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Rotational Speed Control

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1 INTRODUCTION

Variable speed electric drives are among the basic elements in mechanical engineering, textile industry, transport equipment etc. The speed control is a classical control problem. The development of dynamic models of the variable speed electric drives with or without load corresponds to the demands of practice. The experiment complies with these requirements. The load is caused by a motor in a generator operation and can be varied with a number of resistors.

The main aims of this experiment are:

1. To develop a mathematical model of the process based on a theoretical analysis and to transform it into the simulation program Matlab and Simulink and perform simulation experiments.

2. To investigate the properties of the model through simulation experiments. The actual measured dynamic behavior of the process is available for the verification.

3. The focus of the programming work is to the development of Simulink programs that describe this dynamic system in the configuration with fixed and with flexible coupling between motor (source) and tachogenerator (measured output).

2 PROCESS DESCRIPTION

The control process (Fig. 1) includes a DC motor (M) and a generator (D). The rotational axes of both parts are coupled with the clutch (EC). The coupling can be elastic or solid. The speed of the generator is measured by the tachogenerator (SM), which is firmly coupled with the generator. The rotational speed of the DC motor is controlled by the armature voltage u_M. The output signal is the voltage of the tachogenerator u_{SM}. The controlled variable is the speed of the generator n or the angular velocity $\omega_D = \omega_{SM}$. The velocity is not measured directly. The immeasurable disturbance (e.g. loads) is caused by switching of load resistors (RL) to the generator (D). The load braking torque is proportional to the current of the generator.

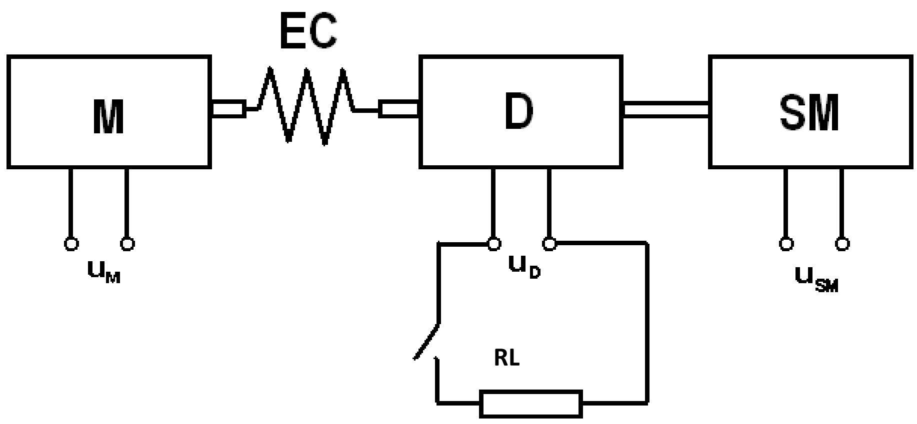

Fig. 1: Block diagram of the control process

3 DESCRIPTION OF THE EXPERIMENTAL EQUIPMENT

The functional diagram of the laboratory test rig with amplifiers, converters, power sources, incremental sensor, digital multimeters, measurement I/O-I/O card and the PC is depicted Fig. 2. The normalized digitized variables $y(kT)$ and $d(kT)$ are processed in the PC. The normalized, digital manipulated variable $u(kT)$ is the output from the PC. You can output the signal from the controller (closed control loop test) or a jump generator (open loop study).

There is a description of all abbreviations for Fig. 2 in Tab. 1. The general signal description with their ranges is given in Tab. 2. The Tab. 4 includes the measured and the controlled signals with a detailed description.

Tab. 1: Description of components

I/O card	Measurement I/O-card	**D**	Generator P2TV553
SW	Software	**IC**	Incremental sensor
AO0	Analog output signal	**I/U**	I/U converter ($1\ \mathrm{V}/1.5\ \mathrm{A}$)
AI0, AI1	Analog input signals	**RL_i**	Load resistors
PS	Controlled power source	**SW1, SW2**	Switches
M	Permanent magnet DC motor P2TV553	**VM1**	Digital multimeter – motor voltage u_M
EC	Clutch	**VM2**	Digital multimeter – generator voltage u_{SM}
SM	Tachogenerator (rotational sensor)	**FM**	Digital multimeter – incremental sensor

Tab. 2: Signal description

Signal	Description	Range
u	Matlab input signal (manipulated variable)	$-1\,..\,1$
u_{IN}	Measurement I/O- card output	$0\,..\,5\ \mathrm{V}$
u_M	DC motor armature voltage	$0\,..\,28\ \mathrm{V}$
u_D	Generator terminal voltage	$0\,..\,28\ \mathrm{V}$
u_{SM}	Tachogenerator terminal voltage	$0\,..\,30\ \mathrm{V}$
u_{OUT}	Measurement I/O- card input (engine speed)	$0\,..\,10\ \mathrm{V}$
u_d	Measurement I/O-card input (generator speed)	$0\,..\,10\ \mathrm{V}$
y	Matlab output signal (controlled variable)	$0\,..\,1$
d	Matlab output signal (disturbance)	$0\,..\,1$

Note that the (colored) light bulbs (lamps) in the block diagram indicate only that the load is on or off. (The orange lamp indicates a load of 50 %, the red lamp indicates the load of 100 %). The switching logic and the actual value of the nominal load for all combination are shown in Tab. 3.

