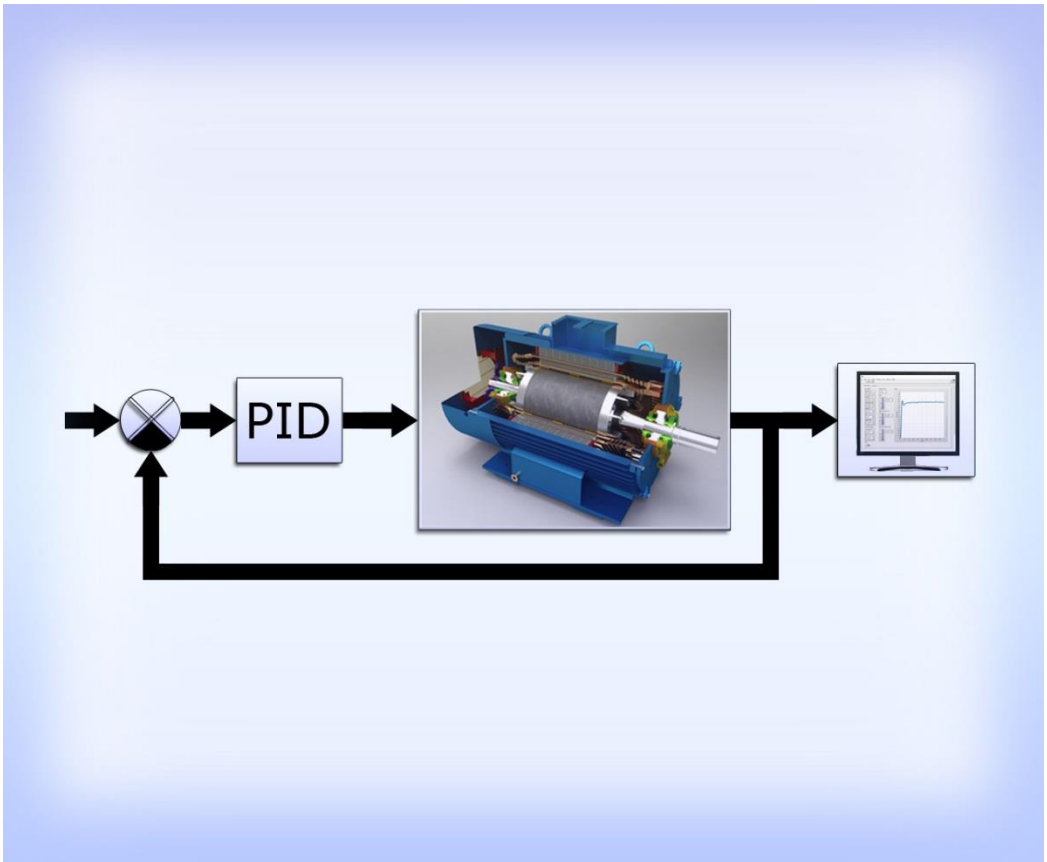
Electromechanical Machines Simulation Toolkit

User Manual



Ovak Technologies
2015

Contents

1. Introduction

1.1. Definitions and acronyms

EMMSim – Electromechanical Machines Simulation

LV – LabVIEW

BL – Brushless

DC – Direct current

AC – Alternating current

EMF – Electromotive force

BLDC – Brushless direct current electric motor

1.2. Purpose

This document is designed to provide necessary information to LabVIEW developers in order to create applications using EMMSim toolkit. The document describes the architecture of the toolkit and provides the necessary information about how to use it.

1.3. Scope

EMMSim is a set of electrical motors' models that is designed to help user to create systems simulations where electrical engines are needed. The user can choose the motor type, its parameters, connect it to any other system and follow the way it works.

1.4. Overview

EMMSim is a palette of different types of motors and additional subsystems, which will help user to simulate motors' controls.

2. Structure

2.1. Brushed DC motor

The brushed DC motor is a classic motor, which is widely used in control systems. The main principle is based on **Fleming's left-hand rule**. In order to understand this rule, please see the picture below.

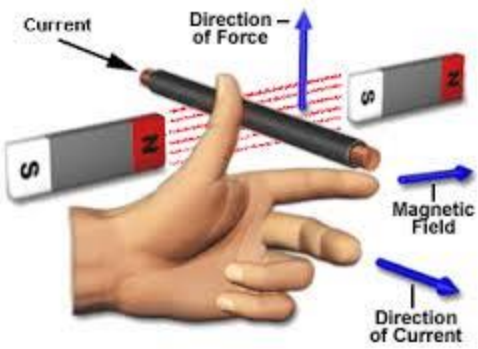


Figure 1 Fleming's left-hand rule

The forces cause a turning effect on the coil, which rotates it.

The motor parameters supposed to be constant during the simulation are the following:

- J – motor inertia, kg.m^2;
- B – viscous damping coefficient;
- R – internal resistance, Ohm;
- L – internal inductance, mH;
- K_t – torque constant, N-m/A;
- K_{emf} – back EMF constant, V/rad/s;
- Omega (t=0) – angular speed of the motor right before it was started, rad/sec.

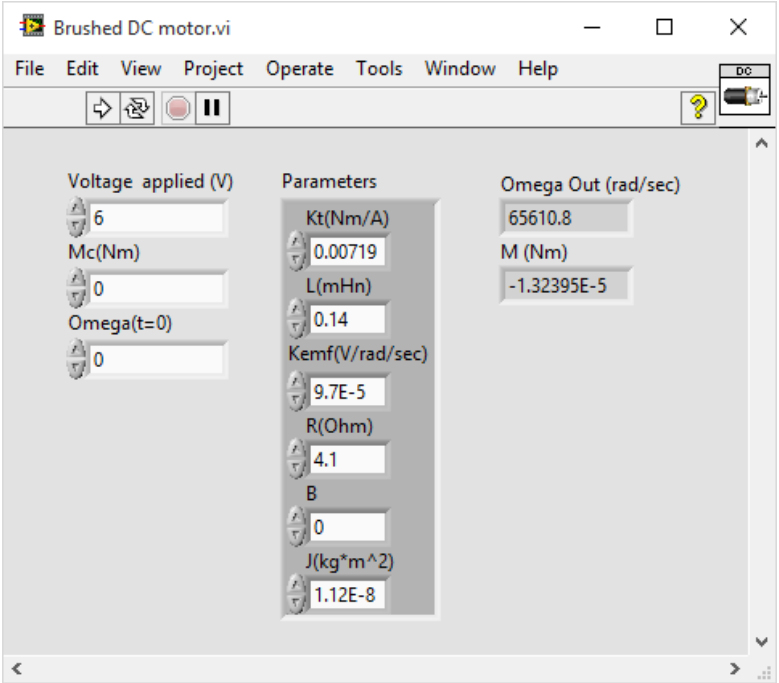


Figure 2 Brushed DC Motor Front Panel

Motor input signals are the following:

- V_{app} – voltage applied, V;
- M_c – load torque, N-m.

