# PRESENTATION OF THE DC MACHINE SIMULTANOUSLY BUT SEPARATELY CONTROLLED BY TWO VOLTAGES USING THE STATE-SPACE METHOD

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*Summary*: The following paper presents the DC machine working as a motor, described by means of the state-space method. A computer model of the machine, compiled in the MATLAB/SIMULINK® environment is described as well. This model takes into account the phenomenon of dynamic inductance in the excitation circuit of the DC machine. This study presents also a comparison between the conventional (linearized) model and the model with a magnetization curve analytically approximated by the arc cotangent function. State trajectories are presented against a background of static characteristics occurring here in the form of a steady-state surface (SSS). The computer model compiled may be used to determine optimal control of these voltages in accordance with the quality coefficient employed.

Keywords: DC machine controlled by two voltages

## 1. INTRODUCTION

Modern methods of optimization are based on the state-space method [1,6], which excels over classic methods and holds many advantages. The classic control theory is convenient in designing a single input-output system. However modern control theory, which is based on the state-space method, allows for examination of systems subjected to control of signals pertaining to a broad class of input signals, not only in the impulse, step or sinusoidal form. As distinguished from classic methods, the state-space method allows for start and end conditions of the system. The vector-matrix notation simplifies solving of differential equations. However, apart from simple calculations, it is necessary to use a computer, what requires knowledge of numerical values of parameters of the object.

This article describes movement of a drive system based on a direct current motor by the means of the space-state method. For heed establishing, simulations were carried out for a test DC machine – model PZB632a with rated of nominal power 0.8 kW, armature voltage 220 V, armature current 4,6 A, excitation current 0,24 A and nominal rotations 1500 rpm. Simulations were prepared under the assumption of four load types occurring in engineering practice. During model assembly, almost all machine

parameters ware variabled, which allows modeling of a broad class of DC machines, from small machines up to large mine hoist motors. Results are presented in a new and unexpected manner, i.e. in the form of a steady-state surface (SSS). The state vector movement is presented against the background of this surface.


## 2. MATHEMATICAL MODEL

This model allows for taking into account the dynamic inductance phenomenon of the machine excitation circuit [2, 9]. It may, therefore, present an accurate description of the phenomena occurring in DC machine. However, simplifying assumptions does not make allowances for the following:
a) a voltage drop across the brushes,
b) inducing a flux screening the main flux under the influence of fast, dynamic changes of armature current,
c) inaccuracies of machine compensation, and
d) allowing for the character of the magnetization curve, (phenomenon of a machine magnetic core material hysteresis is omitted).

On the basis of the generalized machine model, the following DC machine equations were derived [8]:

$$\left.\begin{array}{l} \dfrac{\mathrm{d}\,\Psi_{\mathrm{sd}}(t)}{\mathrm{d}t} = U_{\mathrm{sd}}(t) - \dfrac{1}{T_{\mathrm{sd}}}\,\Psi_{\mathrm{sd}}(t) \\[3mm] \dfrac{\mathrm{d}\,\Psi_{\mathrm{wq}}(t)}{\mathrm{d}t} = U_{\mathrm{wq}}(t) - \omega(t)\Psi_{\mathrm{wsd}}(t) - \dfrac{1}{T_{\mathrm{wq}}}\,\Psi_{\mathrm{wq}}(t) \\[3mm] \dfrac{\mathrm{d}\omega(t)}{\mathrm{d}t} = \dfrac{1}{JL_{\mathrm{wq}}}\,\Psi_{\mathrm{wq}}(t)\Psi_{\mathrm{wd}}(t) - \dfrac{1}{J}M_{\mathrm{op}}(t) \end{array}\right\} \qquad (1)$$

The variable presented in these equations $\Psi_{\mathrm{wsd}}$ can be formulated through $\Psi_{\mathrm{sd}}$ as follows:

$$\Psi_{\mathrm{wsd}} = \frac{M_{\mathrm{wsd}}}{L_{\mathrm{sd}}}\Psi_{\mathrm{sd}} = \alpha\Psi_{\mathrm{sd}} \; , \qquad (2)$$

where:

$\alpha$     – ratio, constant of the machine

$\Psi_{\mathrm{sd}}$     – stator flux linkage in d axis,

$\Psi_{\mathrm{wq}}$     – rotor flux linkage in q axis,

$\Psi_{\mathrm{wsd}}$     – stator in relation to the rotor flux linkage in d axis, and

$L_{\mathrm{wq}}, M_{\mathrm{wsd}}, T_{\mathrm{sd}}, \omega, J, M_{\mathrm{op}}$ respectively: inductance of armature in q axis, inductance of armature in relation to stator in d axis, average time-constant of excitation circuit, angular velocity, moment of inertia, resistance torque.

For marking simplification, the following equations were assumed (Fig. 1.):

$$\left.\begin{array}{l} \Psi_{sd} = \Psi_m \, ; U_{sd} = U_m \\ \Psi_{wq} = \Psi_t \, ; U_{wq} = U_t \\ L_{wq} = L_t \, ; T_{wq} = T_t \\ T_{sd} = T_m \end{array}\right\} \tag{3}$$
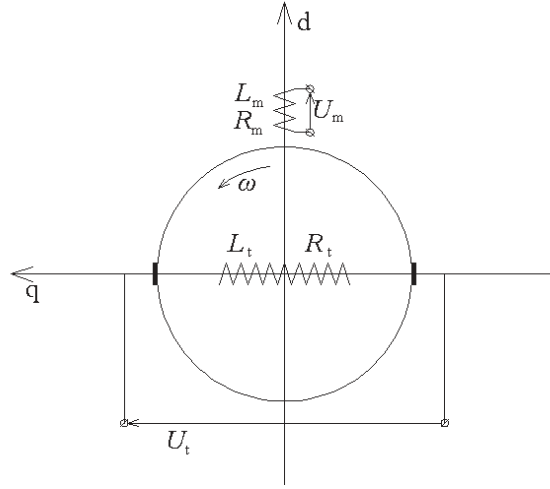


