

# Computer Aided Analysis And Design Of D.C. Motor Starting

Liviu Modran

“L. Blaga” University of Sibiu  
e-mail: liviu.modran@ulbsibiu.ro

## Abstract

*In electrical engineering education, model and digital simulation represent tools in order to understand the behavior of the different components of electric drive-systems in transitory regimes. In this paper, the direct, rheostat and chopper starting of DC machine are simulated. The models and the simulation use the environment Matlab – Simulink. The model represents an experimental circuit and the oscillograms give the instantaneous electrical variables in electrical equipment. The design of electrical devices and their interconnection can be proved without or before working in the laboratory.*

## Introduction

The drive's main purpose is to restrict the duration of transitory regimes and to protect the machine and the other devices in these regimes. The start is the first and consequently the most important transitory regime which has different aspect for every motor [1]. The static convertor can frequently improve the transitory regimes, but nowadays machines which don't have any convertor operate as well.

## Start Analysis

Constant excitation ( $\Phi = \text{constant}$ ) DC machine starting takes into consideration the load torque on the shaft and has the following methods: direct start, with rheostat starter and via electronic converter. Because of the great current,  $I_p = (8,5-13,5)I_n$  in idle running and 1,2 greater in rated load, the direct start can be applied only to small power motors ( $P_n < 2\text{kW}$ ). Rheostat starter needs to calculate the values of each resistance and how long it remains connected in the armature circuit. The starter resistances are arranged in geometric progression with common ratio the ration between the maximal and minimal armature current or torque [6]:

$$\delta = \frac{i_{max}}{i_{min}} = \frac{m_{max}}{m_{min}} \quad (1)$$

where the lower cases, respectively  $i$ ,  $m$  are referred to the machine rated quantities. The initial starting current is:

$$I_{max} = \frac{Ua}{R_a + R_p}, \quad i_{max} = \frac{1}{r_a + r_p} = \frac{1}{r_t} \quad (2)$$

Consequently the common ratio of geometric progression is:

$$\delta = \sqrt[z]{\frac{1}{r_a i_{max}}} \quad (3)$$

The starter steps are:

$$r_x = \delta^{z-x} (\delta - 1) r_a \quad (4)$$

The entire resistance on the x step is:

$$r_{tx} = \delta^{z-x+1} r_a \quad (5)$$

The DC model can be elaborated easily as the ac machine models; because of non-existent electromagnetical coupling

$$\begin{aligned} u_a &= R_a i_a + L_a \frac{di_a}{dt} - e_a \\ m - m_R &= J \frac{d\omega}{dt} \\ e_a &= -k\Phi\omega; \quad m = k\Phi i_a \end{aligned} \quad (6)$$

The first step is the first short-circuit connected resistance. It is useful to validate the calculation with simulation on the models. Matlab and Simulink represent a well-known environment which provides the possibility to develop a circuit using signs and connections as in electric circuits. The signs are classified and ordered in toolboxes, for example the power system blockset.

$$\begin{aligned} \frac{di_a}{dt} &= \frac{1}{L_a} (-R_a i_a + u_a - k\Phi\omega) \\ \frac{d\omega}{dt} &= \frac{1}{J} (k\Phi i_a - m_R) \end{aligned} \quad (7)$$

Model (7) consist of two first order differential equations. The equivalent Simulink circuit is represented in fig.1.

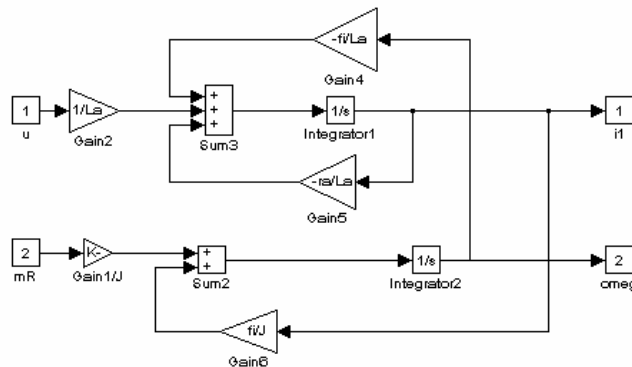


Fig. 1. Simulink circuit of DC motor with constant excitation.

