Fast simulation of the simplest electric motor with back and forth mechanical motion

R R Sattarov¹, P V Morozov²

¹ Ufa State Aviation Technical University, 12, Karla Marksa str., Ufa, 450008, Russia
² Novosibirsk State Technical University, 20, Karla Marksa ave., Novosibirsk, 630073, Russia

E-mail: electro-319@mail.ru

Abstract. The concept of the simplest electrical motor with back and forth mechanical motion as an extended version of a well-known elementary one-conductor DC motor is introduced in the paper. The basic mathematical expressions describing the motor principles of operation were presented. The fast and simple direct approach for the creation of a Simulink model was introduced. The Matlab/Simulink model of the motor consists of the subsystems including an EMF equation, a voltage equation and a movement equation with external load force. The simulation results allow understanding of transient and steady-state processes in the motor. The studying of the simplest electrical motor gives the fast and deep understanding of the main properties of the motors with oscillatory, back and forth motion.

1. Introduction

The rotary electric machines are commonly found and discussed extensively in many technical books and numerous papers [1-7]. In general, each of the electric machine types can be produced in a linear version in addition to the rotary version [1-5]. Both versions of electric machines can be used in electric drives providing a progressive unidirectional motion when the moving part goes in one direction or in oscillatory (back and forth) short-stroke applications.

The rotary machines usually work with the constant steady speed, and the acceleration and braking take relatively little time. On the other hand, unlike most electric motors, linear machines are commonly used for bidirectional, or reciprocating, motion [6-9].

Linear motors are employed in a wide range of devices as transport equipment, electric tools and robots where linear motion (required for positioning and in the operation of manipulators) is a common requirement [10-12]. In addition, reciprocating linear machines are being constructed for driving reciprocating compressors and alternators.

Today, it is a common view that the linear and rotary machine analysis is quite similar. In general, linear dimensions and displacements replace angular ones and forces replace torques. With these assumptions, the expressions for linear and rotary machine parameters are derived similarly and have a similar form [2, 3, 5, 13]. The unidirectional motion can be represented as a special case of the two-directional oscillatory motion. For students and beginners, it is useful to study the simplest machine that has the main features of oscillatory machines.
2. Simple Model of Electric Machine

2.1. Simplest machine
There is a general view that the main objective of a course devoted to the electromechanics and electric machinery is to achieve a good understanding of the basic principles [2-7]. However, the modelling of a real electric machine is not simple and obvious, so for better understanding of physical processes in an electric machine, it seems appropriate to consider a simple model of an electric machine with lumped parameters.

The majority of electric machines are electromagnetic ones, which have a basic element – a moving conductor in the magnetic field. Textbook authors, when introducing basic physics laws and phenomena that are the base of electric machinery, often consider the behaviour of the conductor in the magnetic field [1-3].

Therefore, it is advisable to study the simplest and easiest-to-understand model of a linear DC machine. It operates according to the same principles, exhibits the same behaviour as the real generators and motors [1-3]. For example, its theory and model are directly relating to voice coil actuators [4, 8, 13, 14].

![Figure 1. Simple electric machine](image)

A simple model of an electric machine is shown in figure 1. It consists of the voltage source \( u(t) \) and the resistance \( R \) connected through the switch to the pair of smooth frictionless rails. The resistance \( R \) includes resistances of the bar and parts of rails leading to the voltage source. There is the constant uniform-density magnetic field with the flux density \( B \) between the rails. The flux density is assumed to be directed into the page (Figure 1). The bar made of conducting metal having the length \( l \) is lying across the rails. The inductance of the bar can be neglected as it is rather small. Hence it is possible to focus attention on the effect of the back electromotive force (EMF).

This simple model of the elementary one-conductor electric machine is often used for explaining the principles of electromechanical energy conversion and to understand simulation techniques.

2.2. Basic equations
The four basic equations can describe the behaviour of the machine.

The voltage \( e \) induced in a wire that moves with the velocity \( v \) in the magnetic field is

\[
e = kv,
\]

where \( k = Bl \) is the constant of the simple electric machine.

Kirchhoff’s voltage law with respect to the given positive directions of voltages and current has the form:
where \( i \) is the magnitude of the current in the wire.

The electromagnetic force acting on the wire is

\[
F_{em} = k i.
\]

Newton’s law for the bar across the rails with respect to the given positive directions of the forces and velocity has the form:

\[
F_{em} - F_{ext} = m \frac{dv}{dt},
\]

where \( F_{ext} \) is the external force acting on the wire and \( m \) is the mass of the wire.

2.3. Simulink/Matlab model

The elementary one-conductor machine can be a motor or a generator. Further, the motor is considered.

If the source voltage (Figure 1) is constant, the motor model can be obtained from the linear DC machine model with respect to the ratio of the external voltage and induced voltage. The linear DC machine operation in the steady-state and transient modes is considered \([2, 3]\).

The Simulink model, as it is seen from Figure 2, is just a graphical representation of (1) – (4). The links between the equations (1) – (4) are implemented by the Simulink GoTo and From Blocks.

The elementary electric motor can be considered as a machine of reciprocating or oscillatory motion. In order to obtain this motion, it is necessary that the applied voltage changes periodically in time:

\[
e = E_m \sin(\omega t + \varphi).
\]

This is the only difference between the DC and AC motor, so the switch in the Simulink model allows obtaining the desired state (Figure 2). The DC and AC voltage levels are related as \( U_{DC} = E_m / \sqrt{2} \).