Fig. 1. DC machine diagram

Arranging equations (1) against new designations, the following results were acquired:

$$\frac{d}{dt}\begin{bmatrix} \Psi_m(t) \\ \Psi_t(t) \\ \omega(t) \end{bmatrix} = \begin{bmatrix} U_m(t) - \dfrac{1}{T_m}\Psi_m(t) \\ U_t(t) - \alpha\omega(t)\Psi_m(t) - \dfrac{1}{T_t}\Psi_t(t) \\ \dfrac{\alpha}{JL_t}\Psi_m(t)\Psi_t(t) - \dfrac{1}{J}M_{op}(t) \end{bmatrix}, \tag{4}$$

$$\frac{d}{dt}\begin{bmatrix} \Psi_m(t) \\ \Psi_t(t) \\ \omega(t) \end{bmatrix} = f\big(U_m(t), U_t(t), M_{op}(t), \Psi_m(t), \Psi_t(t), \omega(t)\big), \tag{5}$$

where: $\mathbf{f} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}$ is a vector function of the abovementioned arguments, and

$\Psi_m(t), \Psi_t(t), \omega(t)$ are state vector coordinates. The nonlinear vector-matrix equation (4) constitutes a base for further considerations.

## 3. MODEL TECHNIQUE IN *SIMULINK*®

A comparison of two DC machine models is presented below. A simplified model was built with the assumption, that inductance of the excitation circuit is not undergoing alteration under the influence of the excitation current, and, therefore, is formed by equations (4).

State trajectory equations, allowing for dynamic inductance, were derived on the basis of the following procedure.

The abovementioned equation:

$$U_m = R_m i_m + \frac{\mathrm{d}\Psi_m}{\mathrm{d}t} , \tag{6}$$

after an analysis of a which DC excitation circuit with a ferromagnetic material, the magnetization curve was approximated by an arc cotangent curve of the following parameters $a_0$, $a_1$, $a_2$:

$$\Psi(i_m) = \left( a_0^* \cdot \mathrm{arctg}(a_1 i_m) + a_2^* i_m \right) \quad a_0^*, a_2^* = \frac{a_0}{\alpha}, \frac{a_2}{\alpha} , \tag{7}$$

assumes a new form:

$$\left.\begin{aligned}
\frac{\mathrm{d}\Psi_m}{\mathrm{d}t} &= \left( \frac{a_0^* a_1}{1+(a_1 i_m)^2} + a_2^* \right) \frac{\mathrm{d}i_m}{\mathrm{d}t} \\
\frac{\mathrm{d}i_m}{\mathrm{d}t} &= \frac{U_m - R_m i_m}{\dfrac{a_0^* a_1}{1+(a_1 i_m)^2} + a_2^*} \\
\frac{\mathrm{d}i_m}{\mathrm{d}t} &= \frac{\left(1+(a_1 i_m)^2\right)(U_m - R_m i_m)}{a_0^* a_1 + a_2^*\left(1+(a_1 i_m)^2\right)}
\end{aligned}\right\} \tag{8}$$

Therefore:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_m(t) \\ \Psi_t(t) \\ \omega(t) \end{bmatrix} = \begin{bmatrix} \dfrac{\left(1+(a_1 i_m)^2\right)(U_m - R_m i_m)}{a_0^* a_1 + a_2^*\left(1+(a_1 i_m)^2\right)} \\ U_t(t) - \alpha\omega(t)\Psi_m(t) - \dfrac{1}{T_t}\Psi_t(t) \\ \dfrac{\alpha}{J L_t}\Psi_m(t)\Psi_t(t) - \dfrac{1}{J}M_{op}(t) \end{bmatrix} . \tag{9}$$

Factors $a_0$, $a_1$, $a_2$, were determined in the examination of the test machine. From the examination, a function course was directly assigned and assumed $\alpha\Psi_m = f(i_m)$. The result of this trial is presented on Fig. 2.

Ratio $\alpha$, in the equations, was determined on the basis of the assumption that in the no-load conditions the following relationships are fulfilled:

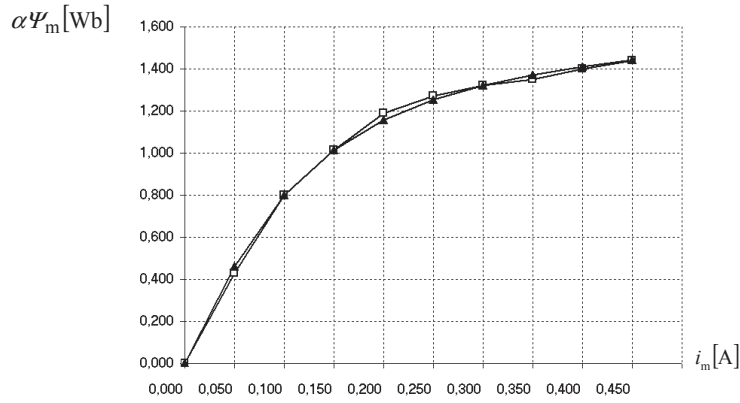$$\alpha = \frac{U_t - i_t R_t}{\omega\Psi_m}; \ i_t = 0 \tag{10}$$

$\alpha\Psi_m[\text{Wb}]$



Fig. 2. Function course $\alpha\Psi_m = \left(a_0 \cdot \text{arctg}(a_1 i_m) + a_2 i_m\right)$; factors a0, a1, a2 amount to, respectively: 1.083; 9.078; 0.002.