On the variable excitation ( $\Phi = \text{nonconstant}$ ) DC motor the magnetization curve of the must be taken into account. The model is represented by the equations set (8):

$$\begin{aligned}
 u_a &= R_a i_a + L_a \frac{di_a}{dt} - e_a \\
 u_e &= R_e i_e + L_e \frac{di_e}{dt} \\
 m - m_R &= J \frac{d\omega}{dt} \\
 e_a &= -k\Phi\omega; \quad \Phi = L_e i_e; \quad m = k\Phi i_a
 \end{aligned}
 \tag{8}$$

Developing the normal form supposes to have on the left side only the derivatives in time , so the system is the equations set (9).

$$\begin{aligned}
 \frac{di_a}{dt} &= \frac{1}{L_a} \{ -R_a i_a + u_a - k\Phi\omega \} \\
 \frac{di_e}{dt} &= \frac{1}{L_e} \{ u_e - R_e i_e \} \\
 \frac{d\omega}{dt} &= \frac{1}{J} \{ -m_R + k\Phi i_a \}
 \end{aligned}
 \tag{9}$$

In the Simulink circuit the *Saturation* block can be replaced with *Look-Up Table* which gives an approximation point to point of the magnetisation curve  $\Phi(i_e)$ . Power system blockset allows to appeal a model which was already elaborated and verified, so it is suitable in fast laboratory work. There are three DC start automation circuits: dependent of time, of time – current and of counter-electromotive force.

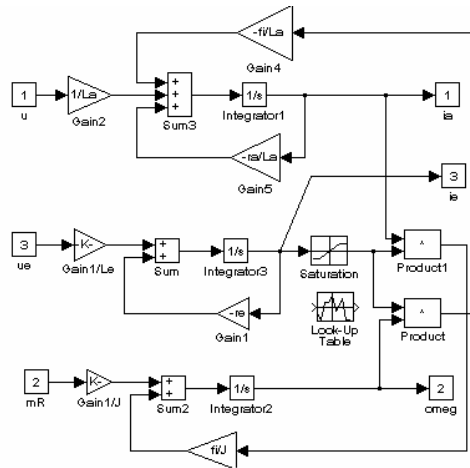


Fig. 2. Simulink circuit of DC motor with variable excitation.

The starter steps calculation is the same only the time delays depend on the load torque. If the load torque is constant ( $M_R=const.$ ) the time delays are given by the following expression [6]:

$$t_{px} = T_{mx} \ln \frac{m_{max} - m_R}{m_{min} - m_R} = T_{mx} \ln \frac{i_{max} - i_R}{i_{min} - i_R}
 \tag{10}$$

where the electromechanical time constant on each starter step is:

$$T_{mx} = \frac{J(R_a + R_x)}{K^2} = J \frac{\Omega_0}{M_n} (r_a + r_x) \tag{11}$$

if the excitation flux remains constant, the case of the DC armature reaction is completely compensated:  $K=k\Phi_e$ . The first circuit to analyze is the rheostat starting with the constant load torque. The Simulink DC motor circuit is represented in fig. 3.

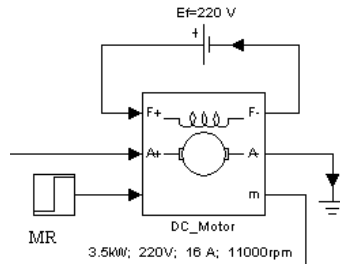


Fig. 3. DC motor with independent excitation and constant load torque [7].

