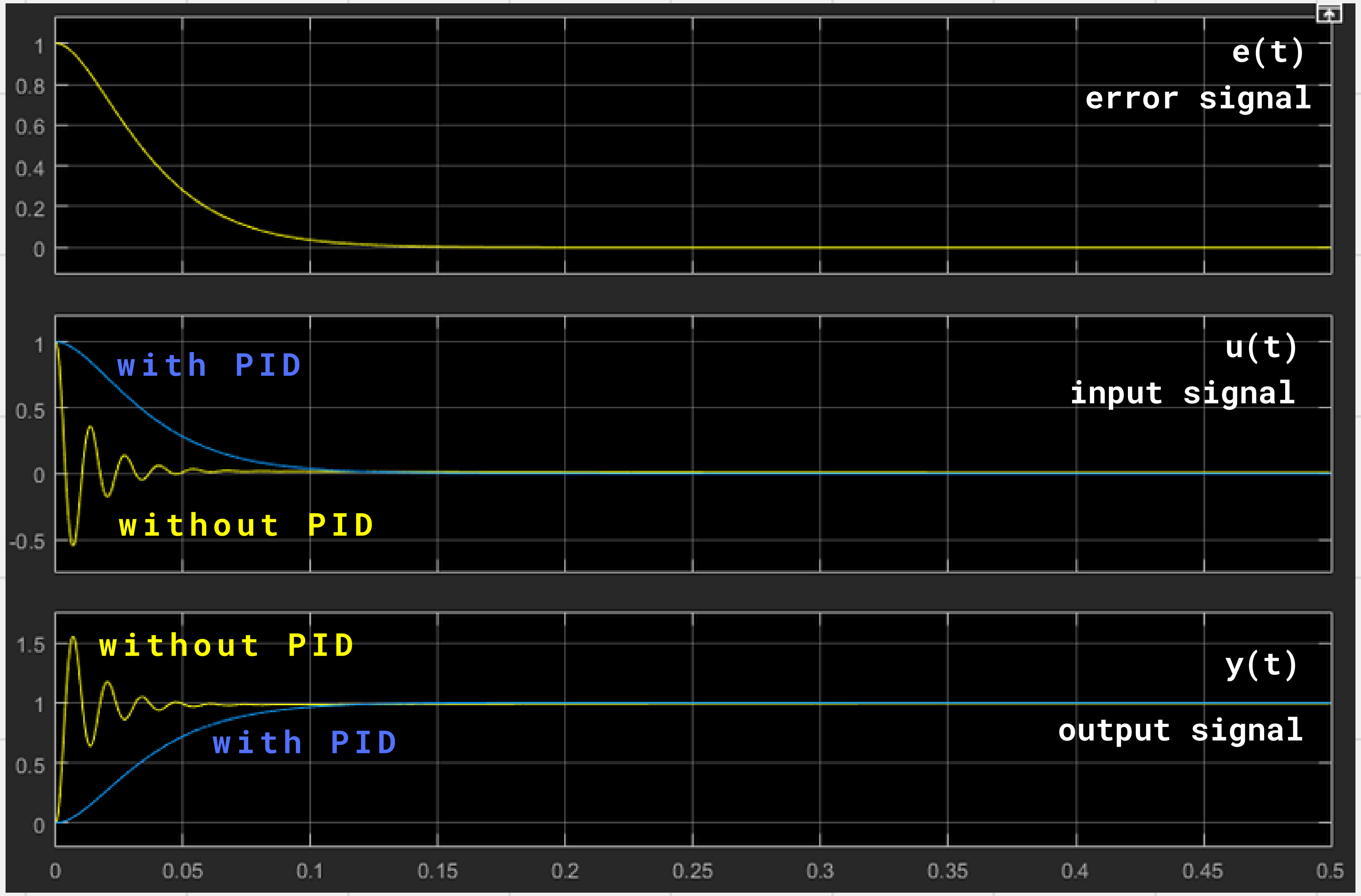
AVR_settings.m

```
Kg = 0.85;
Tz = 0.15;
Td = [0.73 0.016];

Ke = 200;
Te = 0.001;

N = 1/Tz;
n = [Td(1)*Td(2); Td(1)+Td(2); 1];
C = [0 0 N^-1; 0 N^-1 -N^-2; N^-1 -N^-2 N^-3];
K = C*n;
```

Workspace

Name	Value
C	[0,0,0.1500;0,0.1500,-0....
H	1
Kd	-0.0117
Ke	200
Kg	0.8500
Ki	0.1500
Kp	0.0894
n	[0.0117;0.7460;1]
N	6.6667
Td	[0.7300,0.0160]
Te	1.0000e-03
Tz	0.1500





The system has a settling time at **150** millisecond and **no overshoot**. That's means **the transient surge will not occur**.