Tab. 3: Load switching logic

SW1 (orange light)	SW2 (red light)	Load nominal value [%]
OFF	OFF	0
OFF	ON	100
ON	OFF	50
ON	ON	100

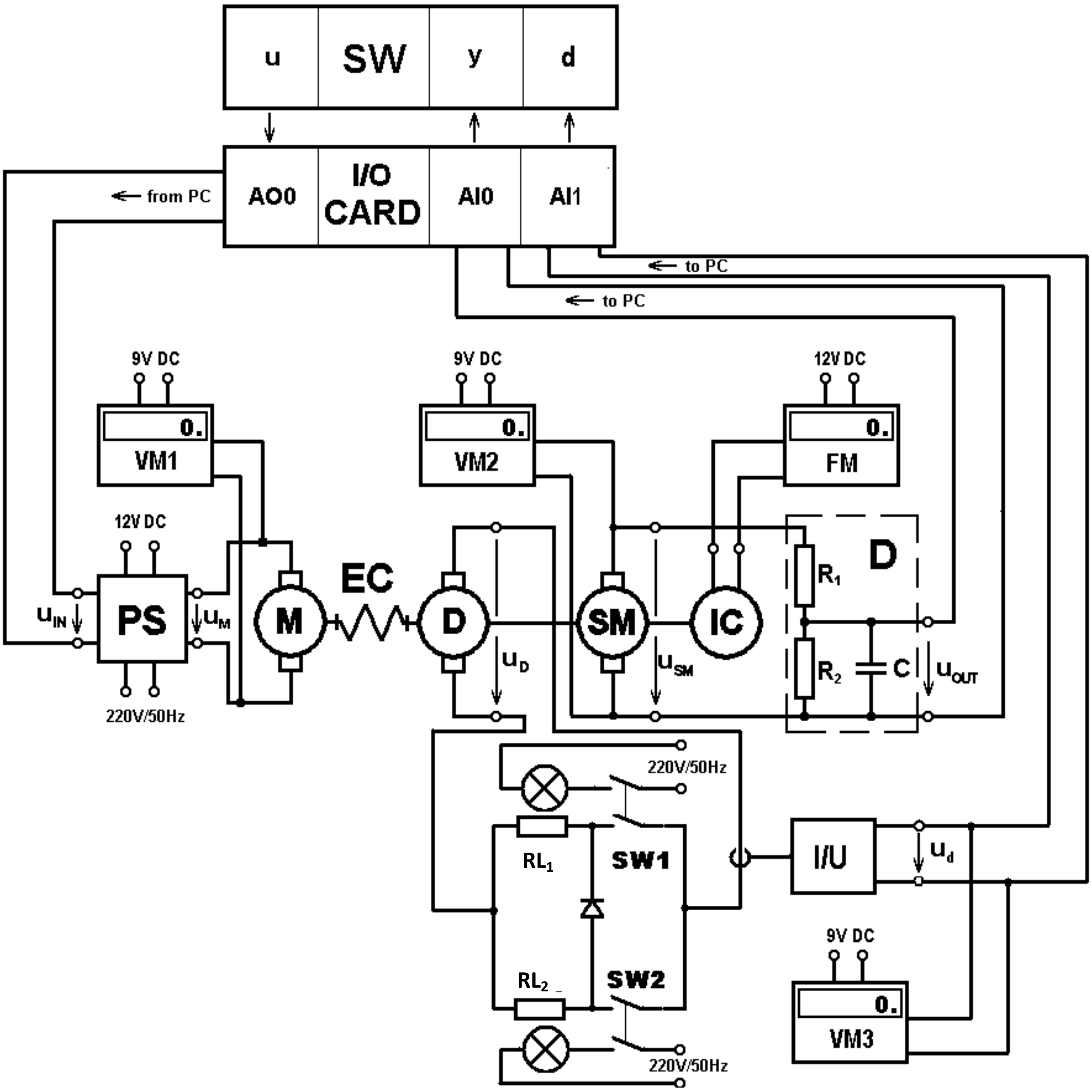

Fig. 2: Functional diagram of the test rig

Tab. 4: Matlab signals (Real Time Toolbox)

Signal	I/O type	Voltage range	Channel	Scaling range	Description
u	AO0	$0..5$	1	$-1..1$	DC motor voltage
y	AI0	$0..10$	1	$0..1$	Rotational speed
d	AI1	$0..10$	2	$0..1$	Load current

4 MATHEMATICAL MODEL OF THE PROCESS

A mathematical model of a process can be build up on the theoretical analysis of the process or on the experimental process analysis (identification). The theoretical analysis provides a process model in the form of differential equations on a physical basis. In both cases it is useful to simplify the technological scheme and develop an alternative representation (1st level of abstraction).