The value of excitation circuit temporal constant $T_{\text{msr}}$ might be accepted as an average, given by the manufacturer and amounting to 27ms for this machine. Then, for the machine considered, $\alpha$ amounts to 0.3.
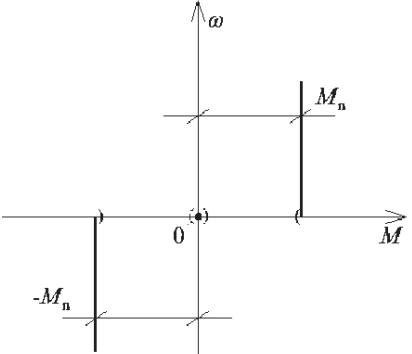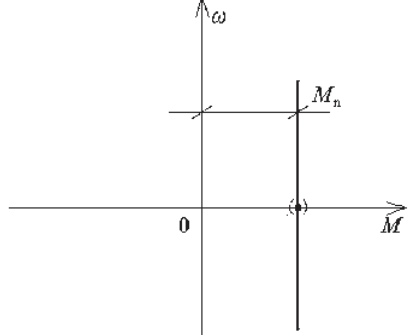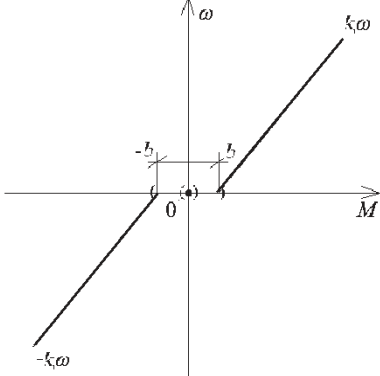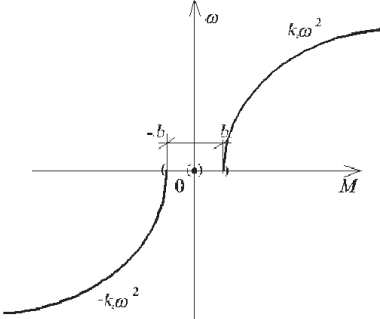
## 3.1. DISTURBANCES INFLUENCING MACHINE WORK

A number of disturbance classes influencing the machine ware considered. The resistance torques, which frequently occur in engineering, are: active resistance torque, generator torque, fan torque, and constant passive torque. These four aspects of load torques may be described by one equation, the versions of which are presented below.

The shape and course of the SSS directly depends upon the course and values of a resistance torque on the shaft. Assuming that operation of a resistance torque, of one of the aforementioned aspects, occurs, it is possible to determine a state-space surface for each of them. Such an approach towards the matter indicates that a specified SSS corresponds to a resistance torque of a chosen class.

$$M(\omega) = \text{sign}(\omega)\left(b + ak\omega^\gamma\right), \quad \gamma \in \{0, 1, 2\}, \tag{11}$$

where: resistance torque load ratio $a = \dfrac{M_{\text{op}}}{M_n}$, value of initial friction torque $b$, factor of proportionality between resistance torque and angle velocity $k$.

| Characteristic of torque | Equation | Type |
|---|---|---|
|  | $M(\omega) = \mathrm{sign}(\omega)aM_n$<br>$k = 1,$<br>$\gamma = 0,$<br>$b = 0,$<br>$M(0) = 0$ | **Passive constant resistance torque** |
|  | $M(\omega) = aM_n$<br>$k = 1,$<br>$\gamma = 0,$<br>$b = 0,$<br>$M(0) = M_n$ | **Active constant resistance torque (crane torque)** |
|  | $M(\omega) = \mathrm{sign}(\omega)(b + ak_1\omega)$<br>$k_1 > 0,$<br>$\gamma = 1,$<br>$b > 0,$<br>$M(0) = 0$ | **Passive generator resistance torque** |
|  | $M(\omega) = \mathrm{sign}(\omega)(b + ak_2\omega^2)$<br>$k_2 > 0,$<br>$\gamma = 2,$<br>$b > 0,$<br>$M(0) = 0$ | **Passive fan resistance torque** |

State trajectory depends on start and end conditions. The application, while altering voltage $U_m$ and $U_t$ in the external and internal loop enables plotting of these surfaces.

**The case of active resistance torque**

$$\left. \begin{aligned} \Psi_m &= a_0^* \cdot \operatorname{arctg}\left( \frac{U_m a_1}{R_m} \right) + a_2^* \frac{U_m}{R_m} \\ \Psi_t &= \frac{L_t M_{op}}{\alpha \Psi_m} \\ \omega &= \frac{U_m - \Psi_t / T_t}{\alpha \Psi_m} \end{aligned} \right\} \tag{12}$$

**The case of generator resistance torque and passive constant resistance torque ($k_1 = 0$, $b = M_{op}$)**

The SSS course of the active resistance torque proceeds according to the following equalities:

$$M_{op} = \operatorname{sign}(\omega)(b + ak_1\omega), \text{ where: } \operatorname{sign}(\omega) = \operatorname{sign}(U_m U_t) \tag{13}$$

Therefore:

$$\left. \begin{aligned} \Psi_m &= a_0^* \cdot \operatorname{arctg}\left( \frac{U_m a_1}{R_m} \right) + a_2^* \frac{U_m}{R_m} \\ \Psi_t &= \frac{L_t \cdot \operatorname{sign}(U_m U_t)(b + ak_1\omega)}{\alpha x_1} \\ \omega &= \left( 1 + \frac{R_t ak_1 \cdot \operatorname{sign}(U_m U_t)}{(\alpha \Psi_m)^2} \right)^{-1} \left( \frac{U_t}{\alpha \Psi_m} - \frac{R_t b \cdot \operatorname{sign}(U_m U_t)}{(\alpha \Psi_m)^2} \right) \end{aligned} \right\} \tag{14}$$

**The case of fan resistance torque**

The SSS course of the active resistance torque was determined according to the following equations:

$$M_{op} = \operatorname{sign}(\omega)(b + ak_2\omega^2) \tag{15}$$

Finally:

$$\left. \begin{aligned} \Psi_m &= a_0^* \cdot \operatorname{aretg}\left( \frac{U_m a_1}{R_m} \right) + a_2^* \frac{U_m}{R_m} \\ \Psi_t &= \frac{L_t \cdot \operatorname{sign}(U_m U_t)(b + ak_1 x_3)}{\alpha x_1} \\ \omega &= \frac{-1 + \operatorname{sign}(U_m U_t)\sqrt{4pq + 1}}{2p} \end{aligned} \right\} \tag{16}$$

where:

$$\text{sign}(\omega)\frac{R_{\mathrm{t}}ak_2}{(\alpha\Psi_{\mathrm{m}})^2} = p ,$$

$$\frac{U_2}{\alpha\Psi_{\mathrm{m}}} - \frac{R_{\mathrm{t}}\cdot\text{sign}(\omega)b}{(\alpha\Psi_{\mathrm{m}})^2} = q$$