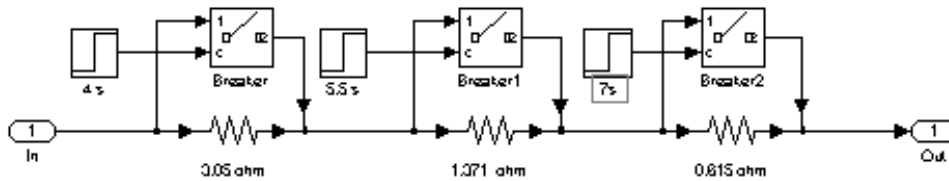


Fig. 4. DC motor starter with step resistances and delay times for the constant load torque.

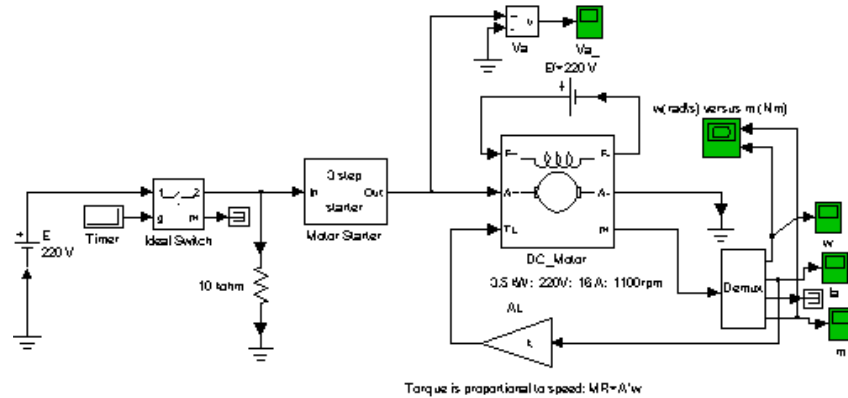


Fig. 5. DC motor Simulink circuit with independent excitation and load torque dependent of the number of rotations.

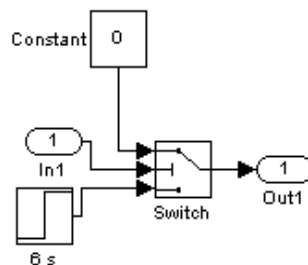


Fig. 6. DC motor starter time - current.

The starter time-current imposes that the time relay shuts the contacts before the current passes over its minimum value ( $i_{min}$ ) and makes possible a more exact short – circuit connection of the starter resistance steps. If the torque is linear, dependent of the rotation speed the delay time can be

calculated with the following expressions [6].

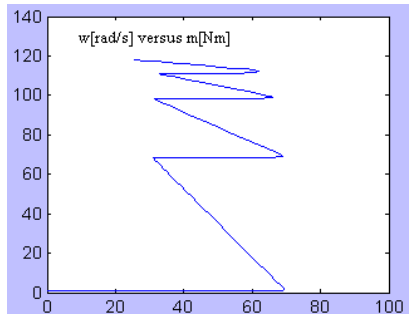
$$m_R = A\omega + B \tag{12}$$

$$t_x = \frac{1}{\alpha_x} \ln \frac{\Omega_R}{\Omega_R - \Omega_x} \tag{13}$$

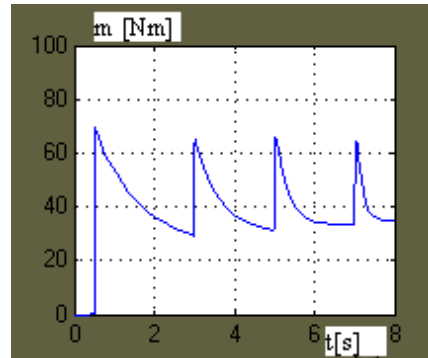
where:  $\alpha_x = \frac{\beta_x - A}{J}$ ;  $\beta_x = \frac{K^2}{R_a + R_x}$  (14)

and:  $\Omega_x = \frac{U_a - (R_a + R_x)I_{min}}{K}$  (15)

Simulation results validate or invalidate the right calculations of the starter resistances and the delay times.