4.1 ALTERNATIVE REPRESENTATION OF THE PROCESS

The alternative technological representation of the process for the theoretical analysis is shown in Fig. 3. This schema consists of the main parts of the process: the DC motor, the clutch and the tachogenerator. The input signal is the armature voltage of the DC motor u_M and the output signal is the terminal voltage of the tachogenerator u_{SM}.

Tab. 5: Signals and parameters in the alternative representation

Parameter	Description
B_M	DC motor rotational damping
k_M	Motor constant
J_M	DC motor inertia
φ_M	Motor rotation angle
ω_M	Motor angular speed
L_M	DC motor armature inductance
R_M	DC motor armature resistance
u_M	DC motor armature voltage
i_M	DC motor armature current
u_i	DC motor inducted voltage
B_D	Generator rotational damping
k_D	Generator motor constant
J_D	Generator inertia
φ_D	Generator rotation angle
ω_D	Generator angular speed
L_D	Generator armature inductance
R_D	Generator armature resistance
u_D	Generator armature voltage
i_D	Generator armature current
u_{iD}	Generator inducted voltage
M_D	Braking torque caused by load
B_{SM}	Tachogenerator rotational damping
J_{SM}	Tachogenerator inertia
R_L	Tachogenerator armature resistance
D_{EC}	Stiffness of the coupling

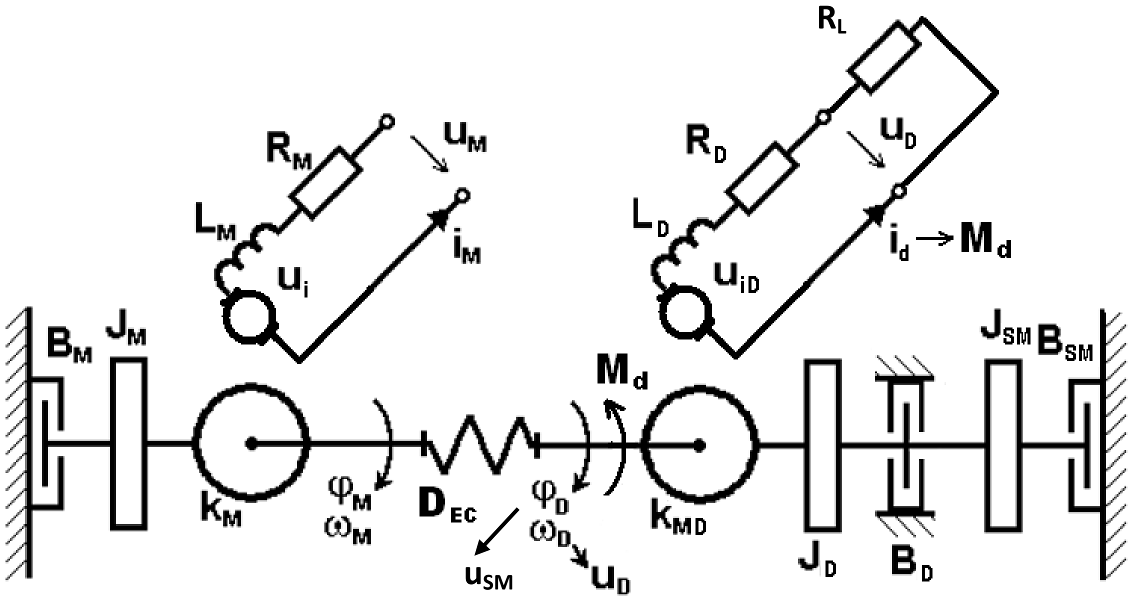

Fig. 3: Alternative representation of the process

4.2 THEORETICAL PROCESS ANALYSIS

The alternative representation of the process (Fig. 3) shows that there is coupled DC motor with generator and speedometer tachogenerator. The angle of rotation of the DC motor is denoted by φ_M. The solid coupling of the generator with the tachogenerator will be referred as load condition with the rotation angle φ_D. The coupling between DC motor and the generator (axis on which the rotational speed is measured) is elastic and described by the stiffness.

The Motion equation for the motor and the load system can be written as

$$J_M \cdot \frac{d^2\varphi_M(t)}{dt^2} + B_M \cdot \frac{d\varphi_M(t)}{dt} + D_{EC} \cdot \big(\varphi_M(t) - \varphi_D(t)\big) = M_M, \tag{1}$$

$$(J_D + J_{SM}) \cdot \frac{d^2\varphi_D(t)}{dt^2} + (B_D + B_{SM}) \cdot \frac{d\varphi_D(t)}{dt} - \\ -D_{EC} \cdot \big(\varphi_M(t) - \varphi_D(t)\big) = -M_D, \tag{2}$$

where M_M is the DC motor torque and M_D is the braking torque representing the disturbance.