The first coordinate of the state vector $\Psi_m$ indicates the linkage flux in the excitation circuit and, the state trajectory, allowing for dynamic inductance, is calculated [7] in relation to magnetizing current $i_{\mathrm{m}}$. It is necessary, therefore, to establish initial conditions of the integrator, in relation to this current. The current $i_{\mathrm{m}}$ determination for the given $\Psi_m$ from equation (8) is not possible due to function implisiting. In this case, for the given current, $\Psi_m$ the value of the current $i_{\mathrm{m}}$ is determined iteratively each time on the basis of the following calculation:

$$\Psi_{\mathrm{m}} = a_0^* \cdot \text{arctg}\left(\frac{U_{\mathrm{m}}a_1}{R_{\mathrm{m}}}\right) + a_2^*\frac{U_{\mathrm{m}}}{R_{\mathrm{m}}} \tag{17}$$

After appropriate conversions we have equation:

$$\text{tg}\left(\frac{\Psi_{\mathrm{m}} - a_2^*i_{\mathrm{m}}}{a_0^*}\right) - a_1i_{\mathrm{m}} = |\varepsilon_{\mathrm{m}}| \tag{18}$$
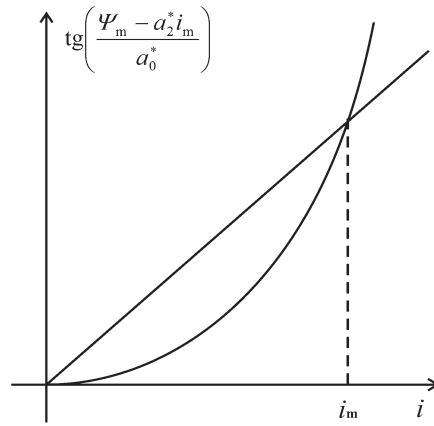


Fig. 3. Interpretation of iterative method of magnetizing current determination, accurate to $\varepsilon_{\mathrm{m}}$ (here employed accuracy of: 0.0000001)

Solving this allows for creating a model [3, 4, 5], which, as author argues, presents courses of a real DC machine in a rather accurate manner.

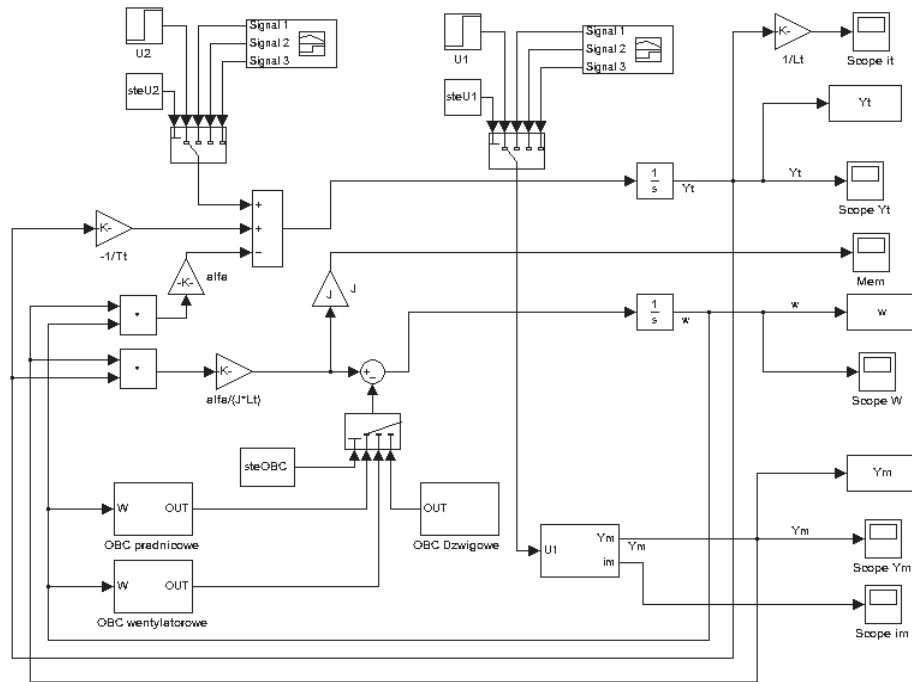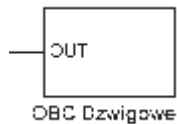**The block diagram in *SIMULINK*® corresponding to the vector equation of state trajectory (9)**

Fig. 4. Block diagram of the DC machine allowing for dynamic inductance of excitation circuit, where $Y_t = \Psi_t$, $Y_m = \Psi_m$, $w = \omega$.

Diagrams included in blocks.

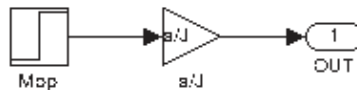This element includes a hidden diagram presented in Fig. 5.

Fig. 5. Active resistance torque simulation diagram.

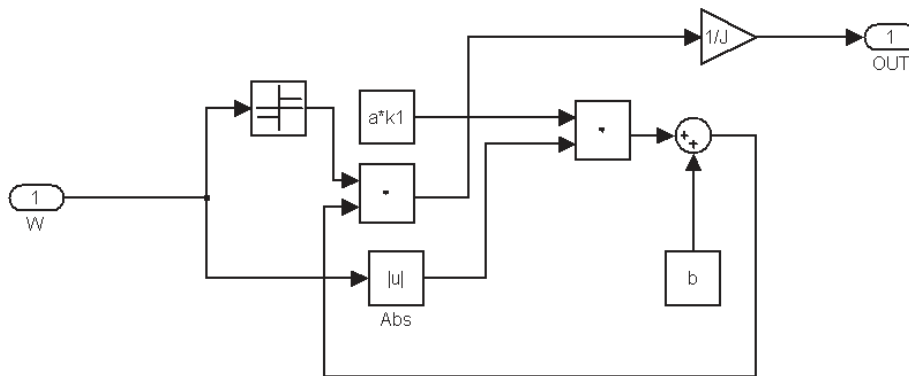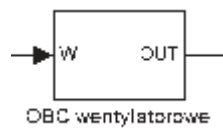This element includes a hidden diagram presented in Fig. 6.



Fig. 6. Generator torque simulation diagram.