The user can follow transient phenomena. The following differential equations were used to create the model: [1]

$$\left(I(t)K_T - \dot{\theta}B\right)\left(\frac{1}{J}\right) = \ddot{\theta}$$

$$\left[V_{app} - \dot{\theta}K_{emf} - RI(t)\right]\frac{1}{L} = \frac{di}{dt}$$

The angular speed is the following:

$$\omega = \frac{d\theta}{dt}\,(\text{rad/sec})$$

The torque equation is the following:

$$M = J\frac{d\omega}{dt} - M_c$$

The purpose is to calculate motor angular speed and torque.

2.2. BLDC motor

Brushless motors are synchronous motors, which are powered by DC electric source. They are permanent magnet motors where the function of commutator and brushes were implemented by solid-state switches. There are single-phase, two-phase and three-phase BLDC motors. However, the most popular and widely used are three-phase motors. They produce a trapezoidal back EMF, and motor current generates a pulsating torque.

The motor parameters supposed to be constant during the simulation are the following:

- *R* – stator resistances per phase are equal for all phases. *Ra=Rb=Rc=R*;
- *L* – stator inductances per phase are equal for all phases. *La=Lb=Lc=L*;
- M – the mutual inductances are equal too. *M=Mab=Mac=Mbc=Mba=Mca=Mcb*;
- *B* – damping constant;
- *J* – inertia of the motor;
- K_{emf} – back EMF constant.

The motor input signals are:

- V_a, V_b, V_c (V) voltage inputs on phases;
- Mc (N-m) load torque.

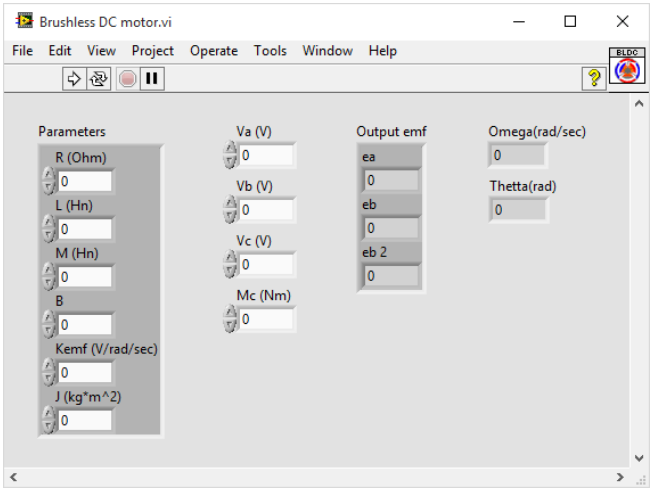


Figure 3 Brushless DC motor Front Panel

The purpose is to calculate motor angular speed and rotor angle θ.

Three-phase BLDC motor equations are the following:

$$V_a = i_a R + L\frac{di_a}{dt} + M\frac{di_b}{dt} + M\frac{di_c}{dt}$$

$$V_b = i_b R + L\frac{di_b}{dt} + M\frac{di_a}{dt} + M\frac{di_c}{dt}$$

$$V_c = i_c R + L\frac{di_c}{dt} + M\frac{di_b}{dt} + M\frac{di_a}{dt}$$

When a BLDC motor rotates, each winding generates a back EMF voltage. It opposes the main voltage supplied to the windings according to *Lenz's Law*. The speed increases, back EMF also increases and the polarity of the back EMF is opposite to the energized voltage. The back EMF is a function of rotor position (θ) and has the amplitude E=K_{emf}* ω (K_{emf} is the back EMF constant).

The respective back EMF in the windings is represented by the following equations: [2]

$$e_a = \begin{cases} \left(\frac{6E}{\pi}\right)\theta \left(0 < \theta < \frac{\pi}{6}\right) \\ E\left(\frac{\pi}{6} < \theta < \frac{5\pi}{6}\right) \\ -\left(\frac{6E}{\pi}\right)\theta + 6E\left(\frac{5\pi}{6} < \theta < \frac{7\pi}{6}\right) \\ -E\left(\frac{7\pi}{6} < \theta < \frac{11\pi}{6}\right) \\ \left(\frac{6E}{\pi}\right)\theta - 12E\left(\frac{11\pi}{6} < \theta < 2\pi\right) \end{cases}$$

$$e_b = \begin{cases} -E\left(0 < \theta < \frac{\pi}{2}\right) \\ \left(\frac{6E}{\pi}\right)\theta - 4E\left(\frac{\pi}{2} < \theta < \frac{5\pi}{6}\right) \\ E\left(\frac{5\pi}{6} < \theta < \frac{9\pi}{6}\right) \\ -\left(\frac{6E}{\pi}\right)\theta + 10E\left(\frac{9\pi}{6} < \theta < \frac{11\pi}{6}\right) \\ -E\left(\frac{11\pi}{6} < \theta < 2\pi\right) \end{cases}$$

$$e_c = \begin{cases} E\left(0 < \theta < \frac{\pi}{6}\right) \\ -\left(\frac{6E}{\pi}\right)\theta + 2E\left(\frac{\pi}{6} < \theta < \frac{\pi}{2}\right) \\ -E\left(\frac{\pi}{2} < \theta < \frac{7\pi}{6}\right) \\ \left(\frac{6E}{\pi}\right)\theta - 8E\left(\frac{7\pi}{6} < \theta < \frac{9\pi}{6}\right) \\ E\left(\frac{9\pi}{6} < \theta < 2\pi\right) \end{cases}$$

The generated electromagnetic torque is the following:

$$T_e = K_{emf}\{f_a(\theta)i_a + f_b(\theta)i_b + f_c(\theta)i_c\}(\text{Nm})$$

$$f(\theta) = \frac{e}{E}$$

The simple system equation of motion is:

$$J\frac{d\omega}{dt} + B\omega = T_e - M_c$$

Where, M_c is the load torque.

2.3. Stepper motor

Stepper motors are usually used in positioning problems via digital control. There are two, four and eight phase motors. The current motor is two-phase stepping motor and is controlled by two impulse voltage signals.

The physically constant parameters for the motor are the following:

- R – active resistance of a stator wind, Ohm;
- L, L0, M, M0 – to calculate *L1*, *L2*, *M* which are correspondingly first and second phase inductions and their mutual induction;
- D – viscous damping coefficient;
- J_{sum} – rotor complete moment of inertia, kgm^2;
- 2p – number of rotor poles;
- λ – angle between two phases, rad;
- Ψ_m – maximum flux linkage, weber;
- Omega (t=0) – angular speed right before motor starts.