The drive torque of the motor can formulated in the form

$$M_M(t) = k_M \cdot i_M(t). \tag{3}$$

The armature current of the DC motor i_M can be calculated from the differential equation of the alternative representation of the DC motor by the following equation

$$u_M(t) = R_M \cdot i_M(t) + L_M \cdot \frac{di_M(t)}{dt} + k_M \cdot \frac{d\varphi_M(t)}{dt}. \tag{4}$$

The braking torque of the generator is given by the formula

$$M_D(t) = k_D \cdot i_D(t). \tag{5}$$

The armature current of the tachogenerator i_D can be calculated from the alternative electrical circuit representation of the generator.

$$u_{iD}(t) = (R_D + R_L) \cdot i_D(t) + L_D \cdot \frac{di_D(t)}{dt} \tag{6}$$

It is known that the induction voltage of the generator u_{id} is proportional to the angular velocity of the generators' axis rotational speed

$$u_{iD}(t) = k_D \cdot \frac{d\varphi(t)}{dt}. \tag{7}$$

Substituting the equation (7) to equation (6) leads to the new formula for the generator current

$$k_D \cdot \frac{d\varphi_D(t)}{dt} = (R_D + R_L) \cdot i_D(t) + L_D \cdot \frac{di_D(t)}{dt}. \tag{8}$$

The system of equations (1) to (8) represents the mathematical model of the process.

4.3 MATHEMATICAL MODEL FOR THE SOLID CLUTCH

If the solid clutch is used, then speed and angle of rotation of the DC motor and the speedometer tachogenerator are equal.

$$\varphi(t) = \varphi_M(t) = \varphi_D(t). \tag{9}$$

Substituting this formula to the equation (1) and equation (2) and summing it together transfers these equations to the following one

$$(J_M + J_D + J_{SM}) \cdot \frac{d^2\varphi(t)}{dt^2} + (B_M + B_D + B_{SM}) \cdot \frac{d\varphi(t)}{dt} = M_M - M_D. \tag{10}$$

The same formula changes also equation (4) and equation (8) to the form

$$u_M(t) = R_M \cdot i_M(t) + L_M \cdot \frac{di_M(t)}{dt} + k_M \cdot \frac{d\varphi(t)}{dt}, \tag{11}$$

$$k_D \cdot \frac{d\varphi(t)}{dt} = (R_D + R_L) \cdot i_D(t) + L_D \cdot \frac{di_D(t)}{dt}. \tag{12}$$

For programming in Simulink, the term for the angular velocity ω is introduced with $\omega = \omega_M = \omega_D = \dot{\varphi}$. The equation (10) than has the form

$$(J_M + J_D + J_{SM}) \cdot \frac{d\omega(t)}{dt} + (B_M + B_D + B_{SM}) \cdot \frac{d\omega(t)}{dt} = M_M - M_D. \tag{13}$$

If equations (3) and (5) are substituted into the equation (13), a differential equation for the angular velocity is obtained in the form

$$\boxed{\frac{d\omega(t)}{dt} = -\frac{B_{GES}}{J_{GES}} \cdot \omega(t) + \frac{k_M}{J_{GES}} \cdot i_M(t) - \frac{k_D}{J_{GES}} \cdot i_D(t),} \tag{14}$$

where $J_{GES} = (J_M + J_D + J_{SM})$ and $B_{GES} = (B_M + B_D + B_{SM})$.

It is necessary to find both current i_M and i_D. It is possible to use equation (11) and (12).

$$\begin{aligned} u_M(t) &= R_M \cdot i_M(t) + L_M \cdot \frac{di_M(t)}{dt} + k_M \cdot \omega(t) \quad \rightarrow \\ \rightarrow \quad \frac{di_M(t)}{dt} &= -\frac{R_M}{L_M} \cdot i_M(t) - \frac{k_M}{L_M} \cdot \omega(t) + \frac{1}{L_M} \cdot u_M(t) \end{aligned} \tag{15}$$

$$\begin{aligned} k_D \cdot \omega(t) &= (R_D + R_L) \cdot i_D(t) + L_D \cdot \frac{di_D(t)}{dt} \quad \rightarrow \\ \rightarrow \quad \frac{di_D(t)}{dt} &= -\frac{(R_D + R_L)}{L_D} \cdot i_D(t) + \frac{k_D}{L_D} \cdot \omega(t) \end{aligned} \tag{16}$$

It is necessary to implement the load switch into the simulation. The DC motor can run without load, with 50 % load and with 100 % load. The load resistance R_L for 50 % load is equal to R_Z and for 100 % load is equal to $R_Z/2$. The eq. (16) will than have the form

$$\frac{di_{D,50}(t)}{dt} = -\frac{(R_D + R_Z)}{L_D} \cdot i_D(t) + \frac{k_D}{L_D} \cdot \omega(t) \tag{17}$$

for 50 % load and

$$\frac{di_{D,100}(t)}{dt} = -\frac{\left(R_D + \frac{R_Z}{2}\right)}{L_D} \cdot i_D(t) + \frac{k_D}{L_D} \cdot \omega(t) \tag{18}$$

for 100% load. If there is no load presented, the current i_D is equal to zero!

$$i_{D,0}(t) = 0 \tag{19}$$

The right equation actually used in the experiment simulation must be controlled by a multiport switch.

Finally, equations (14), (15), (17) and (18) represent a model whose input is the voltage u_M in the real range $< 0\,..\,29\ \mathrm{V} >$ and the output is the angular velocity ω in real range (see Fig. 4).