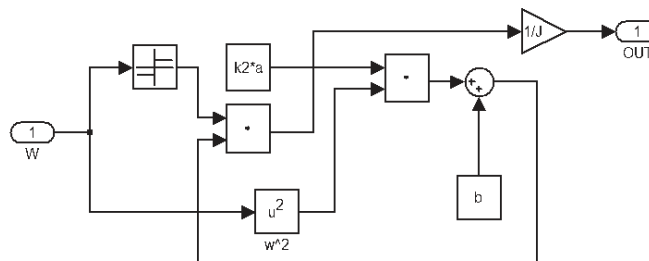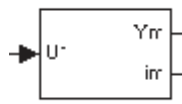This element includes a hidden diagram presented in Fig. 7.



Fig. 7. Fan torque simulation diagram.

The block contains the first trajectory equation for the case taking into account dynamic inductance. The input quantity is a signal of $U_m$, the output signals are: $\Psi_m$ and $i_m$. The internal diagram is presented in Fig. 8.
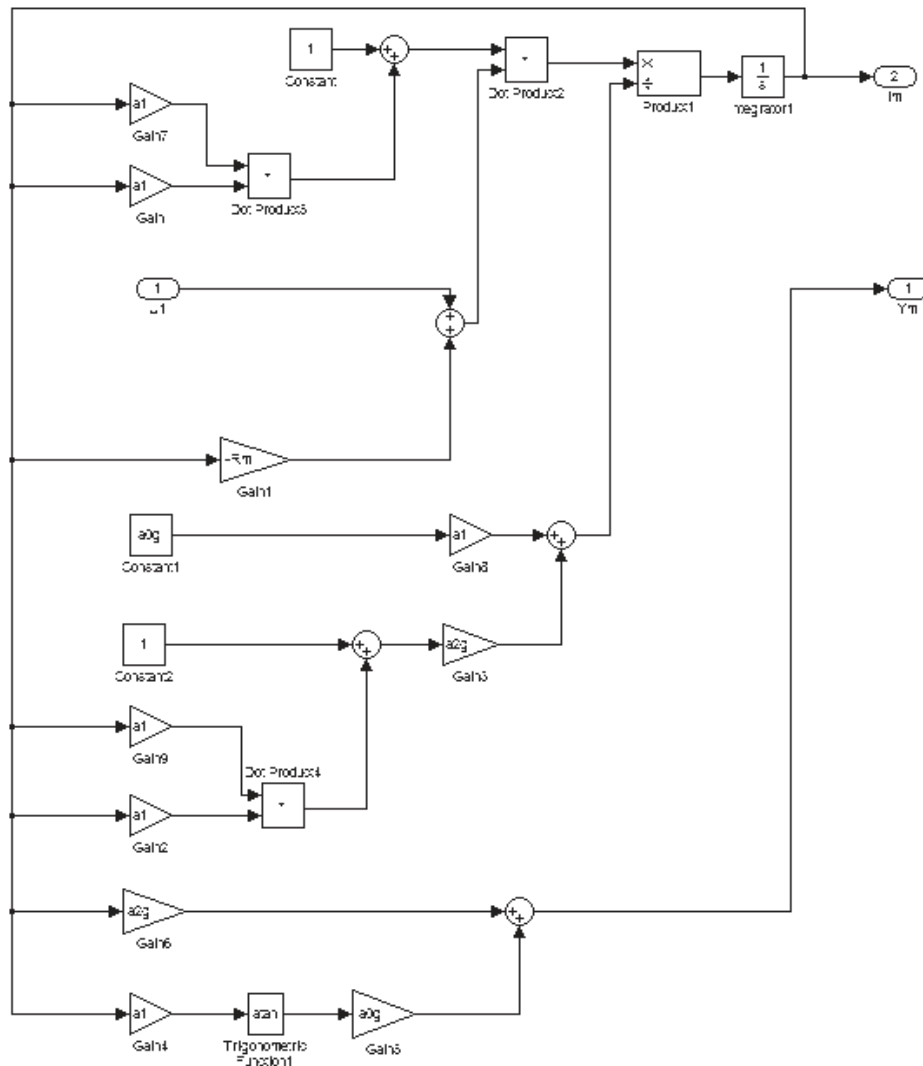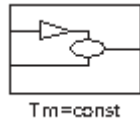


Fig. 8. Excitation circuit simulation diagram of the DC machine allowing for dynamic inductance of excitation circuit.

The interior of the block includes state equations for the linearized circuit, i.e. omitting dynamic inductance. The simulation diagram can be activated in a separate window. This element is included in the diagram presented in Fig. 9.
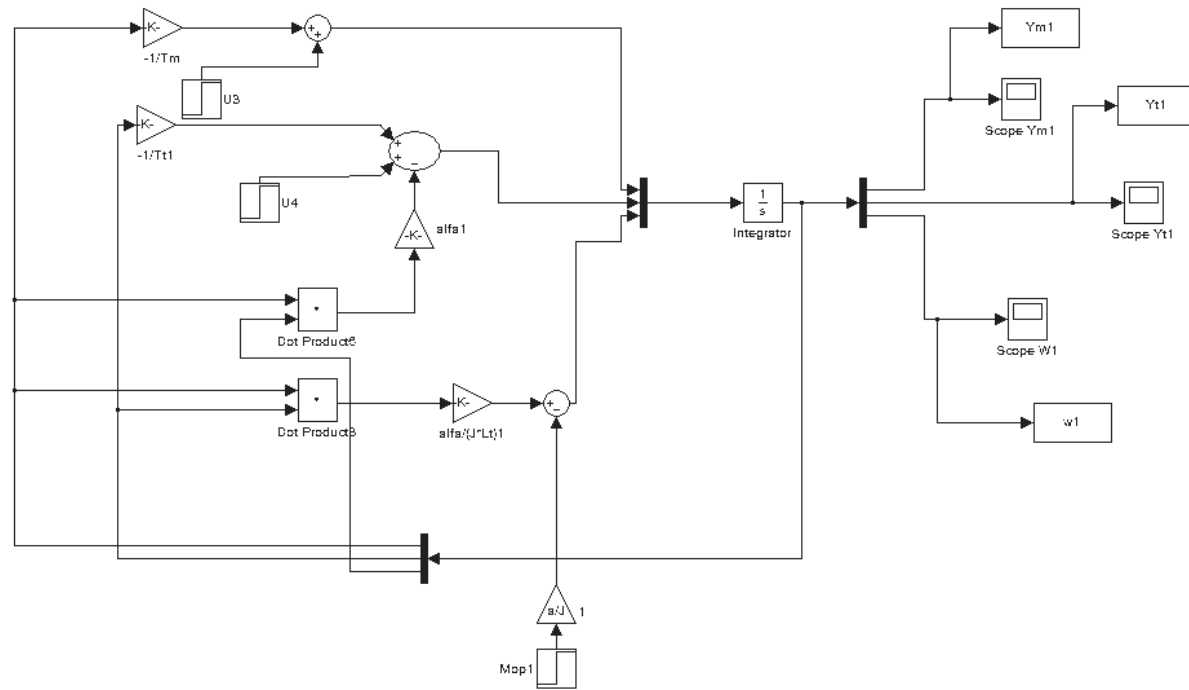


Fig. 9. Excitation circuit simulation diagram of a DC machine with linearized magnetization curve.