The external force depends on the load and can have a very complex form. However, in most cases \([6, 8, 15–18]\), it can be assumed that the external force is the sum of the damping force that proportional to the velocity:

\[-F_{ext} = -k_d v\]

and the inertia force that is raised due to carrying the load mass by the motor:

\[-F_{ext} = -M \frac{dv}{dt}\]

In general, it could be assumed that the external force is the combination of these two forces, which can be implemented by the PID block in the Simulink (Figure 2).

3. Simulation Results

The example of the simulation is stated below.

The parameters of the simulated motor and load are the following: \( R = 1 \) Ohm; \( B l = 2 \) T·m; \( m = 0.2 \) kg; \( M = 3m \); \( k_d = 0.1 \) N·s/m. The AC source has the parameters: \( E_m = 10 \) V ; \( f = 10 \) Hz and the DC voltage is \( U_{DC} = E_m / \sqrt{2} \).

Figure 3 shows two plots of the motor velocity (m/s) and current (A) as time (s) functions. The left plot contains the simulation results for DC excitation, and the right plot contains the simulation results for AC excitation.
**Figure 2.** Simulink/Matlab model

**Figure 3.** Simulation results for DC (left) and AC (right) excitation

Figure 3 describes the transient process in the linear DC motor. The motor velocity and current levels change exponentially. Therefore, the motor works without current and velocity overshoots that
can damage the motor. The transient time is less than 1 s. The motor time constant is relatively short, and the motor operation mode becomes stationary in a short time. The velocities and currents become constant when steady state is achieved.

When AC voltage is applied, the velocity and current change is periodical in the steady-state model. The transients have the same speed in the electric subsystem, while the velocities achieve their steady values faster due to damping in the mechanical subsystem. Further simulation can give the understanding that the motor during a cycle also works in generator mode in this AC case. The inertia of the moving mass prevents the increase of the speed during acceleration and maintains its value during braking. As the velocity effects on the EMF and voltage, it is easy to understand that in this case, the effect of the moving mass kinetic energy is similar to the effect of electric field energy of a capacitor.

4. Conclusion
The proposed model clearly describes the principles of operation of the simplest linear electric motor. The model implementation completely reflects the basic equations describing the physical processes inside the motor. The subsystems of the model take into account the main features of linear motors for the derived mathematical relations describing motion processes in the considered motors. As it follows from the mathematical simulation in Matlab/Simulink, the current and transient velocity-time is short enough. For a particular set of parameters, the current and velocity setting time was less than 1 s. The motor operation is stable without any overshoots that can cause its damage.

The proposed simplest motor with back and forth mechanical motion and its fast simulation model can be the basis for the understanding and studying of the most important properties of electromechanical oscillatory systems.

References
[1] Petrov G N 1974 Electric Machines vol 1 (Moscow: Energiya)
[2] Booth D A 1990 Contactless Electric Machines (Moscow: Higher School)
[3] Chapman S J 2005 Electric Machinery Fundamentals (New York: McGraw-Hill)
[4] Boldea I and Nasar S A 1997 Linear Electric Actuators and Generators (Cambridge: Cambridge University Press)
[5] Gieras J F 1994 Linear Induction Drives (U.K.: Oxford Univ. Press)
[6] Svecharnik D V 1988 Electric Machines of Direct Drive: Gearless Electric Drive. (Moscow: Energoatomizdat)
[7] Boldea I and Nasar S A 2001 Linear Motion Electromagnetic Devices (New York: Taylor&Francis)
[8] Sattarov R R, Enikeev R D and Razyapov M V. 2019 Dynamics of Fast-Switching Electrodynamic Actuator for Fuel Injection in Internal Combustion Engines Proceedings of the 13th International IEEE Scientific and Technical Conference Dynamics of Systems, Mechanisms and Machines, Dynamics 2019 (Omsk, Russia: IEEE) 1–6
[9] Simonov B F, Neyman V Y and Shabanov A S 2017 Pulsed Linear Solenoid Actuator for Deep-Well Vibration Source Journal of Mining Science 53(1) 117–125
[10] Isermann R 2003 Mechatronic Systems (Berlin: Springer)
[11] Shan Y and Leang K K 2009 Repetitive Control With Prandtl-Ishlinskii Hysteresis Inverse for Piezo-Based Nanopositioning American Control Conference St. Louis, MO
[12] Neiman V Yu and Smirnova Yu B 2006 New principles and increase of energy efficiency of electromagnetic machines Proceedings of the 1st International Forum on Strategic Technology (Ulsan: University of Ulsan) 314–315
[13] Gieras J F and Piech Z J 2000 Linear Synchronous Motors: Transportation and Automation Systems (Boca Raton FL: CRC Press)
[14] Sattarov R R 2016 Electromechanical transients in passive suspension systems with eddy current dampers 2016 9th International Conference on Power Drives Systems, ICPDS 2016 - Conference Proceedings (Perm, Russia: IEEE) 1–5

[15] Sheng Gu Gu 2008 Fundamentals of Electrical Machines and Drivers (China Mechina Press, Beijing)

[16] Jouaneh M 2012 Fundamentals of Mechatronics 1a ed. United States of America: Cengage Learning

[17] Neyman L A and Neyman V Y 2016 Dynamic model of a vibratory electromechanical system with spring linkage 11 International forum on strategic technology (IFOST 2016) 2 23–27

[18] Neyman L A, Neyman V Y and Obukhov K A 2017 New method of the synchronous vibratory electromagnetic machine mechatronic module control The 18 international conference of young specialists on micro/nanotechnologies and electron devices (Novosibirsk: NSTU) pp 516–519.