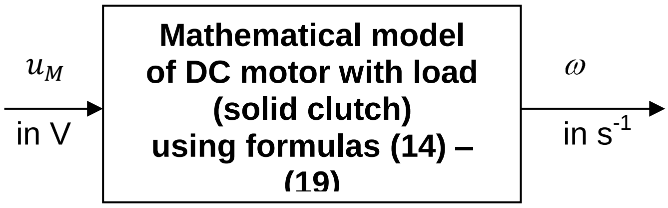

Fig. 4: Mathematical model of the process with solid clutch in real inputs and outputs

4.4 MATHEMATICAL MODEL FOR THE FLEXIBLE CLUTCH

The differential equation for the DC motor and the generator can be formulated by the same way as in the case with solid clutch. The rotational speed of the motor axis is not equal to the rotational speed of the generator and tachogenerator axis, so the equation (9) cannot be used. The interesting value for the model will be the second derivation of the axes angles – the acceleration. Equations (1) and (2), where the drive torque from equation (3) resp. (5) is substituted, will have the form

$$\frac{d^2\varphi_M(t)}{dt^2} = -\frac{B_M}{J_M}\cdot\frac{d\varphi_M(t)}{dt} - \frac{D_{EC}}{J_M}\cdot\left(\varphi_M(t) - \varphi_D(t)\right) + \frac{k_M}{J_M}\cdot i_M(t), \tag{20}$$

$$\frac{d^2\varphi_D(t)}{dt^2} = -\frac{B_{DSM}}{J_{DSM}}\cdot\frac{d\varphi_D(t)}{dt} + \frac{D_{EC}}{J_{DSM}}\cdot\left(\varphi_M(t) - \varphi_D(t)\right) - \frac{k_D}{J_{DSM}}\cdot i_D(t). \tag{21}$$

where $J_{DSM} = J_D + J_{SM}$ and $B_{DSM} = B_D + B_{SM}$.

The equation for the armature current of the DC motor will have the form derived from equation (11)

$$\begin{aligned}\frac{di_M(t)}{dt} &= -\frac{R_M}{L_M}\cdot i_M(t) - \frac{k_M}{L_M}\cdot\omega_M(t) + \frac{1}{L_M}\cdot u_M = \\ &= -\frac{R_M}{L_M}\cdot i_M(t) - \frac{k_M}{L_M}\cdot\frac{d\varphi_M(t)}{dt} + \frac{1}{L_M}\cdot u_M(t),\end{aligned} \tag{22}$$

where $\omega_M(t) = \frac{d\varphi_M(t)}{dt}$.

Similarly for 50 % load and 100 % load it is possible to use equations (17) and (18), where the common rotational speed ω is changed to the rotational speed of the generator ω_D.

$$\frac{di_{D,50}(t)}{dt} = -\frac{(R_D + R_Z)}{L_D}\cdot i_D(t) + \frac{k_D}{L_D}\cdot\omega_D(t) \tag{23}$$

$$\frac{di_{D,100}(t)}{dt} = -\frac{\left(R_D + \frac{R_Z}{2}\right)}{L_D}\cdot i_D(t) + \frac{k_D}{L_D}\cdot\omega_D(t) \tag{24}$$

$$i_{D,0}(t) = 0 \tag{25}$$

5 SIMULATION

The inputs and outputs of the model with the measured real inputs and outputs of the process are compared during verification. The mathematical model represents only the red dashed line rectangle part of the real process in Fig. 5. It is shown that this model does not contain the output from the I/O card (AO0) and the power control unit PS on the input of the DC motor. This part is marked by blue dotted lines. Similarly, the model does not contain the voltage divider (D) and the input part of the I/O card (AI0, AI1). This part is marked by the green dashed lines.