**Diagram parameters used in calculations are listed in the following table:**

| PARAMETRY MASZYNY | | |
|---|---|---|
| Mn [Nm] = | 5.1 | Rated torque |
| Rm [Ohm] = | 726.29 | Effective resistance of excitation circuit |
| Lt [H] = | 0.01284 | Inductance of armature circuit |
| Rt [Ohm]= | 4.28 | Effective resistance of armature circuit |
| Tm [s]= | 0.019 | Aver. time-constant of excitation circuit |
| U1n [V]= | 230 | Final excitation voltage |
| U2n [V]= | 230 | Final armature voltage |
| alfa = | 0.3 | Ratio, constant of the machine acc. to eq.(2) |
| a0 = | 1.0827 | Magnetization curve shape fac. |
| a1 = | 9.0783 | Magnetization curve shape fac. |
| a2 = | 0.002 | Magnetization curve shape fac. |
| J [kgm^2]= | 0.010039 | Inertia moment of drive |
| a (Mop=a*Mn) = | 1 | Relative load torque |
| b (Mt=b*Mn) = | 0.05 | Relative load of an initial friction passive torque |
| k1 [Nms]= | 0.034 | Gen. torque factor acc. to Fig. 5 |
| k2 [Nms^2]= | 0.000226 | Fan torque factor acc. to Fig. 6 |
| U1 [V] = | 0 | Initial value of excitation volt. |
| U2 [V] = | 0 | Initial value of armature volt. |
| steOBC (1-P,2-W,3-D)= | 1 | Load type choice (1- generator, 2- fan, 3- crane) |
| steU1 (1,2,3,4)= | 1 | Excitation voltage - choice of function course |
| steU2 (1,2,3,4)= | 1 | Armature voltage - choice of function course |
| cw (1-1cw 2-4cw) | 1 | Chart illustration method choice (1 - in the first quarter, 2 - in four quarters) |

Buttons: OK and run, load

Fig. 10. Method of introducing DC machine data to the simulation program.

## 4. DESCRIPTION OF SIMULATIONS

The test was performed by using the machine parameters obtained from laboratory studies. However, it is necessary to stress that this model is general enough to allow simulation and examination of any given DC machine.

The 3D chart presents the SSS in Fig. 15. Its color depends on the quarter in which the panel was placed; first quarter – red ($U_m+$ i $U_t+$); second quarter – yellow ($U_m+$ i $U_t-$); third quarter – blue ($U_m-$ i $U_t-$); fourth quarter – green ($U_m-$ i $U_t+$). The blue line in the chart presents the state trajectory. The next charts also present courses of each vector components versus time function.

**Comparison of DC motor allowing for dynamic inductance in excitation circuit to DC machine allowing for static inductance**
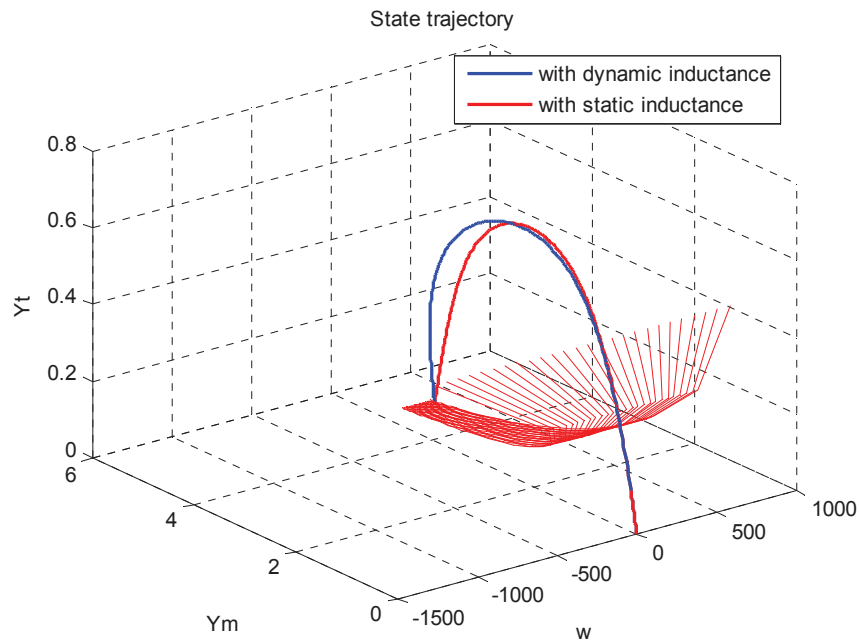


Fig. 11. Result of simulation comparison of a linearised model and a model allowing for changing inductance during start-up.

Fig. 11 presents the results of a comparison between two motor models, based on the trajectory course of the state, during machine start-up. While the red line is the course of the state vector, not allowing for excitation circuit dynamic inductance, the blue line is the response of the system allowing for nonlinearity of the magnetization curve in the machine magnetic core. The results of modeling were inserted for comparison purposes. Although static values of the state vector are the same, the transients differ from each other. Therefore, the model with dynamic inductance of the excitation circuit was assumed for further consideration.