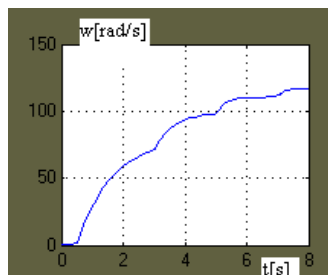


**Fig. 7.** Mechanical characteristic by resistance starting and constant load torque.

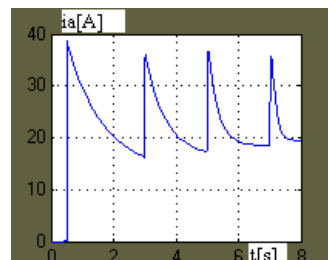


**Fig. 8.** DC motor electromagnetic torque oscillogram.

The mechanical characteristic linearity is clear and the slope increases directly proportional with the entire connected armature resistance. On the mechanical characteristic the step rheostat shorting times cannot be displayed but they appear on the oscillograms. The maximal current limit is imposed by the sliding commutator and must be preserved [3]. It is well to have two appropriate limits, which give a small torque jump and consequently protect the mechanical transmission, but it imposes more steps. Keeping the same limits of couple or current, they are non-variable if the excitation remains constant at its rated value, the start is correct. That can also be seen in the case of in line variable load torque.



**Fig. 9.** DC motor rotation speed oscillogram.



**Fig. 10.** DC motor armature current oscillogram.

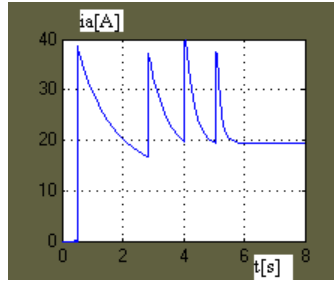


Fig. 11. DC motor armature current oscillogram with faults on the starter step .

The rotation speed oscillogram can be used for the electromotive force calculation and for the computer aided design of the voltage relays if the automation start is dependent of the voltages. A crossing over the maximal value can be done by a too small resistance or a too early connection, or both. The second starter resistance is too fast disconnected (after 4s.) and the maximal current crosses over its maximal value (40A) in fig.11. The time delays calculations must be done once more. Direct starting develops very rapidly (1s) and the current is almost 20 more grater as the rated current. The mechanical characteristic shows the same graphical variation.

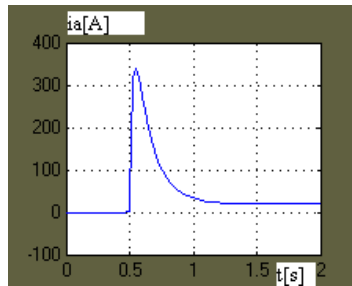


Fig. 12. Direct starting DC motor armature current oscillogram.

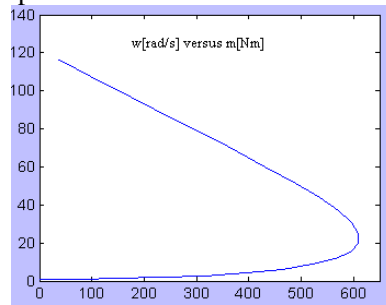


Fig. 13. Mechanical characteristic by DC motor direct starting.

**Chopper starting** has two closed loops: the external loop controls the speed and provides the reference for the internal current control loop. During the start the current is restricted by hysteresis to a maximal value of 30A (two more than its rated value): The current and speed oscillograms demonstrate that after the speed gets across its prescribed value because of over-control the current decreases below its stationary value and comes back to it. The chopper consist of a GTO thyristor (Gto) and a run diode (D1), fig. 16 supplying the DC motor with an average value ( $u_{aver}$ ) smaller than the DC voltage source and directly proportional with the chopper duty function as long as the DC motor armature current is continuous. A series connected inductor ( $L_s$  in fig. 16) smoothes out the DC motor armature current [6].

$$u_{aver} = \gamma U_{dc}; \quad \gamma \leq 1 \tag{16}$$

The required trigger signal for the GTO main thyristor is generated by the hysteresis current controller. It remarks the hysteresis band on the armature current oscillogram ( $i_a$  in fig.15).