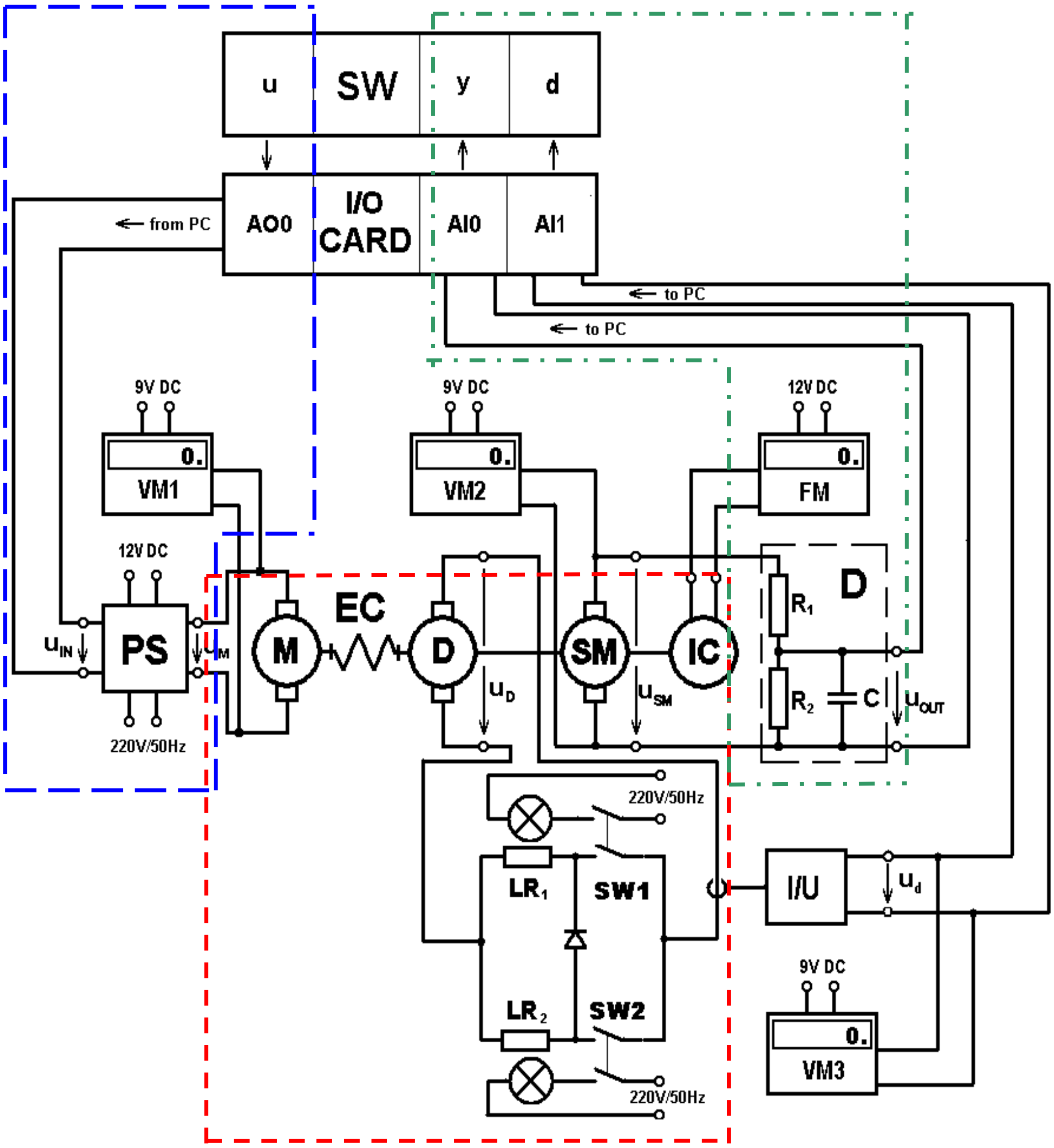

Fig. 5: Block diagram of the process with marked subsystems

The verification has to be performed with data that were measured on the real process with the aid of the ‘Real Time Toolbox’ from Matlab. The input signal of the process (manipulated variable) u is a Matlab variable that is in the range $< -1\,..\,1 >$, the output signal of the process (controlled variable) y is a Matlab variable in the range $< 0\,..\,1 >$. For this reason, necessary conversions are explained and implemented!

5.1 INPUT SIGNAL CONVERSION

The measured input signal u excites the mathematical model through the block 'From Workspace' in a Simulink program (see Fig. 6). This means that this signal has to be converted to the armature voltage of the DC motor u_M. First, the Matlab signal with a range $< -1\,..\,1 >$ (u) is converted on the I/O card to the real card output voltage range $< 0\,..\,5\text{ V} >$ (U_{IN}). The signal from the block 'From Workspace' in the Simulink simulation is therefore multiplied by a gain of size 2.5 and then shifted by 2.5. Moreover the power control unit includes a filter. The filter transfer function is

$$F_{FILTER}(s) = \frac{25}{(s+5)^2}. \tag{26}$$

The power control unit supplies the armature with the voltage u_M in the range $< 0\,..\,29\text{ V} >$. This voltage is calculated from U_{IN} by a gain of size $28.8/5$.

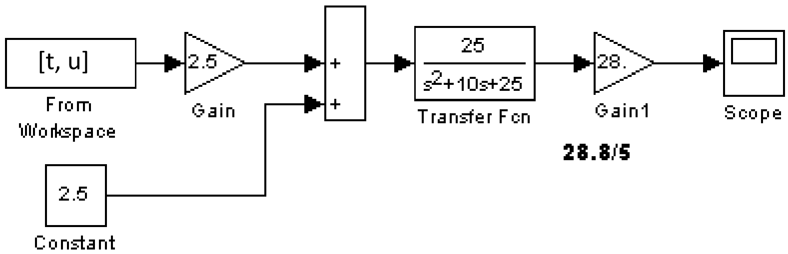

Fig. 6: Input signal conversion

5.2 OUTPUT SIGNAL CONVERSION

The speedometer tachogenerator output voltage u_{SM} is converted with a divider to the new one (see Fig. 7 left). The output signal from the voltage divider u_{OUT} is the input to the I/O card. The input of the I/O card contains an A/D converter.