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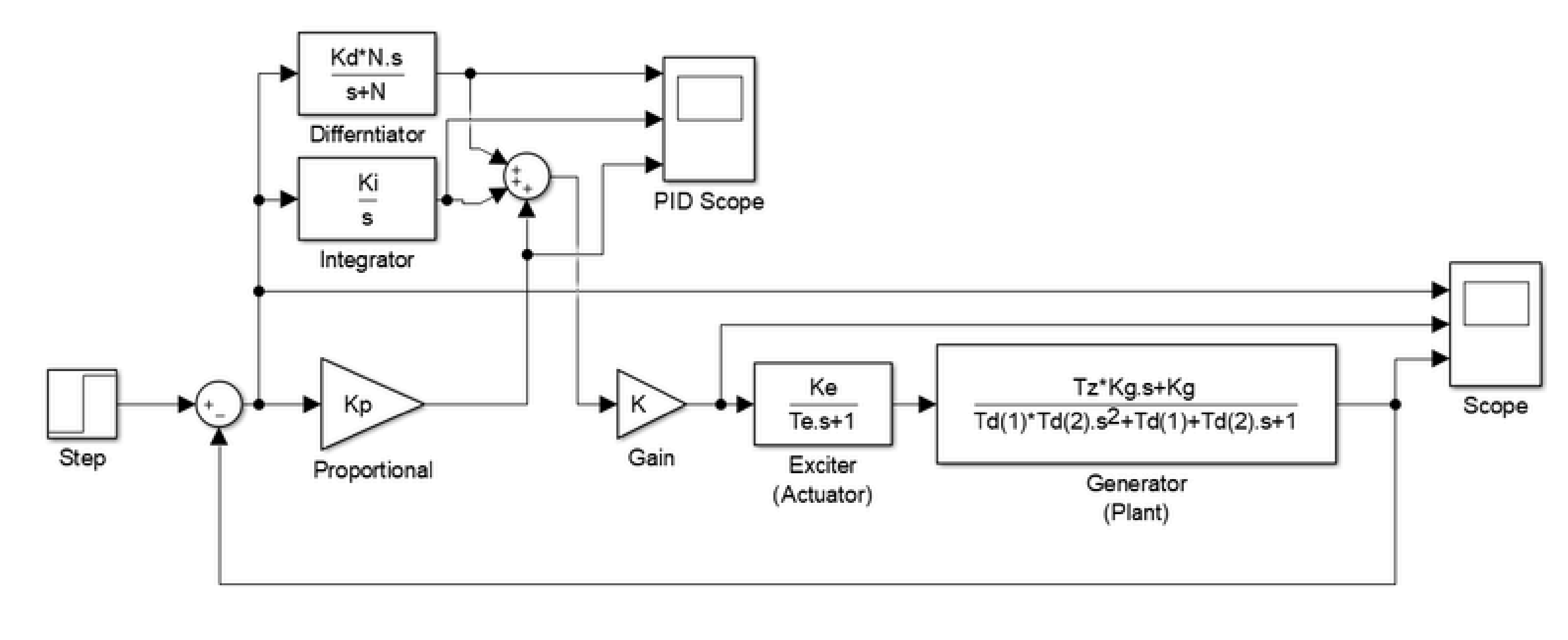
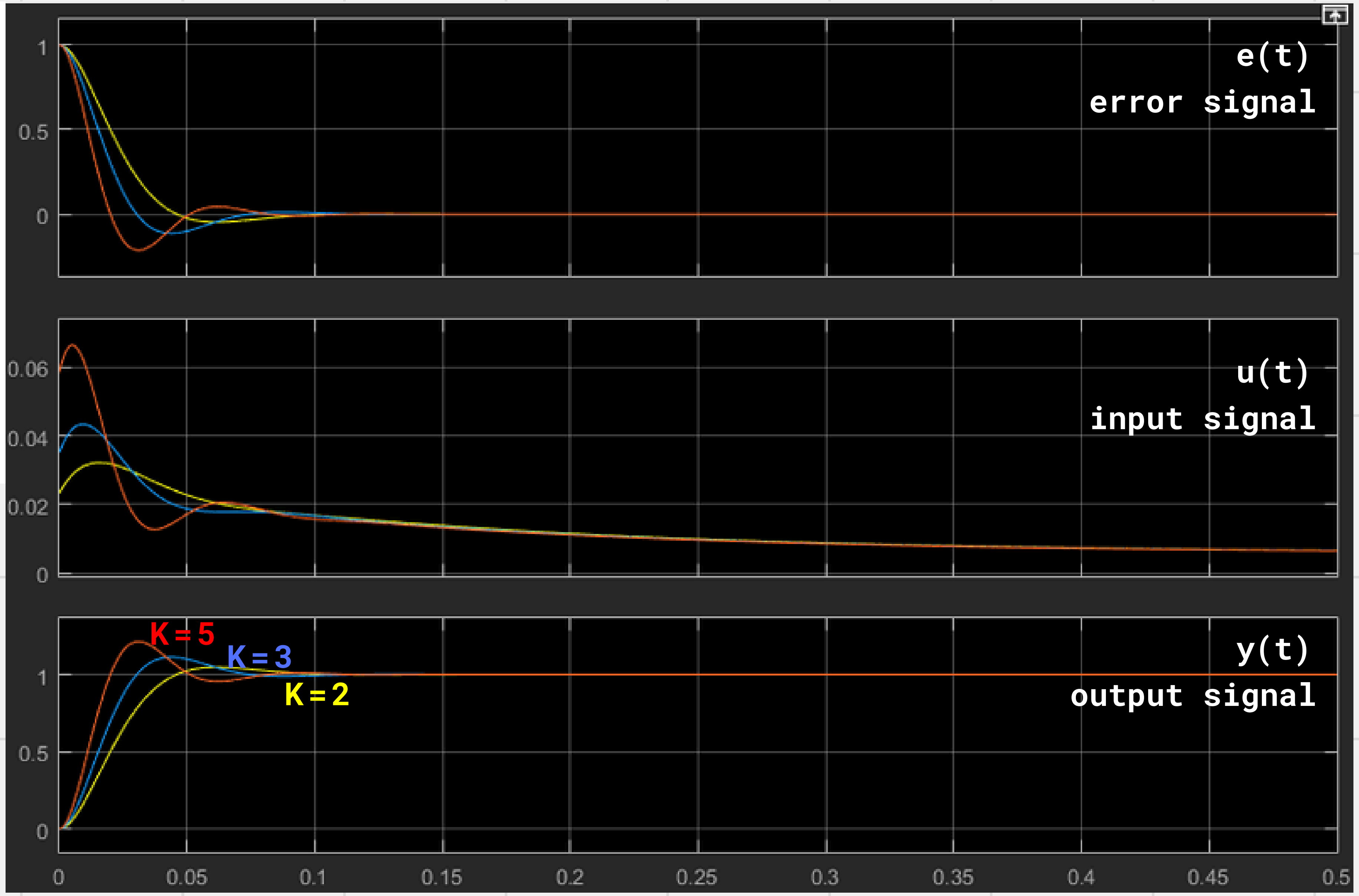
AMPLIFYING INPUT SIGNAL





