Electrical Machines

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Servomotors

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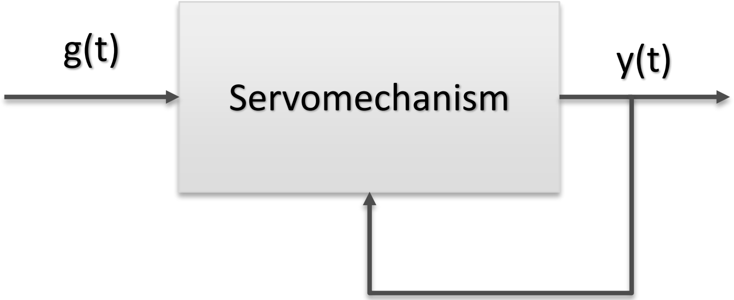
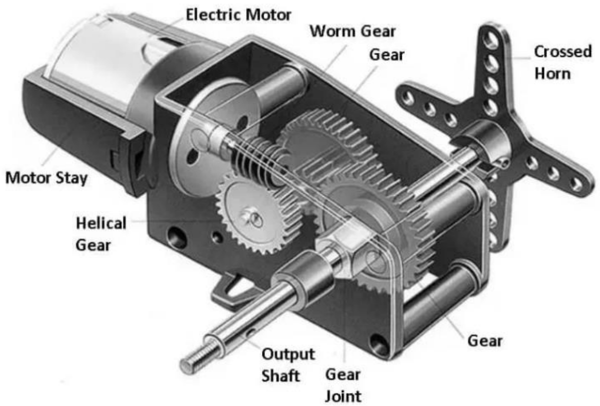
Definitions

- is a feedback system (sensors are needed)
- has large energy gain (power amplifier is needed)
- the controlled output is a mechanical position or a derived time function of this position.





- g(t) – reference (input) signal
- y(t) – output signal
- $\varepsilon(t) = g(t)-y(t)$ – tracking error

In high-performance servo, tracking error must be a zero in steady state

Requirements

- ❑ large torque at stand still
- ❑ high impulse torque so that a large acceleration and a fast response is possible
- ❑ large speed control range
- ❑ good controllability at (very) low speed
- ❑ low torque ripple
- ❑ high accuracy.

Servo types

by controlled value:

- position
- velocity
- acceleration (torque)

by actuator type:

- electric
- hydraulic
- pneumatic

Applications

Everywhere☺

Machines and mechanisms that require positioning: X-Y tables, telescopes and antennas, transportation machine (vertical), synchronized feeding (coating line), press roll feeder

Machines that require a wide transmission range: various axes of printing machines, paper-making machines, film manufacturing lines, wire drawing machines, various specialized machine feeding, various transportation machines, winders/rollers, and woodworking machines

High-frequency positioning: press feeders, bag-making machines, sheet cutting, loaders/unloaders, filling machines, various transportation machines, mounters, bonders, mounter and base inspection.

Torque control: slitters and laminators, winding devices, mold injection machines

Types of position tracking

- **Point to point**

  the requirements which are applicable are the speed to go from point A to point B together with the accuracy of the positioning and the dynamic behavior.

- **Trajectory control**

  in addition to the requirements above accurately and fluently following a predetermined trajectory is important. Fluent means a speed change of maximum 0.1% during one revolution of the motor shaft

Types of position tracking

The device can operate in both modes

Example: telescopes

When telescope is finding new space object it is operating in **point-to-point mode**.

When telescope has already found the object and it starts to estimate this moving object, it operates in **trajectory mode (or tracking mode)**

Types of position tracking

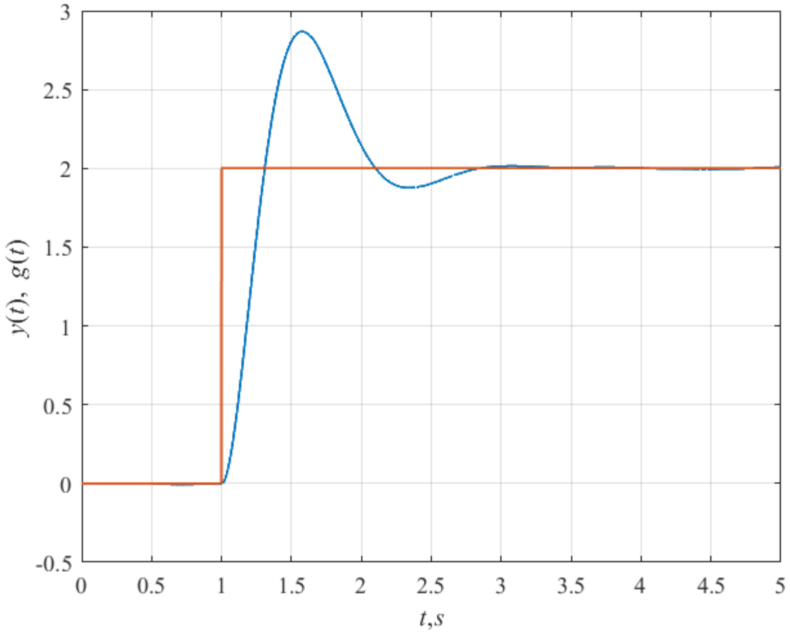
Examples:

- If we need to rotate some device from 90° to 240° with maximal velocity 15°/s and mean squared error of positioning must be less than 0.1° - **it is problem of point-to-point control.**

- If we need to rotate some device continuously with mean squared error of angular position less than 0.2° - **it is problem of trajectory control.**