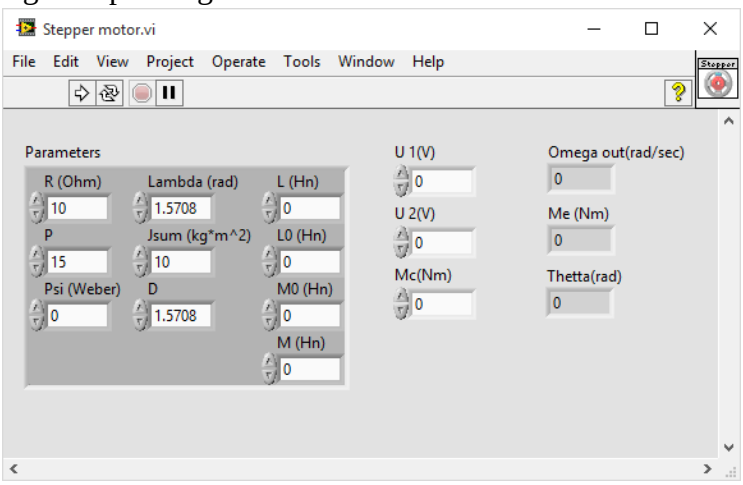


Figure 4 Stepper motor Front Panel

Motor input signals are the following:

- U1, U2 (V) voltage inputs on phases;
- Mc (N-m) load torque.

The purpose is to have the following outputs:

- Omega out (rad/sec) – motor angular speed;
- Theta (rad) – rotor angular position.

The following equations are used to create dynamic characteristics of the system:[4]

$$U_1 = i_1 R + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} + M \frac{di_c}{dt} + \frac{d}{dt}(\psi_m \sin p\theta)$$

$$U_2 = i_2 R + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} + M \frac{di_c}{dt} + \frac{d}{dt}(\psi_m \sin p(\theta - \lambda))$$

Where,

$$L_1 = L_0 + L\cos 2p\theta$$

$$L_2 = L_0 + L\cos 2p(\theta - \lambda)$$

$$M = -M_0 + M\cos 2p\left(\theta - \frac{\lambda}{2}\right)$$

The equation of torques on the rotor:

$$\mathrm{M_e} = \mathrm{h}\psi_m i_1 \sin \mathrm{p}\,\theta - \psi_m i_2 \sin p(\theta - \lambda)$$

$$\frac{J_{sum}}{p}\frac{d^2\theta}{dt} + D\omega = M_e - M_c$$

Where *i1* and *i2* currents are calculated in *"Stepper motor subsystem 1.vi"*.

2.4. Asynchronous AC motor

The second name of this motor is *"Induction motor"*. This motor's rotor and generated magnetic field are rotating with different frequencies. The rotating torque is generated as a result of interaction between stator's rotating magnetic field and current in the rotor. The motor's parameters which are supposed to be constant during the simulation are in the *"Parameters"* cluster [5].

- J – inertia moment of the rotating parts;
- r1 – resistance;
- x1 – inductive resistance of the rotor;
- x'2 – inductive resistance of the rotor;
- r'2 – resistance;
- c – coefficient;
- Phase num – number of phases;
- Pole pairs num – number of pole pairs.

The input signals of the motor are:

- Amplitude – input AC voltage amplitude;
- Frequency – input AC voltage frequency;
- Load torque – external torque influencing on the rotor.

This VI is designed to calculate output angular speed and generated torque.

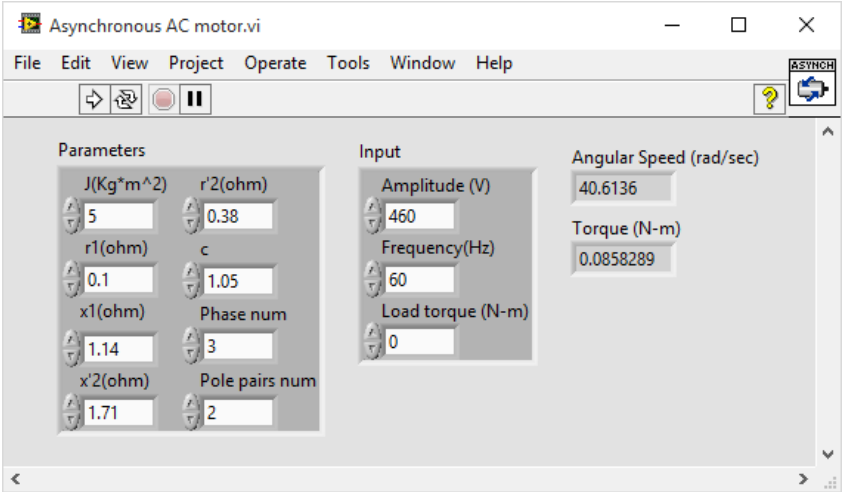


Figure 5 Asynchronous AC motor Front Panel

The rotating torque is:

$$M = \frac{m_1 I'^2{}_2 \left(R'^2/_S\right)}{\omega_1}$$

This equation can be transformed using replacement diagram. Thus, the current can be calculated in the following way:

$$I'_2 = \frac{U_1}{\sqrt{\left(r_1 + \frac{cR'_2}{S}\right)^2 + (x_{s1} + cx'_{S2})^2}}$$

As $\omega_1 = 2\pi n_1/60 = 2\pi f/p$

Assuming that p, m_1, r_1, R'_2, x_{s1}, x'_{S2}, U_1, f are constant we have

$$M = \frac{m_1 p U_1{}^2 r_2{}'}{2\pi f[(r_1 + cr_2{}')^2 + (x_{s1} + cx_{S2}{}')^2]}$$

2.5. Synchronous AC motor

The synchronous motors are AC motors which rotation speed is synchronized with rotation of the magnetic field generated in stator. In order to have a mathematical model of a pole synchronous motor we use *d-q* coordinate system. Let us have a look on that system equations after explaining the main principles of synchronous motor's work. Just like the other motors, synchronous motors have stator and rotor. The stator of synchronous motor and stator of induction motor are similar in construction. The rotor is either a permanent magnet or an electrical magnet with DC power supply. DC power either is given to rotor with external supply or is transformed from main AC power. As the field is generated in the stator, it is relating with the rotor field and rotates it. The main feature of this motor is that its speed does not depend on the load. Now let us discuss the mathematical model of this motor.