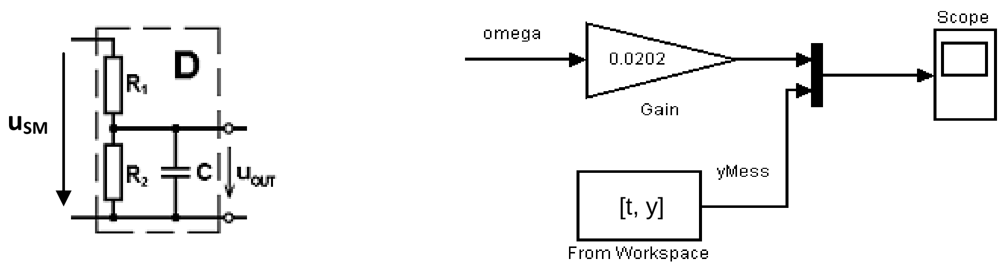

Fig. 7: Voltage divider (left) and Simulink block diagram for the output (right)

Due to the construction of the built-in tachogenerator the terminal voltage is proportional to the angular velocity ω_m.

In detail

$$u_{SM}(t) = \frac{20}{1000} \cdot \omega_m(t), \tag{27}$$

where u_{SM} in Volts is the terminal voltage of the tachogenerator and ω_m in min^{-1} is the angular velocity of the rotational axes. The mathematical model has the angular velocity ω in s^{-1}. The first step has to be to convert it to minutes.

$$\omega_m(t) = 60 \cdot \omega \tag{28}$$

The output voltage u_{OUT} from the voltage divider in the range $< 0 \,..\, 10\ \mathrm{V} >$ is connected as the input voltage to the I/O card. The voltage u_{OUT} is given by the formula

$$u_{OUT}(t) = \frac{R_2}{R_1 + R_2} \cdot u_{SM}(t) = \frac{4.03}{23.9} \cdot \frac{20}{1000} \cdot 60 \cdot \omega(t), \tag{29}$$

where R_1 and R_2 are resistances in divider.

From the equation (29) can be seen that the output voltage u_{OUT} is proportional to the angular velocity ω. The Matlab variable for this output signal y is in the range $< 0 \,..\, 1 >$. The final calculation for this signal can be formulated as

$$y(t) = \frac{1}{10} \cdot u_{OUT}(t) = \frac{1}{10} \cdot \frac{4.03}{23.9} \cdot \frac{20}{1000} \cdot 60 \cdot \omega(t) \doteq 0.0202 \cdot \omega(t). \tag{30}$$

The part of the Simulink program that performs the conversion is shown in Fig. 7 (right). The measured output is transported via the block ‘From Workspace’.

5.3 SIMULATION PARAMETERS

The simulation calculation has to be performed with the parameters that are given in Tab. 6 and Tab. 7.

Tab. 6: Parameters of the DC motor

Parameter	J_M	B_M	D_{EC}	k_M	L_M	R_M
Unit	kg·m^2	kg·m^2·s^{-1}	1	V·s^{-1}	H	Ω
Value	3.5·10^{-4}	0.0002	0.03	0.72	1.6·10^{-3}	0.605

Tab. 7: Parameters of the load

Parameter	J_{DSM}	B_{DSM}	k_D	L_D	R_D	R_Z
Unit	kg·m^2	kg·m^2·s^{-1}	V·s^{-1}	H	Ω	Ω
Value	3.78·10^{-4}	1.5·B_M	0.72	1.6·10^{-3}	0.605	6.6

Parameters B_M and D_{EC} should be optimized!

6 TASKS

6.1 THEORETICAL PROCESS ANALYSIS

Perform a theoretical process analysis and explain the instructions given for the differential equations. Derive the differential equations for

1. the mathematical model with solid clutch and
2. the mathematical model with flexible clutch.

6.2 MATLAB / SIMULINK MODEL DESIGN

The goal is to create a model in the Matlab environment. In principle, a simulation program is written in Simulink (mdl-file), which is controlled by the Matlab program (m-file).

The parameters for the simulations are shown in Tab. 6 and Tab. 7, but mainly the values of parameters B and D_{EC} should be optimized to obtain the same dynamic as was measured.

The aim is to minimize the deviations between model and real system!

6.2.1 Task 1 – solid clutch data preprocessing

Read the file '**pevna.mat**' with the matrix variable '**pevna_id**'. The first column of the matrix contains the time t, the second is the manipulated variable u, the third is the controlled variable y, the fourth is the disturbance d. Use the function '**plot**' to explore the course of the variables t, u, y, d. Explain the measurement!

6.2.2 Task 2 – flexible clutch data preprocessing

Read the file '**pruzna.mat**' with the matrix variable '**pruzna_id**'. The first column of the matrix contains the time t, the second is the manipulated variable u, the third is the controlled variable y, the fourth is the disturbance d. Use the function '**plot**' to explore the course of the variables t, u, y, d. Explain the measurement!

6.2.3 Task 3 – starting file

Realize the program (m-file), which creates all used parameters in the Matlab workspace and realize all conversions.

6.2.4 Task 4 – solid clutch simulation model

Write the Simulink program for the model with solid clutch. The program should calculate

- the motor armature current i_M,
- the common motor-tachogenerator shaft angular velocity ω,
- the armature current i_D of the tachogenerator for 50 % and 100 % of the load. Use the 'multiport switch' block to realize this task. (Extra explanation in Appendix A). For the initial verification use the case without load ($i_d = 0$).