Types of input signals

➢ **Constant signal**

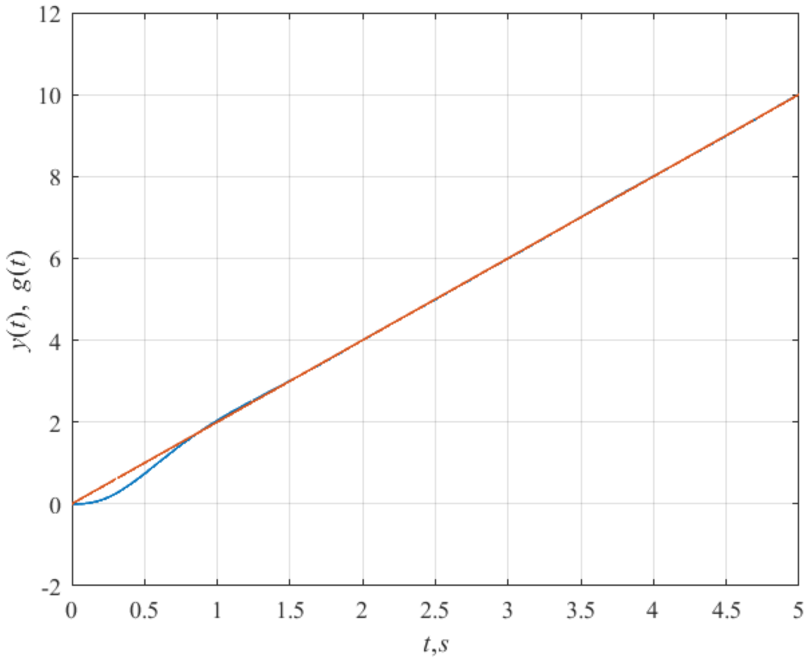


orange curve – input signal

blue curve – output signal (probable variant)

Types of input signals

➢ **Constant rate of change**

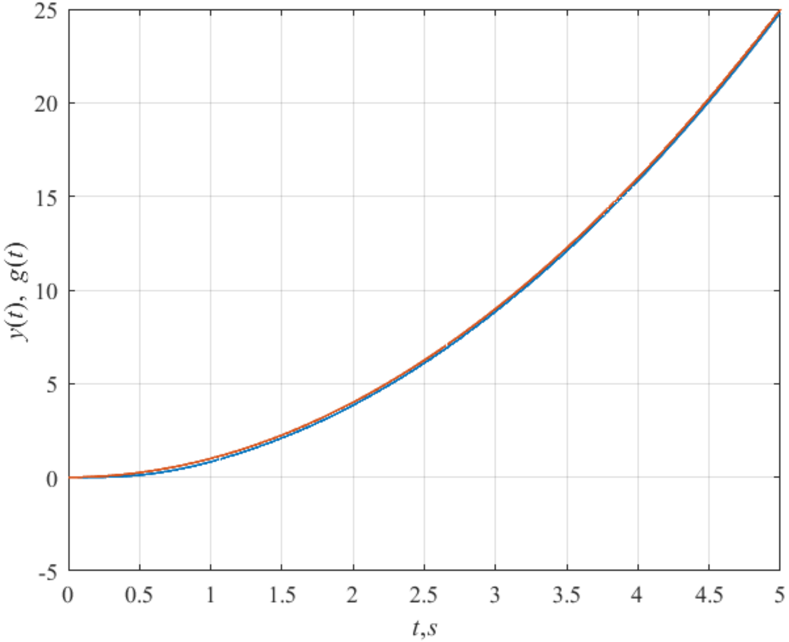


orange curve – input signal

blue curve – output signal (probable variant)

Types of input signals

- **Constant rate of acceleration**



orange curve – input signal

blue curve – output signal (probable variant)

Performance of servo

- **Type 0**

  under steady-state conditions they produce a constant value of the output with a constant error signal

- **Type 1**

  under steady-state conditions they produce a constant value of the output with null error signal, but a constant rate of change of the reference implies a constant error in tracking the reference

- **Type 2**

  under steady-state conditions they produce a constant value of the output with null error signal. A constant rate of change of the reference implies a null error in tracking the reference. A constant rate of acceleration of the reference implies a constant error in tracking the reference.

Electrical servos

Structure

Basically, electrical servos consist of two main parts:

- **Servo drive**

  Electronic amplifier used to power electric servomechanisms.

  A servo drive monitors the feedback signal from the servomechanism and continually adjusts for deviation from expected behavior.

  Servo drives can operate with analog or digital signals. The most of modern servos are digital