The state trajectory of a motor, loaded with generator passive resistance torque, when start voltages are equal to $U_{\mathrm{m}} = -100$, $U_{\mathrm{t}} = -100$ V and end voltages are equal to $U_{\mathrm{m}} = 230$, $U_{\mathrm{t}} = 230$ V, is presented in Fig.12. Load torque is equal to rated motor torque.
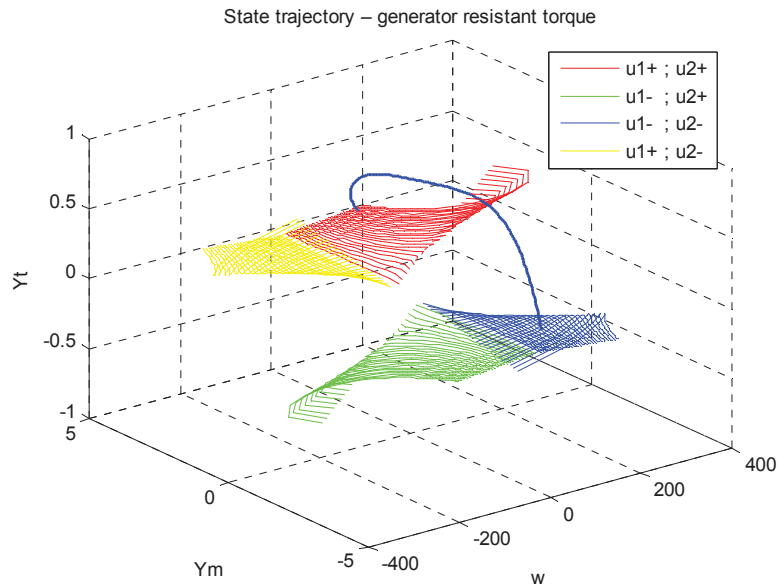


Fig. 12.   State trajectory loaded with generator passive resistance torque, with initial voltages equal to $U_m = -100$ V, $U_t = -100$ V and end voltages equal to $U_m = 230$ V, $U_t = 230$ V presented in four quarters of the state surface. Load torque in steady state  is equal to rated motor torque.

The state vector components alter  the value of $\Psi_{\mathrm{m}}$ and $\Psi_{\mathrm{t}}$ from negative to positive. The shape of the SSS allows that the motor be loaded with the generator passive resistance torque. Courses of the state vector components $\Psi_{\mathrm{m}}$, $\Psi_{\mathrm{t}}$ and $\omega$, and useful variables such as armature current $i_{\mathrm{t}}$ and magnetizing current $i_{\mathrm{m}}$ are presented on figures 13÷16.
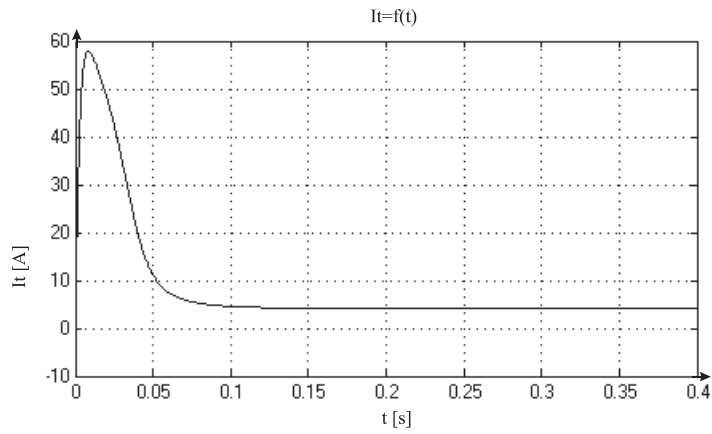
Fig. 13.  Armature current course $i_t$ = f($t$); machine loaded with generator passive resistance torque, with start voltages equal to $U_m = -100$ V, $U_t = -100$ V, and end voltages equal to $U_m = 230$ V, $U_t = 230$ V. Torque in steady state is equal to rated motor torque.
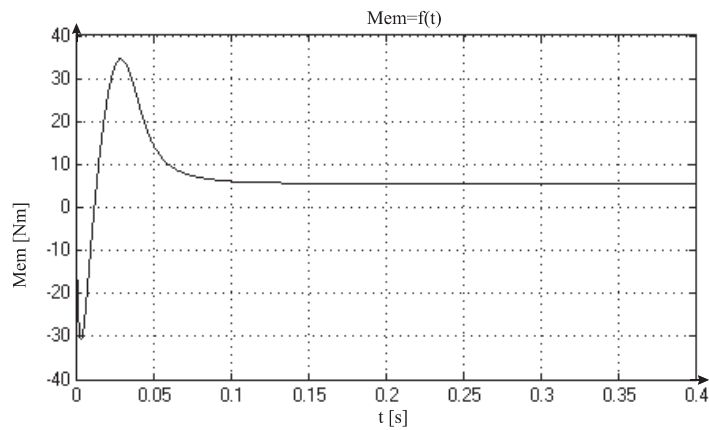