K=2 t_s = 83.7 ms

K=3 t_s = 67.3 ms *(fastest transient response)*

K=5 t_s = 74.1 ms

Performance and Robustness

	Tuned	Block
Rise time	0.544 seconds	0.0298 seconds
Settling time	2.08 seconds	0.0837 seconds
Overshoot	7.02 %	4.59 %
Peak	1.07	1.05
Gain margin	34.1 dB @ 81.4 rad/s	Inf dB @ Inf rad/s
Phase margin	74.2 deg @ 2.89 rad/s	65.2 deg @ 46.3 rad/s
Closed-loop stability	Stable	Stable

K=2

Performance and Robustness

	Tuned	Block
Rise time	0.544 seconds	0.0205 seconds
Settling time	2.08 seconds	0.0673 seconds
Overshoot	7.02 %	11.2 %
Peak	1.07	1.11
Gain margin	34.1 dB @ 81.4 rad/s	Inf dB @ Inf rad/s
Phase margin	74.2 deg @ 2.89 rad/s	57.2 deg @ 64.3 rad/s
Closed-loop stability	Stable	Stable

K=3

Performance and Robustness

	Tuned	Block
Rise time	0.544 seconds	0.0136 seconds
Settling time	2.08 seconds	0.0741 seconds
Overshoot	7.02 %	21.2 %
Peak	1.07	1.21
Gain margin	34.1 dB @ 81.4 rad/s	Inf dB @ Inf rad/s
Phase margin	74.2 deg @ 2.89 rad/s	47 deg @ 93.2 rad/s
Closed-loop stability	Stable	Stable

K=5