Structure

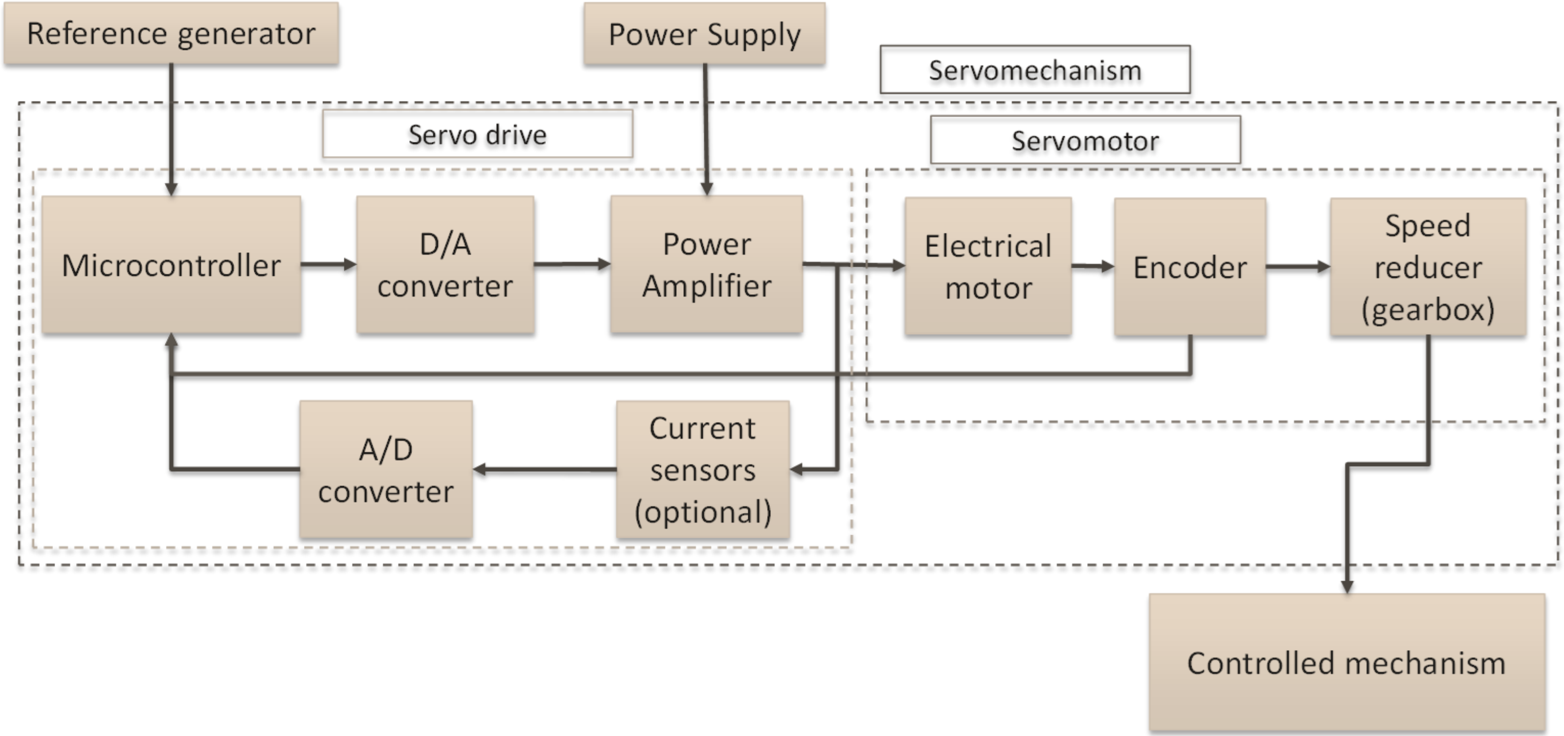
- **Servomotor**

  A rotary actuator or linear actuator that allows for precise control of angular or linear position, velocity and acceleration. It consists of a suitable motor coupled to a sensor for position feedback.

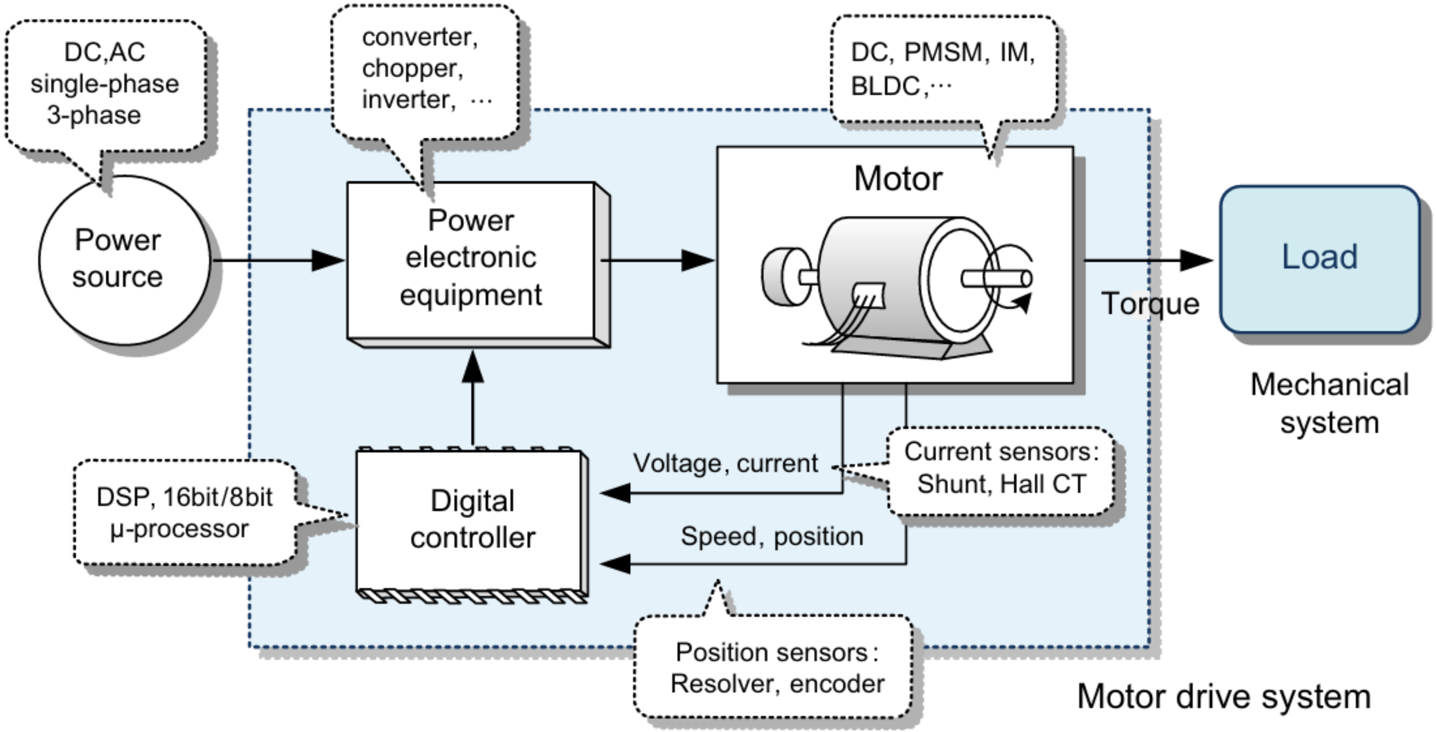
  Almost any type of electrical motors can be used in servomotors:

  - ✓ DC-motors
  - ✓ PMSM
  - ✓ BLDC
  - ✓ Induction motors

Structure of servo



Structure of servo



PMSM

Advantages

- Maintenance-free
- Excellent environmental resistance
- Capable of large torque
- Power generation braking is possible at time of power failure
- Compact, lightweight
- High power rate
- Low torque ripples

Disadvantages

- Servo amplifier is somewhat more complicated than that for a DC motor
- Correspondence of 1:1 motor and servo amplifier necessary
- Risk of magnet demagnetization
- Rather expensive

Good choice for high-performance applications in wide range of speeds

BLDC

Advantages

- Maintenance-free
- Excellent environmental resistance
- Capable of large torque
- Power generation braking is possible at time of power failure
- Compact, lightweight
- High power rate
- Rather simple control

Disadvantages

- Servo amplifier is somewhat more complicated than that for a DC motor
- Correspondence of 1:1 motor and servo amplifier necessary
- Risk of magnet demagnetization
- Presence of torque ripples

Good choice for compact high-speed & low performance applications

Induction motors

Advantages

- Maintenance-free
- Excellent environmental resistance
- Capable of high speeds and large torque
- Good efficiency in a large capacity
- Robust structure

Disadvantages

- Servo amplifier is somewhat more complicated than that for a DC motor
- Braking is not possible with a power failure
- Characteristics change according to temperature
- Correspondence of 1:1 motor and servo amplifier necessary

Good choice for industrial high-power applications and traction applications in wide speed range

➢ DC motors

❑ Advantages

- Configuration of the servo amplifier is simple
- Power generation braking is possible with a power failure
- Low cost with a small capacity
- High power rate