6.2.5 Task 5 – solid clutch simulation model verification

Integrate the measured input and outputs to the simulation model. This makes it possible to evaluate the model behavior. The parameters B and D_{EC} should be optimized.

6.2.6 Task 6 – elastic clutch simulation model

Write the Simulink program for the model with elastic clutch. The program should calculate

- the motor armature current i_M,
- the motor shaft angular velocity ω_M,
- the speedometer tachogenerator shaft angular velocity $\omega_D = \omega_{SM}$,
- the generator armature current i_D for 50 % and for 100 % load with the 'multiport switch'. For the initial verification use the case without load ($i_d = 0$).

6.2.7 Task 7 – elastic clutch simulation model verification

Integrate the measured input and outputs to the simulation model. This makes it possible to evaluate the model behavior. The parameters B and D_{EC} has to be optimized.

6.3 DISCUSSION OF RESULTS

The protocol must include mainly the following points:

1. Developed programs / models in Matlab and Simulink.
2. Model verification and simulation results.
3. Time courses of the major inputs and outputs.
4. Discussion of the results.
5. Tables with parameters that result in a sufficient agreement of the real system with the model.

7 LITERATURE

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APPENDIX A – MULTIPORT SWITCH BLOCK

The Multiport Switch block chooses among several inputs. The first input is the control input, while the others are data inputs. The value of the control input determines which data input passes to the output port. There are some rules that determine the block output. You specify the number of data inputs with Number of data ports. Data inputs can be scalar or vector.

- If you specify only one data input and that input is a vector, the block behaves as an index selector, and not as a multiport switch. The block output is the input vector element whose index matches the control input.
- **If you specify more than one data input, the block behaves as a multiport switch. The block output is the data input that corresponds to the value of the control input.** If at least one of the data inputs is a vector, the block output is a vector. In this case, the block expands any scalar inputs to vectors.
- If the data inputs are scalar, the output is a scalar.

Following figures represents the function of multiport switch block.

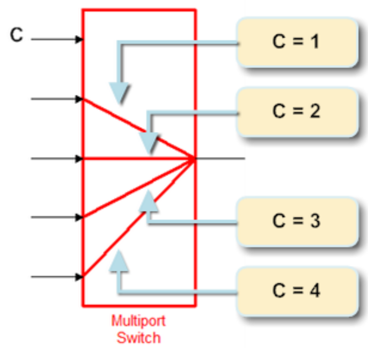

Fig. 8: The principle of the output signal selection

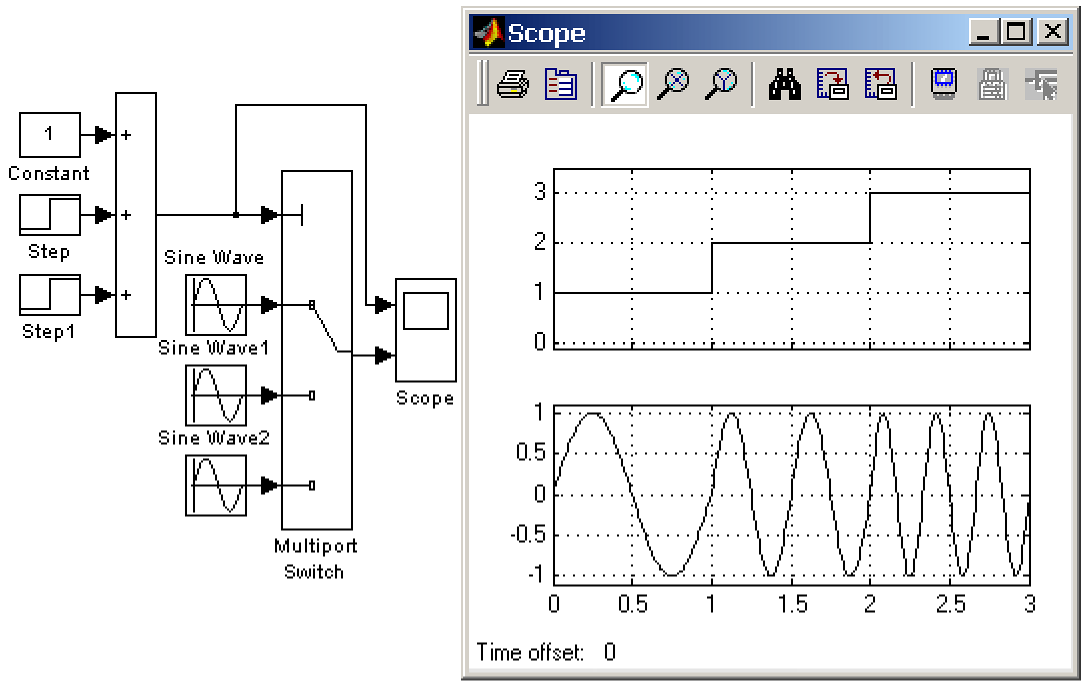

Fig. 9: Multiport switch function – the output is switched in times 1 and 2 seconds to different sine waves