The equations are given as vector equation [6].

$$\vec{U} = R\vec{\imath} + L\frac{d\vec{\imath}}{dt} + \omega_r L_z \vec{\imath},$$

Where,

$$\vec{U} = \left|U_d, U_q, U_f, 0, 0\right|^t,$$

$$\vec{\imath} = \left|i_d, i_q, i_f, i_{dr}, i_{qr}\right|,$$

$$R = \begin{vmatrix} R_s & & & & \\ & R_s & & & \\ & & R_f & & \\ & & & R_{dr} & \\ & & & & R_{qr} \end{vmatrix}$$

$$L = \begin{vmatrix} L_d & 0 & M_d & M_d & 0 \\ 0 & L_q & 0 & 0 & M_q \\ M_d & 0 & L_f & M_d & 0 \\ M_d & 0 & M & L_{dr} & 0 \\ 0 & M_q & 0 & 0 & L_{qr} \end{vmatrix}$$

$$L_z = \begin{vmatrix} 0 & -L_q & 0 & 0 & -M_q \\ L_d & 0 & M_d & M_d & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

- ω_r – rotor rotation speed;
- $R_d, R_q, R_f, R_{dr}, R_{qr}$ – stator active resistances by d-q axes, energizing and damper resistances by d-q axes;
- $L_d, L_q, L_f, L_{dr}, L_{qr}$ – own inductances by *d-q* axes, energizing and damper inductances by *d-q* axes;
- M_d, M_q – mutual inductances between winds by *d-q* axes;
- U_d, U_q – stator voltages by *d-q* axes;
- $i_d, i_q, i_f, i_{dr}, i_{qr}$ – stator currents by d-q axes, energizing and damper currents by d-q axes.

The electromagnetic torque M_e is

$$M_e = U_d i_d + U_q i_q - R_s\left({i_d}^2 + {i_q}^2\right)$$

The rotor movement equation is

$$T_j \frac{ds}{dt} = M_c - M_e$$

$$\omega_r = (1 - s)\omega_s$$

Where,

- T_j – inertia constant;
- M_c – load torque;
- ω_s – synchronous rotation speed.

The discussed matrix equation is equal to a multi circuit diagram.

Where,

- $E_{d1} = -\omega_r L_q R_q$
- $E_{d2} = -\omega_r M_q i_{rq}$
- $E_{q1} = \omega_r L_d i_d$
- $E_{q2} = \omega_r M_d i_f$
- $E_{q3} = \omega_r M_d i_{dr}$

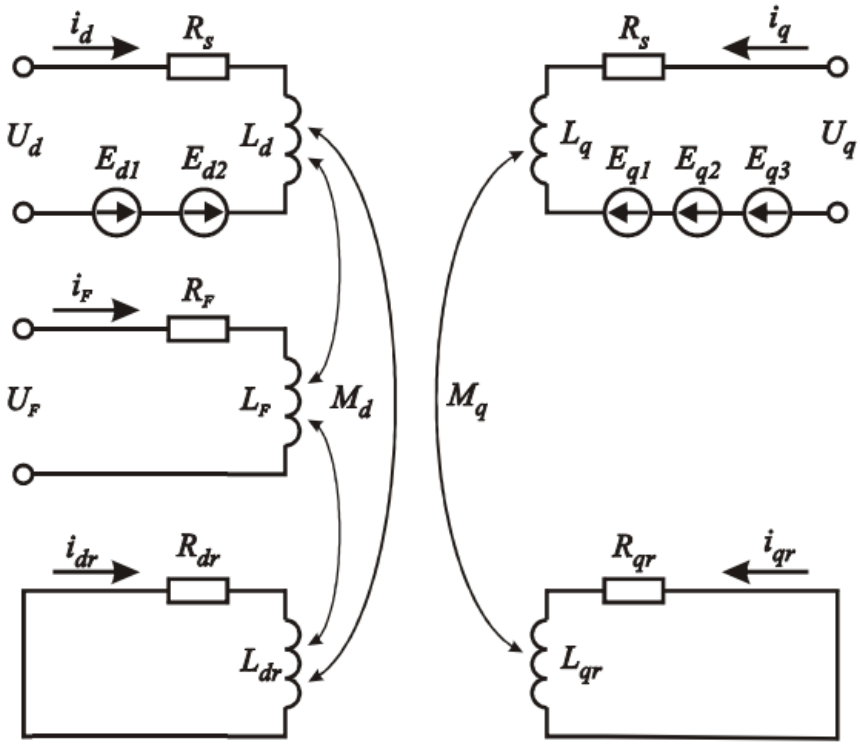


Figure 6 Equivalent circuit

The mathematical model is built according to these circuits.

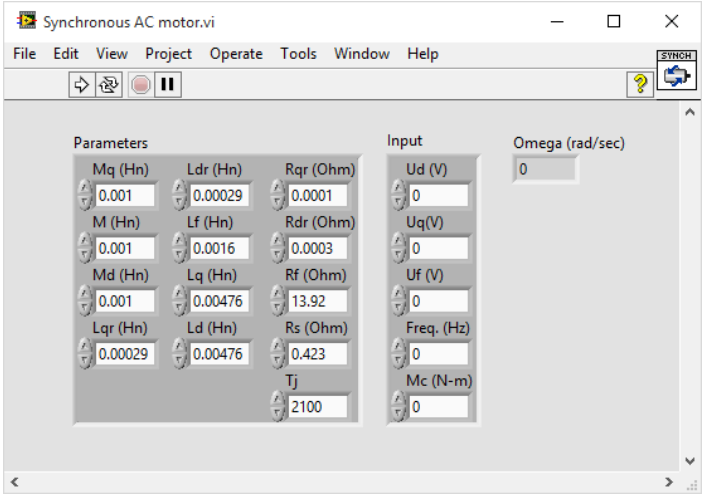


Figure 7 Synchronous AC motor Front Panel

3. Examples

3.1. Angular position control system

An angular position control system is shown in this example. Control system is implemented with Brushed DC motor and PID Subsystem. There are random disturbance torques influencing in the controlled object. User can follow control process on the front panel. Clicking on *"Slow"* button you can follow the process in slow motion. [3]