❑ Disadvantages

- Maintenance and periodic inspection around the commutator is necessary
- Generation of brush abrasion powder; difficult to use in clean places
- Cannot be used with high-speed large torque in relation to a commutating brush
- Risk of magnet demagnetization

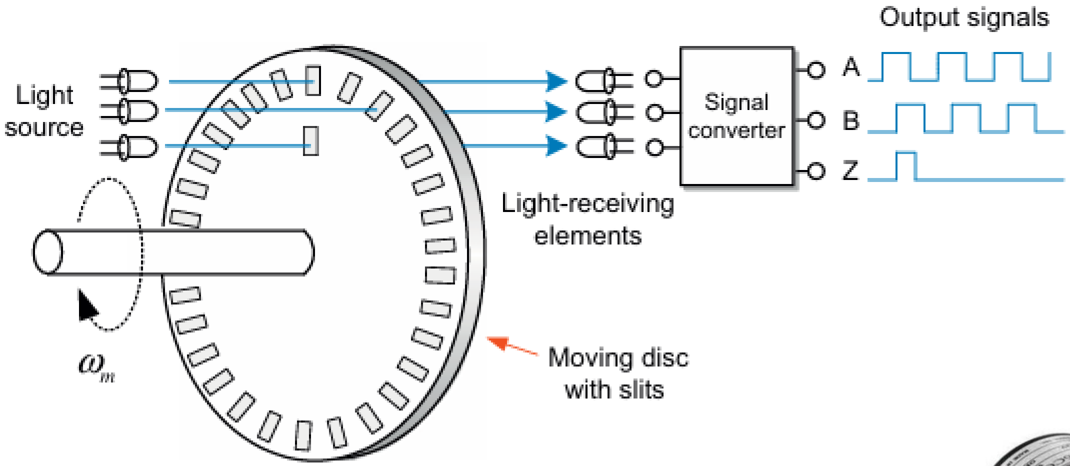
Good choice for prototyping, modelling, low-cost applications.

Periodic maintenance and inspection are needed

Position sensors

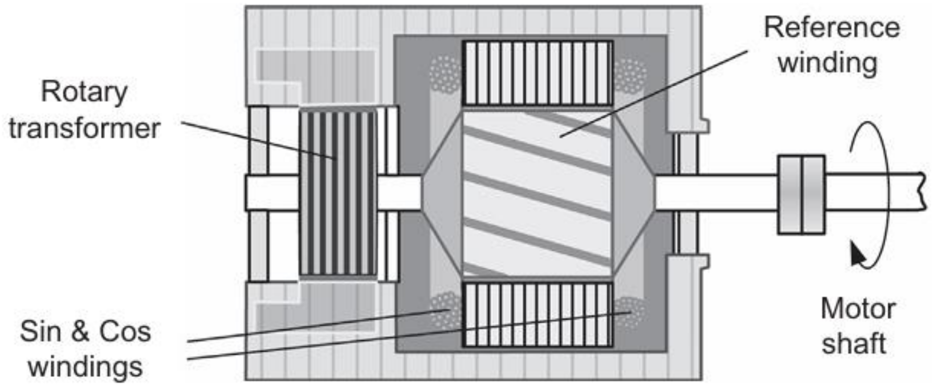
- Resistive potentiometers
  - Cheap and simple
  - Analog output signal
  - Low accuracy
  - Presence of electrical noise
- Rotary encoder (incremental or absolute)
  - Rather expensive
  - Digital output signal
  - High accuracy (depends on cost) up to 2^{26} counts per resolution
- Hall sensors
- Synchros (Selsyn)
- Resolver (Rotary electrical transformer)

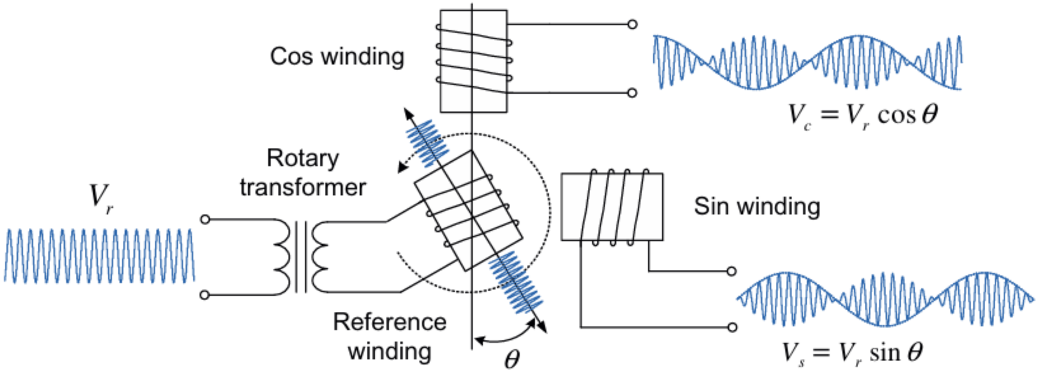
Rotary encoders



ITMO

Resolver





Some issues of working with sensors

If we operate with real sensors, we usually don’t measure the values in their physical units.

Instead of this we measure signals in units of each sensor.

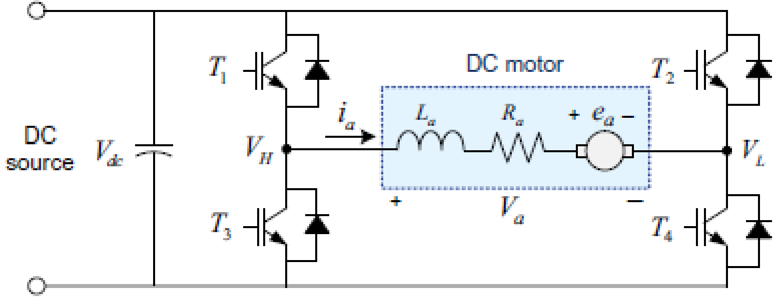
Examples

Consider optical encoder which has 1000 units per one revolution of the motor. It means that if we’ll see for example 500 units as the output of the sensor, it means that the real angle is 180° and so on.

Accuracy of this sensor can’t be higher than 1 unit = 360/1000 = 0.36°.