Fig. 14.  Armature current course $M_{em}$ = f($t$); machine loaded with generator passive resistance torque constant, with initial voltages equal to $U_m = -100$ V, $U_t = -100$ V, and end voltages equal to $U_m = 230$ V, $U_t = 230$ V. Load torque is equal to rated motor torque.
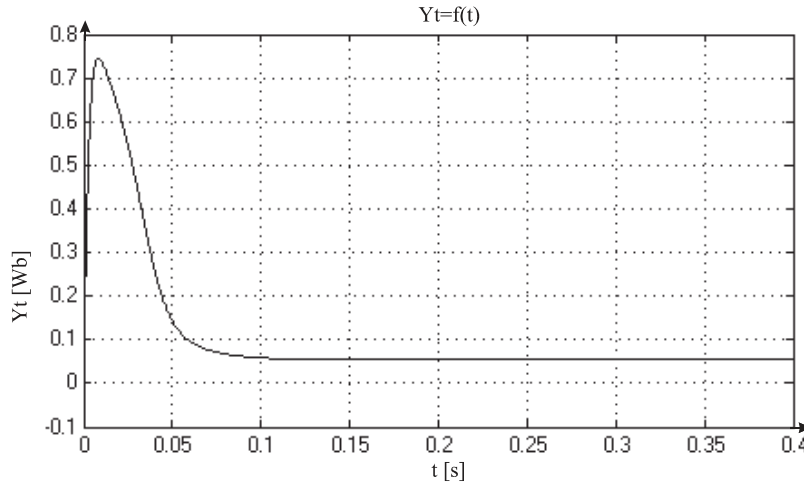
Fig. 15.   Armature linkage flux course $\Psi_t = f(t)$; machine loaded with generator passive resistance torque, with initial voltages equal to $U_m = -100$ V, $U_t = -100$ V, and end voltages equal to $U_m = 230$ V, $U_t = 230$ V.  Load torque is equal to rated motor torque
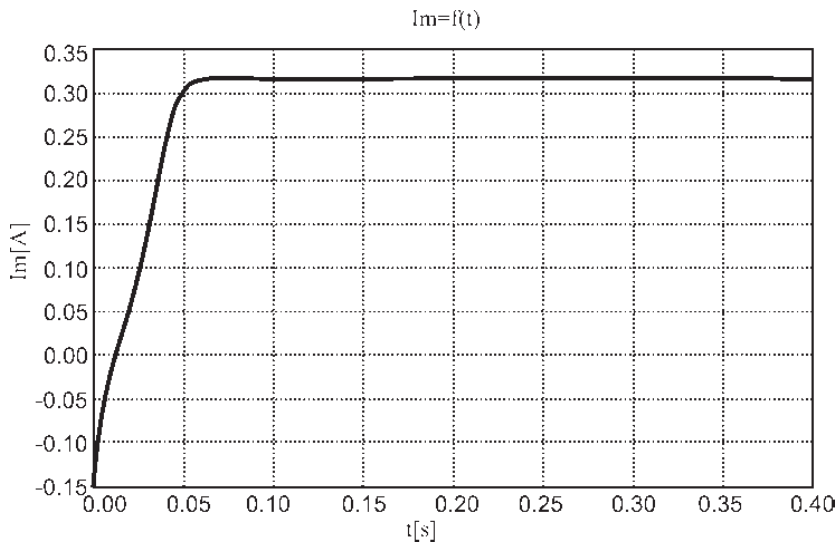


Fig. 16.   Magnetizing current course in excitation circuit $i_t = f(t)$; during voltage alteration from -100V up to 220V. Approximated magnetizing curve is allowed

Another example of DC motor state trajectory loaded with nominal active resistance torque in steady state, with initial voltages equal to $U_m = 120$, $U_t = 120$ V, and end voltages equal to $U_m = 230$, $U_t = 230$ V is presented in Fig. 17.
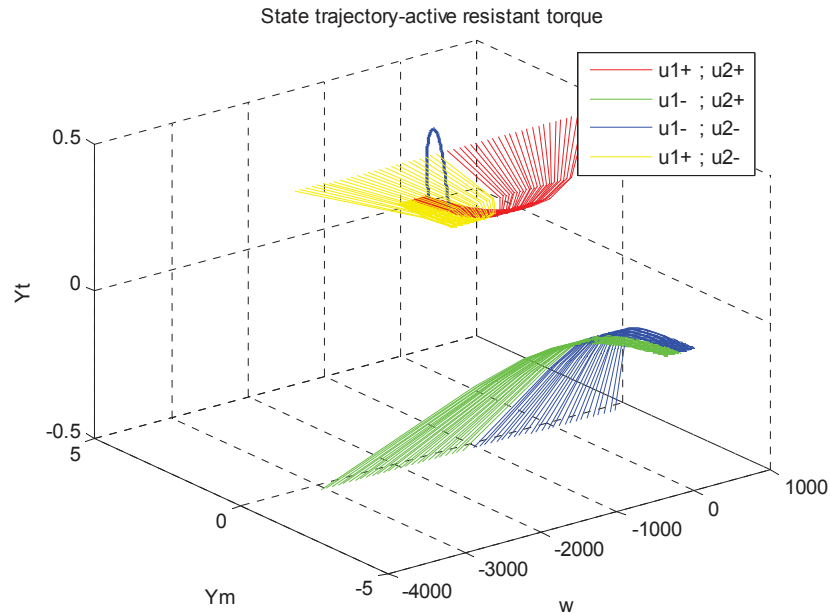
Fig. 17. State trajectories loaded with active resistance torque with start voltages $U_m = 120$, $U_t = 120$ V, and end voltages $U_m = 220$, $U_t = 220$ V presented in four quarters of the state surface. Load torque is equal to rated motor torque.


## 5. CONCLUSION

The article presents results of DC machine simulation based on the independent DC machine simulator, which is developed by the author. It has been illustrared, that the space-state method used in this simulations allows:
- magnetizing curve of this machine to be nonlinear. (approximated by arc cotangent function),
- introduce the dynamic inductance into DC machine excitation circuit calculations,
- to point noticeable differences in the state trajectory course between a linearized and nonlinear machine model,
- to find future methods for optimal motor control in accordance with the employed quality coefficient.

More-over,
- the state-space surface SSS is composed of four panels and it creates static chacteristics in 3D space,
- courses of currents, linkage fluxes and angle velocity of the machine obtained on the basis of simulations confirm the courses available in literature.

This model is universal and enables carrying out simulations loaded with all types of basic load encountered in engineering practice. Motors from small up to large hoist ones, can be simulated, while making allowances for simplification of assumptions.

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PRZEDSTAWIENIE MASZYNY PRĄDU STAŁEGO
STEROWANEJ JEDNOCZEŚNIE DWOMA NAPIĘCIAMI
METODĄ PRZESTRZENI STANU

Streszczenie

W pracy przedstawiono maszynę DC pracującą jako silnik, opisaną metodą przestrzeni stanu. Zaprezentowano model komputerowy napisany przy pomocy programu MATLAB/SIMULINK®. Model ujmuje zjawisko indukcyjności dynamicznej obwodu wzbudzenia maszyny. Trajektorie stanu przedstawiono na tle charakterystyk statycznych występujących tu w postaci powierzchni stanów ustalonych (PSU). Ponadto porównano model konwencjonalny (zlinearyzowany) z modelem o charakterystyce magnesowania przybliżonej analitycznie funkcją arcustangens. Opracowany model komputerowy może zostać wykorzystany do wyznaczenia sterowania optymalnego, niezależnie dwoma napięciami, według przyjętego wskaźnika jakości.

Słowa kluczowe: maszyna DC sterowana jednocześnie dwoma napięciami