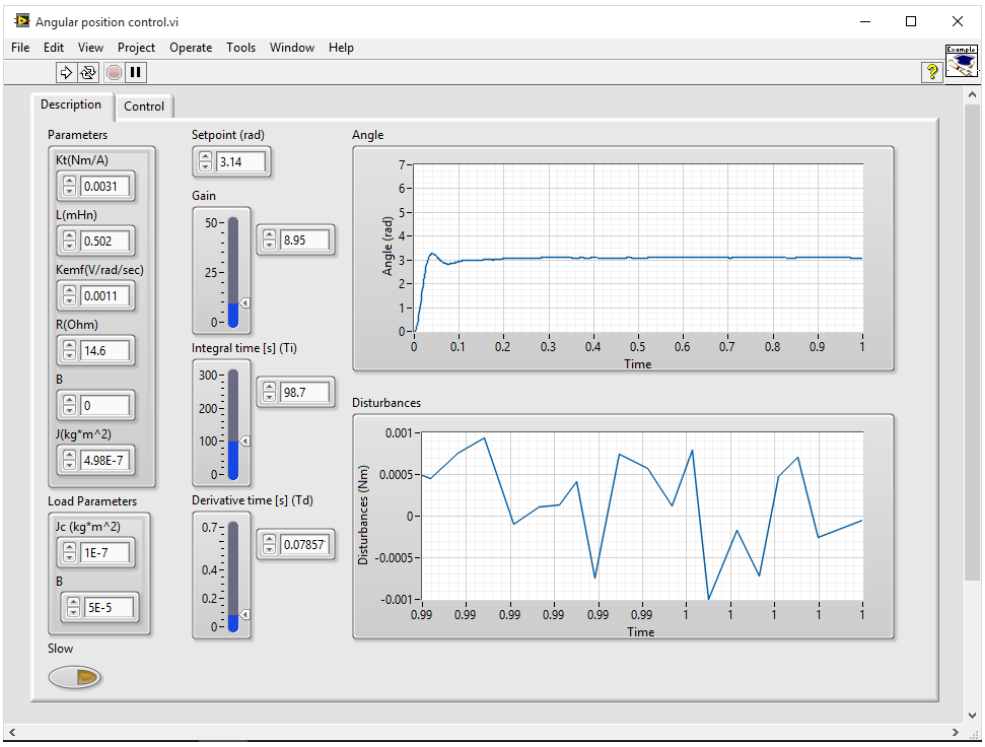


Figure 8 Angular position control "Description" tab

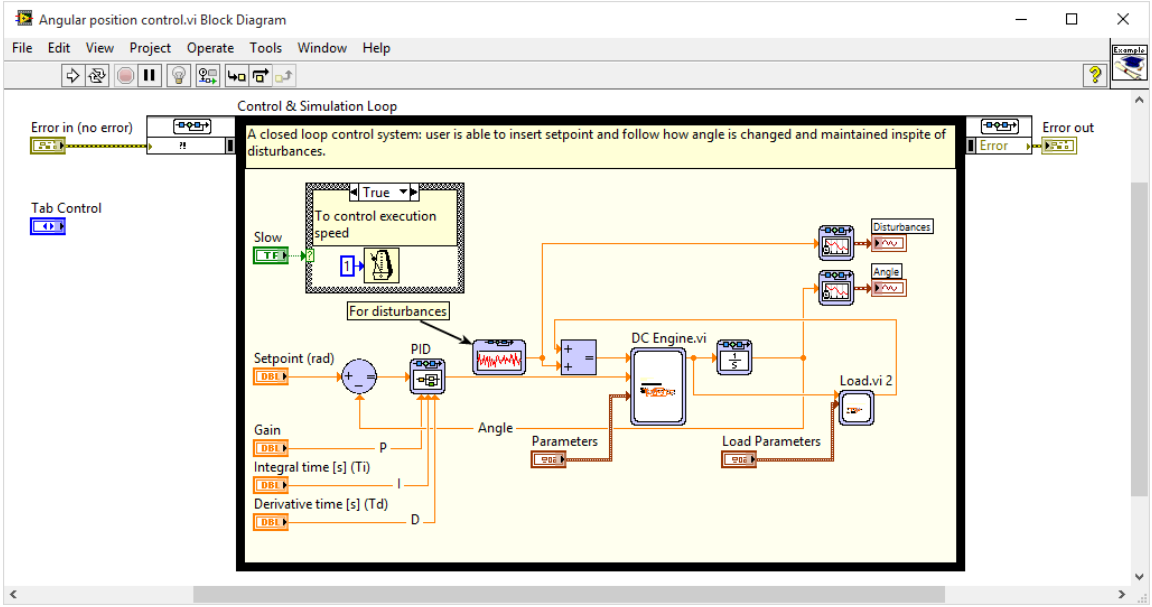


Figure 9 Angular position control Block Diagram

3.2. Stepper motor manual control

This example has been designed for user to have an experience manipulating EMMSim stepper motor and additional elements. In addition, after reviewing this example, you will have some experience in controlling stepper motors. Manual control will let you get the principle of motor. For more instructions, please, see *"Description"* tab.