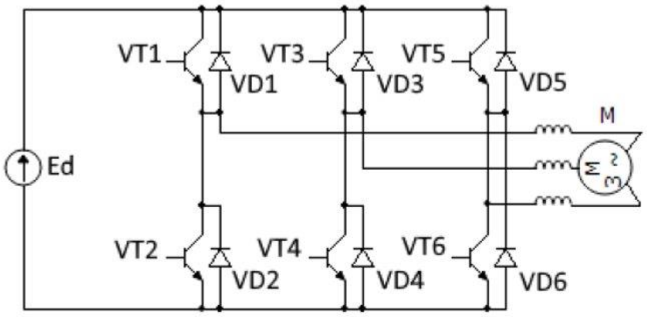
Amplifiers

- **DC motors**



H-bridge

- **AC motors**

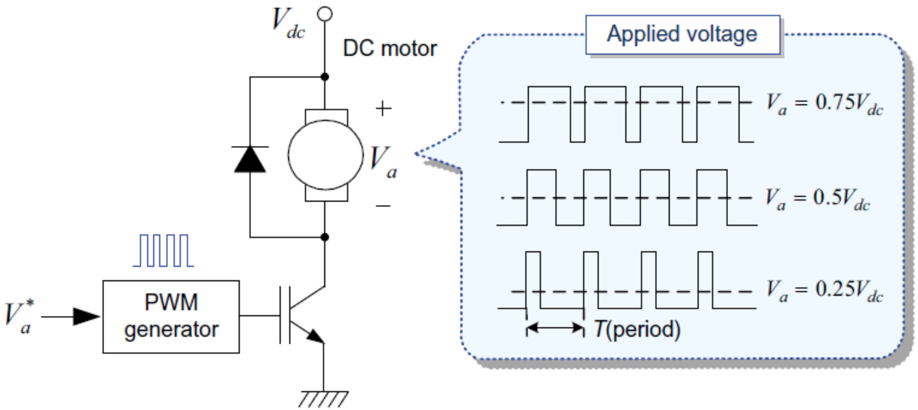


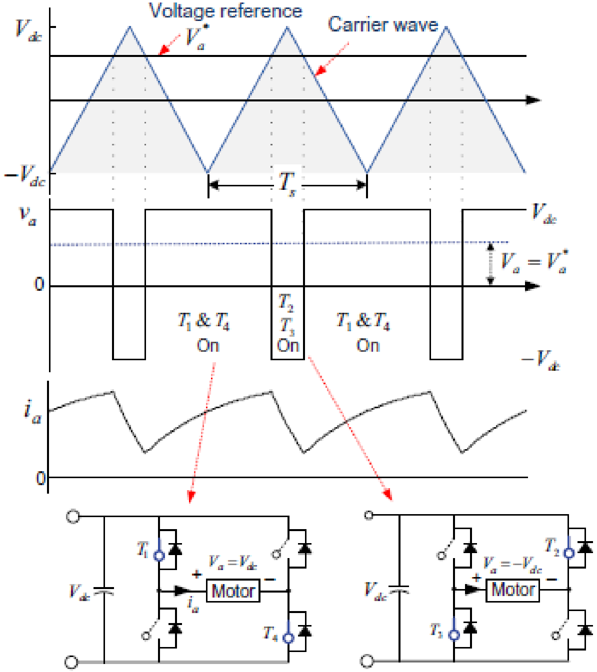
3-phase inverter

MOSFET or IGBT are used as power switches in such electronic devices

Amplifiers

Pulse-width modulation (PWM) technique is used to control input power of servomotor





Input power is proportional to duration of pulses

Amplifiers

Example

Consider the DC motor with H-bridge PWM power amplifier that operates at frequency F_s = 1 kHz. Rated voltage of DC power supply is Udc = 48 V. Reference signal Uc can change from -1 to 1.

In this case PWM period is equal 1/ F_s = 1 ms.

If Uc = 0, duration of positive and negative pulses will be the same and equal to 0.5 ms, average voltage at the input of the motor will be 0 V.

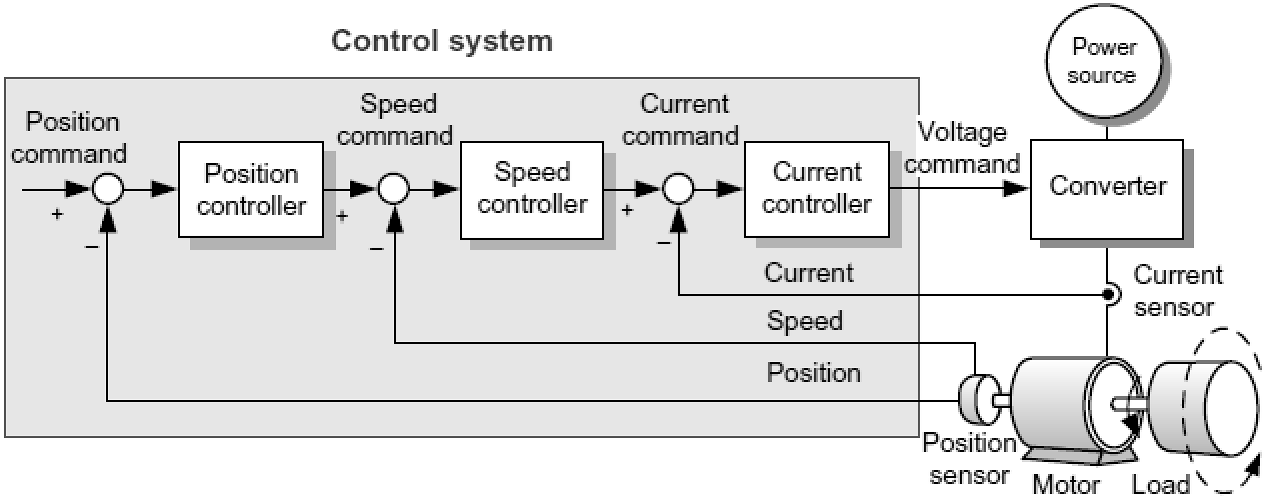
If Uc = 0.2, duration of positive pulse duration will be (0.5 + Uc/2) = 0.6 ms, negative pulse duration will be (0.5 - Uc/2) = 0.4 ms, average voltage at the input of the motor will be Uc* Udc = 9.6 V.

Amplifiers

Example

If $U_c = -0.4$, duration of positive pulse duration will be $(0.5 + U_c/2) = 0.3$ ms, negative pulse duration will be $(0.5 - U_c/2) = 0.7$ ms, average voltage at the input of the motor will be $U_c * U_{dc} = -19.2$ V.