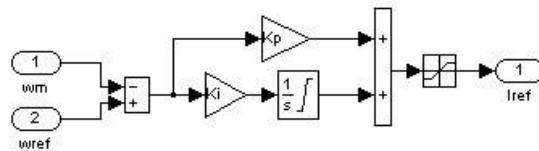


Fig. 14. PID speed cotroller.

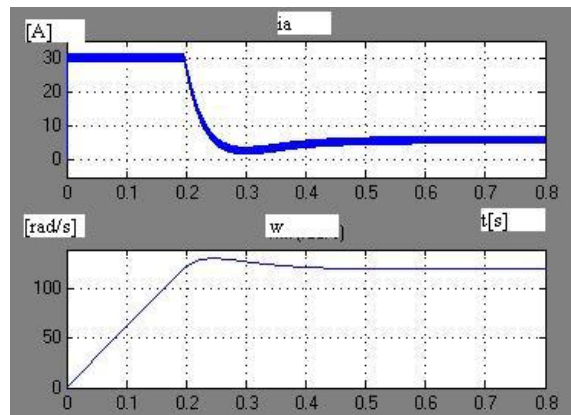


Fig. 15. DC motor armature current and speed oscillograms.

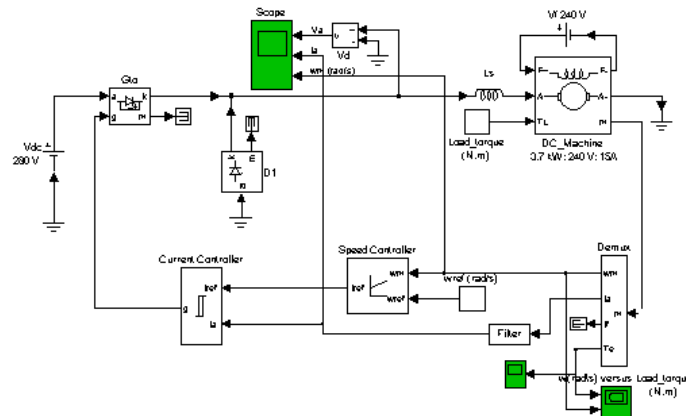


Fig. 16. DC motor drive feeding by the chopper.

## Conclusion

The modelling and simulation allows to develop a virtual laboratory in order to study the behaviour of the electric drives in transitory regimes using simulation results. The DC motor start with or without electronic converter can be studied on the mechanical characteristics and on the torque, speed and currents oscillograms. This characteristics and time variations demonstrate the risks of the direct starting. In case of the rheostat starting the correct design containing the resistance values and the time delays can be validated. Feeding the motor via electronic converter the harmonics content can be analysed and reduced. If an ordinary PID controller must be adjusted, the influence of its coefficients modification on the control quality can be identified.

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## Modelarea și simularea pornirii MCC pentru verificarea proiectării

### Rezumat

*In educația tehnică în inginerie electrică modelarea și simularea numerică reprezintă instrumente pentru a înțelege comportarea diferitelor componente ale unui sistem electric de acționare în regimuri tranzitorii. In prezenta lucrare sunt simulate pornirea directă, reostatică și cu VTC a MCC. Modelele și simularea utilizează mediul Matlab – Simulink Modelul se constituie într-un circuit experimental, iar oscilogrammele redau valorile instantanee ale mărimilor electro-mecanice din motor. Proiectarea dispozitivelor electrice și a conexiunilor poate fi verificată înainte sau fără a lucra în laborator.*