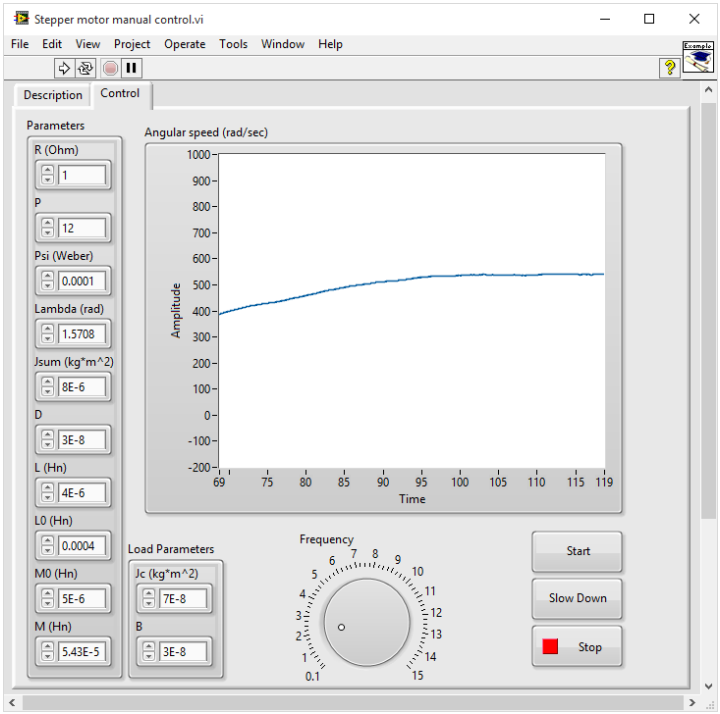


Figure 10 Stepper motor manual control «Control» tab

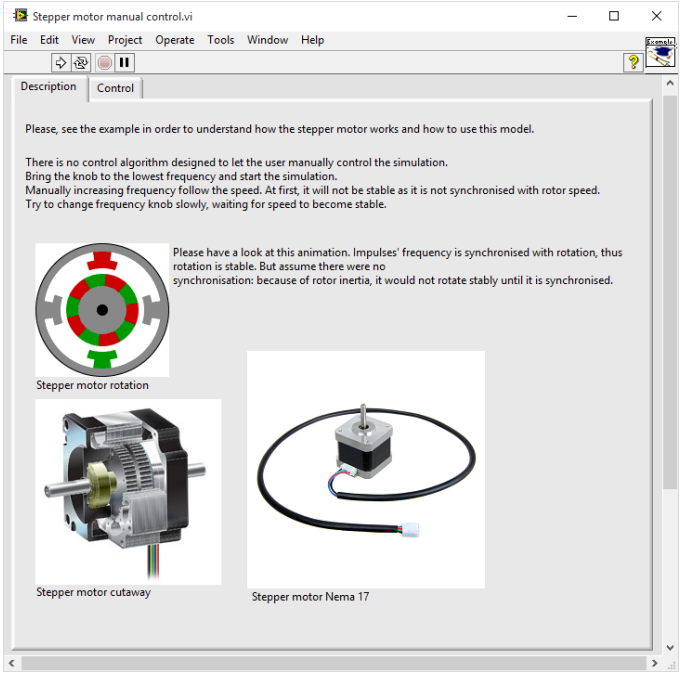


Figure 11 Stepper motor manual control «Description» tab

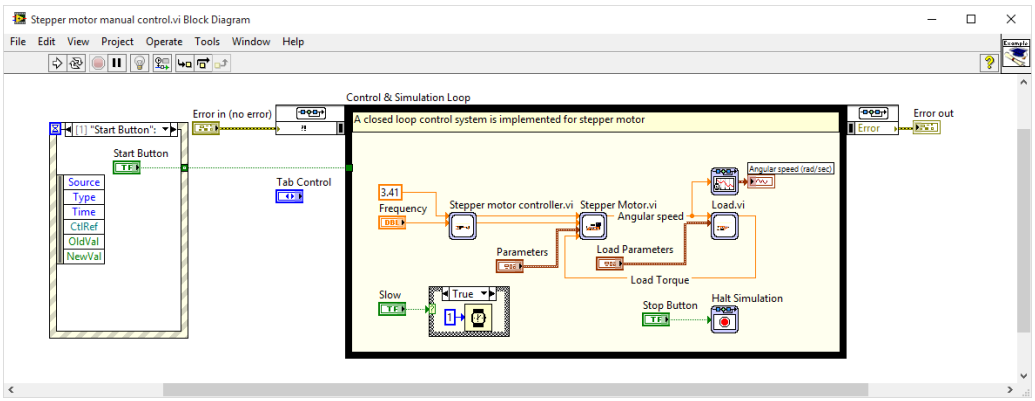


Figure 12 Stepper motor manual control Block Diagram

3.3. BLDC motor hall sensor six-step control system

Hall sensors are usually used in motors for control. Because there is constant magnetic field on the rotor and field rotates. Hall sensors will change voltage direction twice while rotor makes a whole rotation. Our motor is a three-phase motor and assume we have a hall sensor on each of phases. There are six steps, which you can see on the spreadsheet in description. Depending on hall sensors we can find out rotor position (in one of six ranges).

There are the following inputs signal in the spreadsheet:

- Plus
- Minus
- Zero

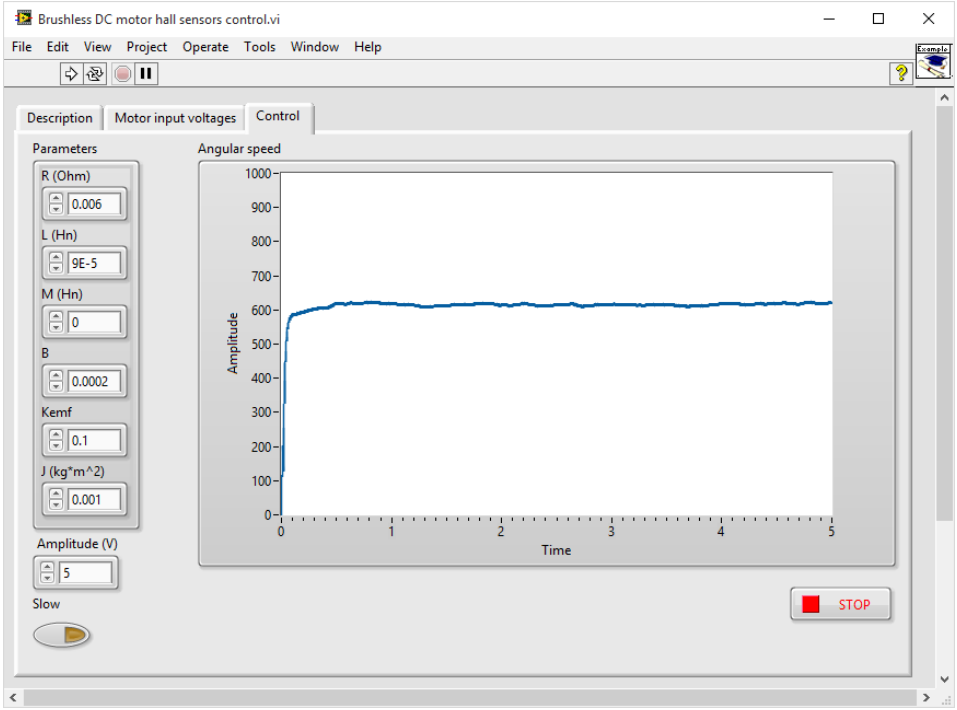


Figure 13 Brushless DC motor hall sensors control "Control" tab

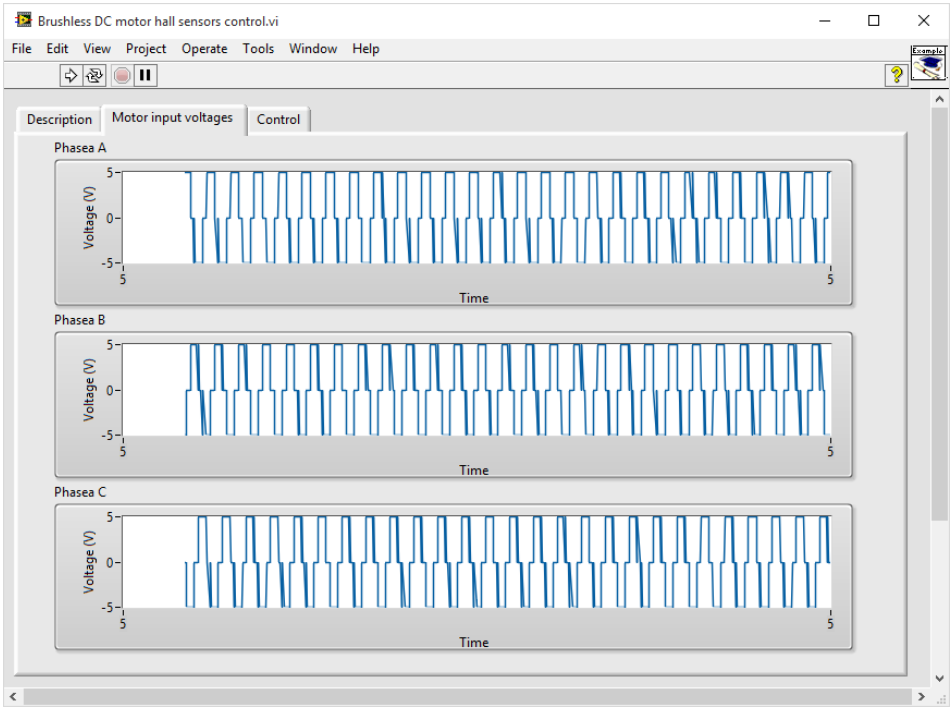


Figure 14 Brushless DC motor hall sensors control "Motor input voltages" tab

On figure below, you can follow rotor position by boolean indicators. The six positions are: *A, A&B, B, B&C, C, C&A.*