Control



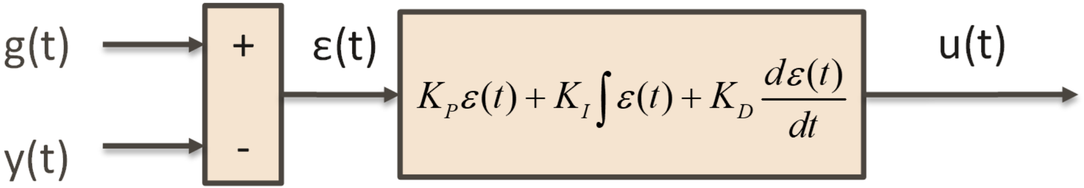
Configuration of the motor control system

Control

Controllers for servomotor is implemented on a microcontroller. The allowable complexity of the control law depends on the performance rate of the microcontroller.

For servomotors feedback-based control laws are used.

The simplest, popular and widely used controller is a proportional–integral–derivative one (PID controller or three-term controller)



Task (3 points)

Design the feedback control system for the speed of the DC motor with PM excitation.

Initial data:

№	Name of data	Notation	Unit of measurement
1	Rated DC supply voltage	V_rated	V
2	Armature resistance	Ra	Ohm
3	Armature inductance	La	H
4	Back-EMF constant	Ke	V*s/rad
5	Rated torque	T_rated	Nm
8	Inertia	J	kg*m^2
9	Rated speed	n_rated	rev/min

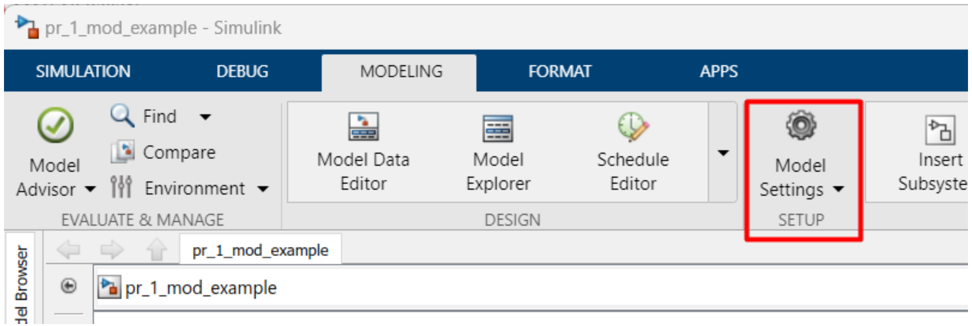
Task (3 points)

Open Matlab and create m-file

```
V_rated = 24; % V
Ra = 1.600; % Ohm
La = 0.011200; % H
Ke = 0.458; % V*s/rad
Kt = Ke; % torque constant
T_rated = 1.4; % Nm
J = 0.004440; % kg*m^2
n_rated = 300; % rev/min
```

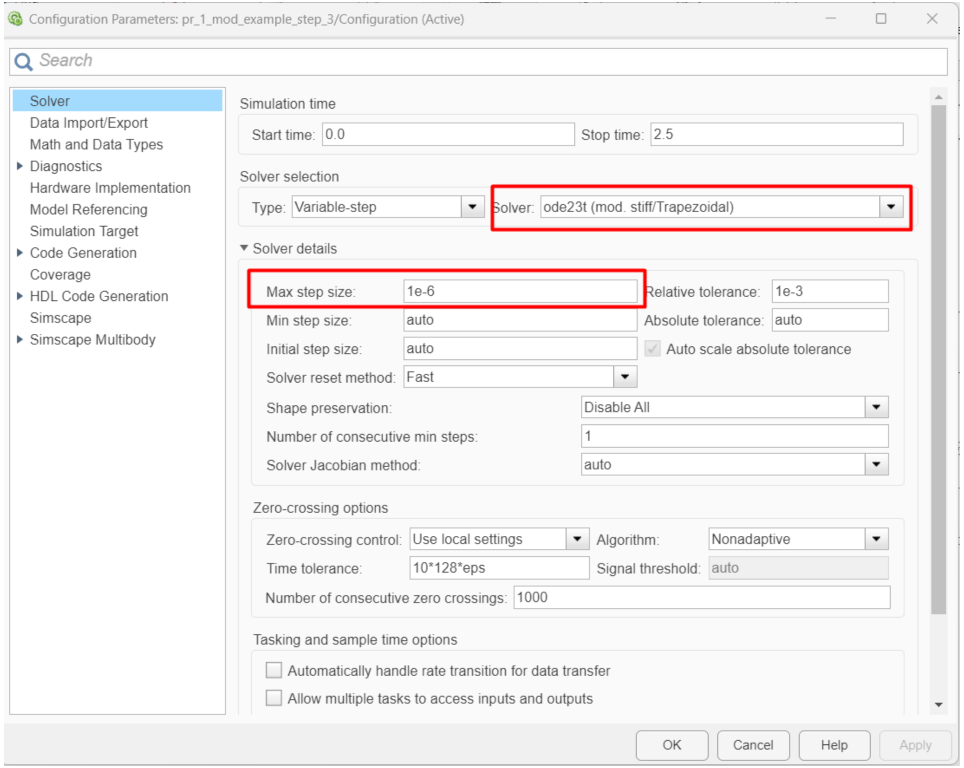
Task (3 points)

Create new model and open Model Settings



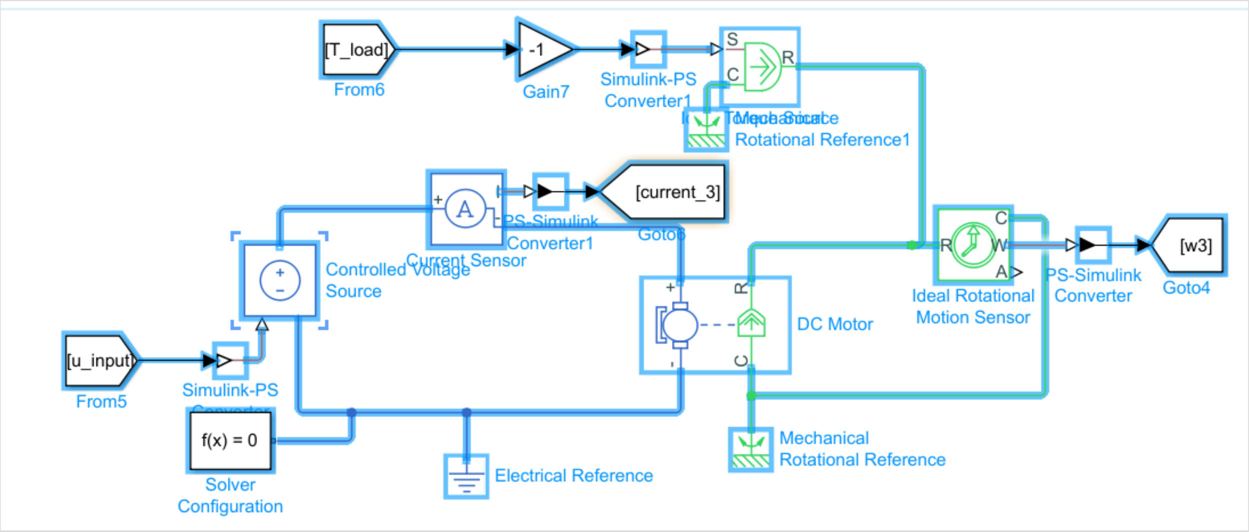
Task (3 points)

Change the settings as follows



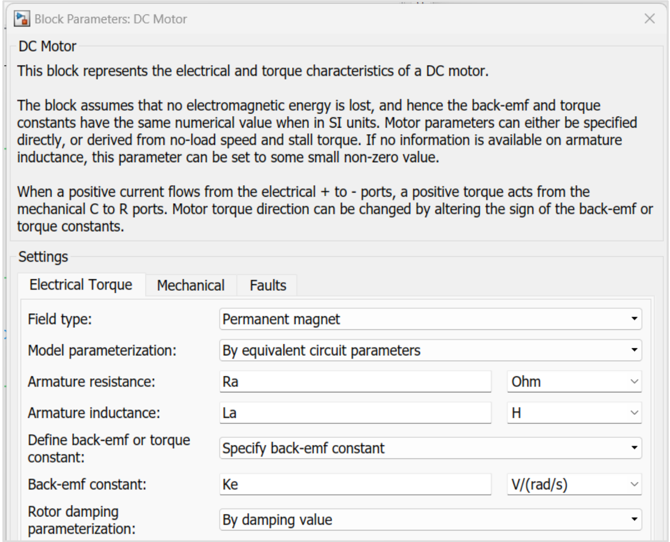
Task (3 points)

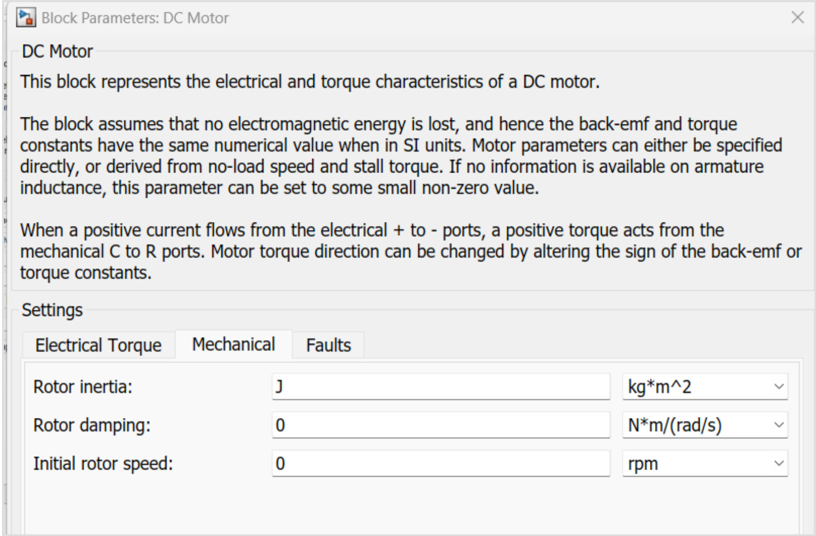
Simscape model



Task (3 points)

Simscape model





Task (3 points)

Transfer function of DC motor with PM excitation

$$\frac{\omega_m(s)}{u(s)} = \frac{U_{rated}\dfrac{K_T}{JL_a}}{s^2 + \dfrac{R_a}{L_a}s + \dfrac{K_T K_E}{JL_a}} = \frac{U_{rated}/K_E}{\left(\dfrac{JR_a}{K_T K_E}\dfrac{L_a}{R_a}s^2 + \dfrac{JR_a}{K_T K_E}s + 1\right)} = \frac{U_{rated}/K_E}{\left(T_m T_a s^2 + T_m s + 1\right)}$$

$$K_E = K_T$$

K_E – back-emf constant

K_T – torque constant

Task (3 points)

If $T_m \gg T_a$:

$$\frac{\omega_m(s)}{u(s)} = \frac{U_{rated} / K_E}{\left(T_m T_a s^2 + T_m s + 1\right)} \approx \frac{K_{ob}}{\left(T_m s + 1\right)\left(T_a s + 1\right)}$$

Here we can use PI controller with follows transfer function:

$$W_c(s) = \frac{K_p\left(T_I s + 1\right)}{T_I s}$$

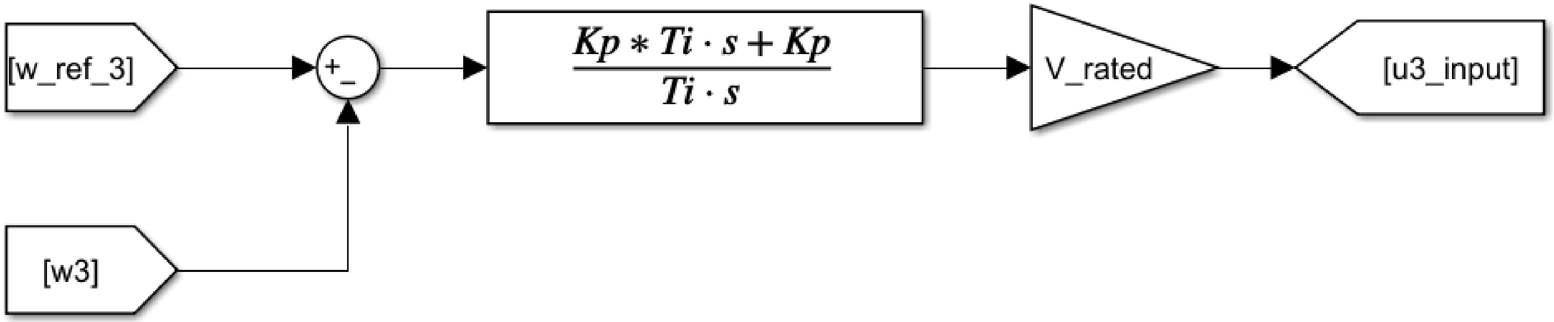
The coefficients of the controller can be defined as follows:

$$T_I = T_m$$

$$K_p = \frac{T_m}{2 T_a K_{ob}}$$

Task (3 points)