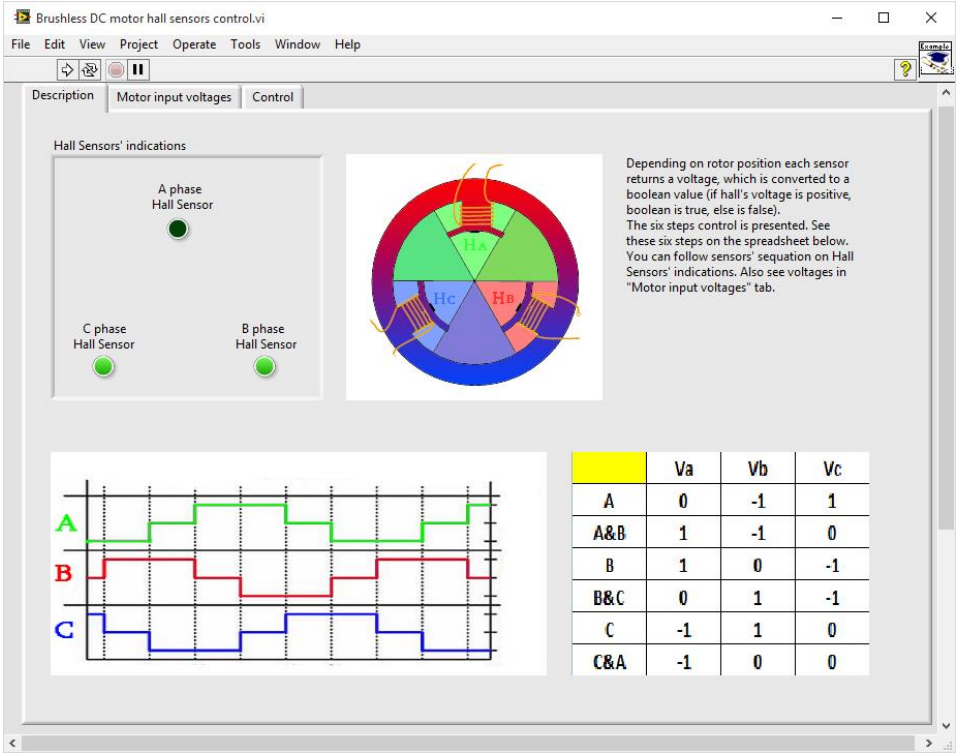


Figure 15 Brushless DC motor hall sensors control «Description» tab

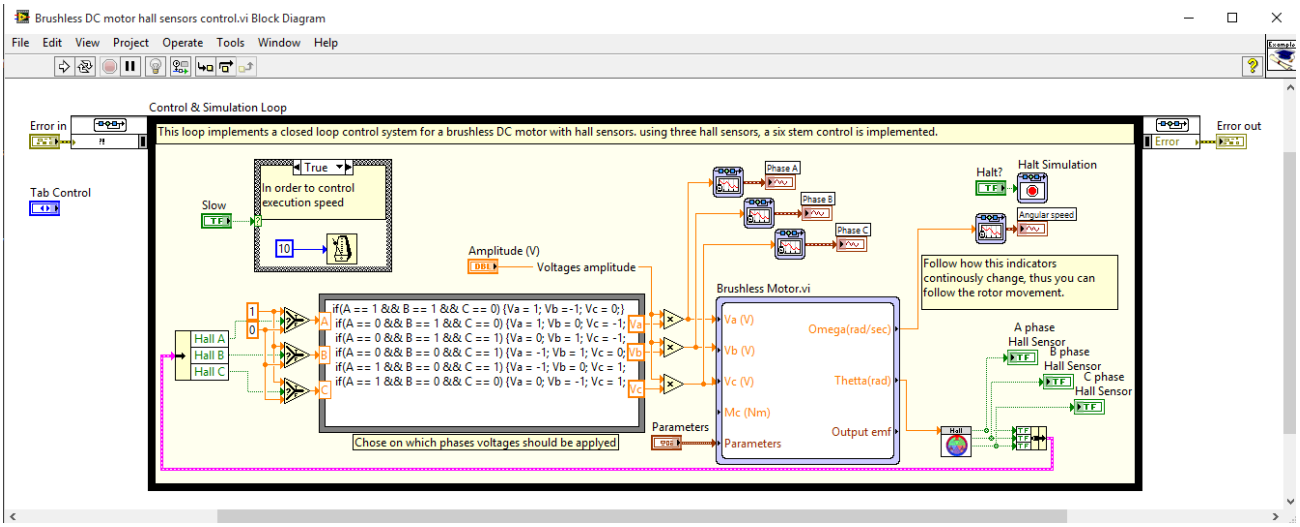


Figure 16 Brushless DC motor hall sensors control Block Diagram

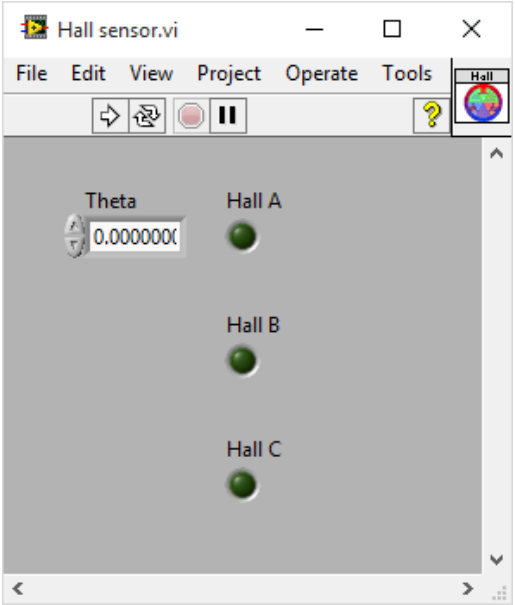


Figure 17 Hall sensor Front Panel

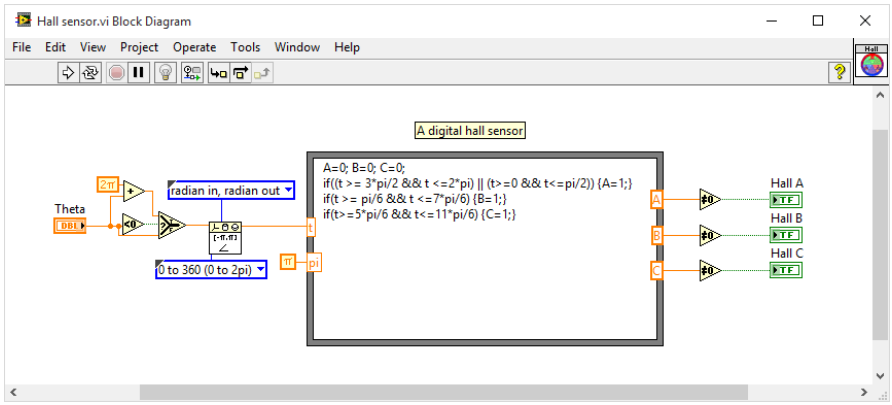


Figure 18 Hall sensor Block Diagram

4. Palettes items

The EMMSim palettes structure is shown in the pictures below.

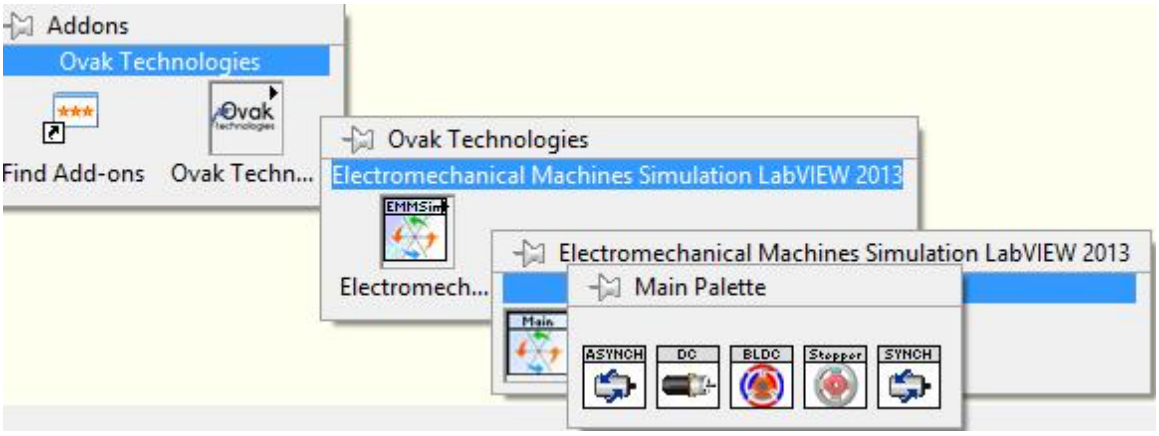


Figure 19 "Main" palette

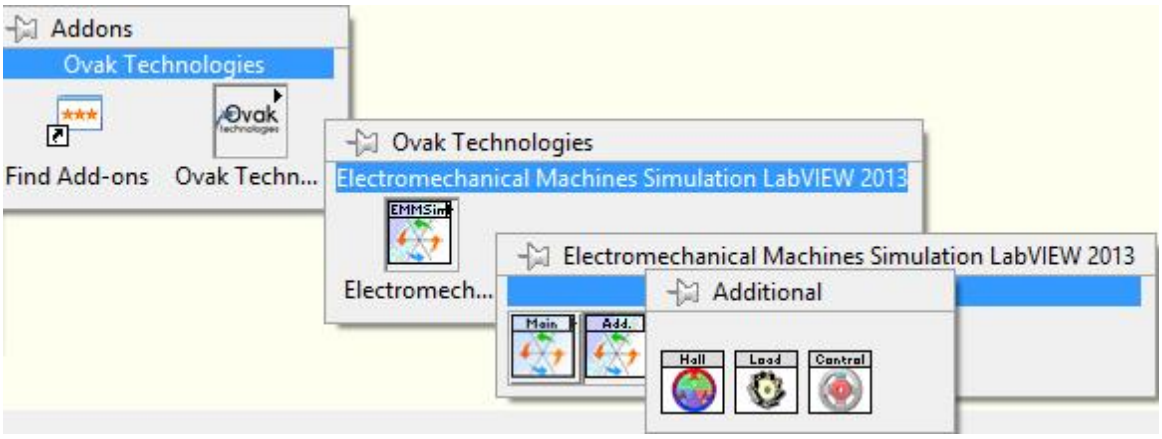


Figure 20 "Additional" palette

	Icons	File names	Descriptions
	Main	**Main palette**	
1	DC	Brushed DC motor.vi	Model of *Brushed DC motor*
2	BLDC	Brushless DC motor.vi	Model of *Brushless DC motor*
3	Stepper	Stepper motor.vi	Model of *Stepper motor*
4	SYNCH	Synchronous AC motor.vi	Model of *Synchronous AC motor*
5	ASYNCH	Asynchronous AC motor.vi	Model of *Asynchronous AC motor*
	Add.	**Additional**	
6	Hall	Hall sensor.vi	Model of *Hall sensor*
7	Load	Load.vi	Model of *Load*
8	Control	Stepper motor controller.vi	Model of *Stepper motor controller*

5. System requirements

- LabVIEW Base, Full, or Professional Development System
- NI Control Design and Simulation Module

6. LabVIEW features sand concepts used

- Formula node
- Case structures
- Control & simulation loop
- Tab controls
- PID

- Control Design and Simulation Module elements

Note: The objects should be used in simulation loop only.

7. Support information

For technical support, please, contact Ovak Technologies at:

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Email: support@ovaktechnologies.com

Web: www.ovaktechnologies.com

8. References

1. Jason Luecht, Matt Rosmarin, Mike Kleinigger - Research Assistants Dr. Kevin Craig, Professor of Mechanical Engineering RPI Mechatronics Laboratory 2007;
2. Hemchand Immaneni / International Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622;
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