Implementation



Task (3 points)

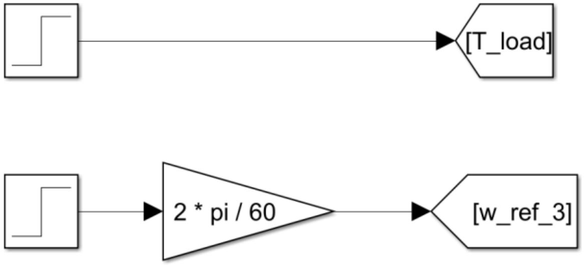
Simulation 1

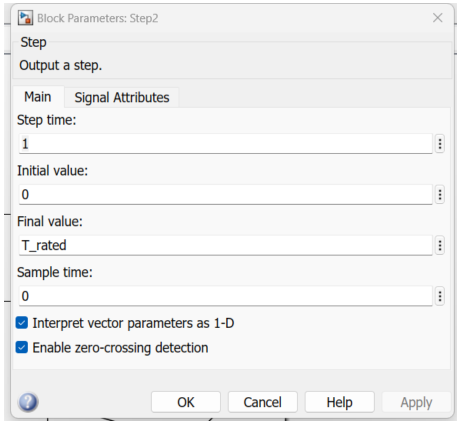
Simulation time 1.5 sec. Initial speed reference – 0 rev/min, initial load – 0 Nm. At the time of 0.5 sec the step of reference speed (to n_rated) is applied to the input of the system. At the time 1 sec the step of load torque (to T_rated) is applied to the input of the system.

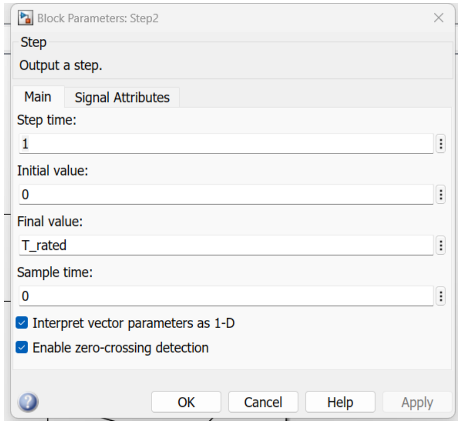
Plot the graphs:

- reference speed and motor speed
- speed adjusting error (w_ref – w_motor)

Task (3 points)







Task (3 points)

Simulation 2

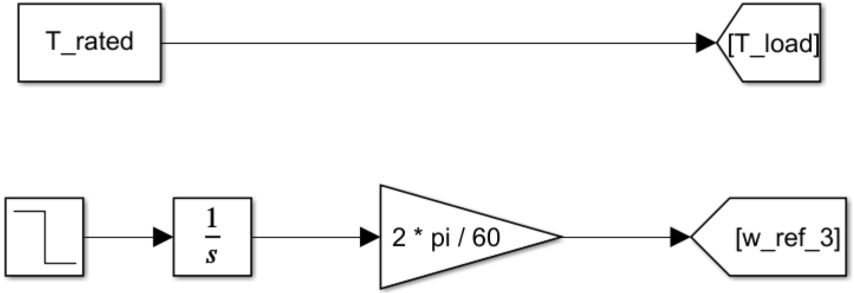
Simulation time 2.5 sec. Initial speed reference – 0 rev/min, initial load is constant and equal to rated torque. During the first 2 seconds the reference speed increases linearly with acceleration of 0.5 * n_rated per second.

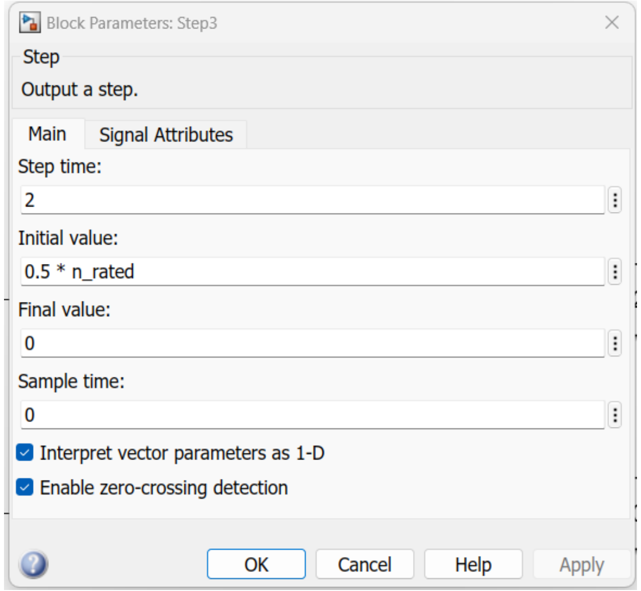
Plot the graphs:

- reference speed and motor speed
- speed adjusting error (w_ref – w_motor)

Using simulation results define the type of the servo (0, 1 or 2).

Task (3 points)





Task (3 points)

Report requirements

Report must contain:

- your name in English, your HDU and ITMO numbers, your photo.
- good resolution screenshots of your model of DC motor with control system
- good resolution figures from simulations (white background, legend, unit of measurements).
- values of all calculated coefficients of the PI controller.
- listing of your m-file with calculations.
- conclusion.

Reports should be uploaded to the folder in DingTalk chat.

[HDU-AT3-24] Electrical Machines/Student_works/Servo Reports

Task (3 points)

Report requirements

Deadline for report: 2024/10/15

Penalties:

- inaccurate figures: - 0.5 points
- skipping the deadline: - 0.5 points
- no conclusions or inadequate conclusion: - 0.5 points
- incorrect calculations: - 1.5 points

IN THE CASE OF PLAGIARISM IN ANY PART OF THE LAB, ALL PARTS OF DC LAB WILL BE EVALUATED BY ZERO POINTS. THE FACT OF PLAGIARISM WILL BE REPORTED TO THE FACULTY.

Thank you!

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