

DC MOTOR MODELING IN AN ELECTRONIC CIRCUIT SIMULATOR – FRICTIONAL TRANSMISSION EXAMPLE

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Abstract: In this paper, the DC motor is modeled. The model is constructed in an electronic circuit simulation program using electro-mechanical analogies. To test the model and to demonstrate its possibilities, as one of the examples, a dry frictional transmission is analyzed.

Key Words: Circuit Simulation, DC motor, Frictional Transmission

1. INTRODUCTION

Many systems today are designed with the aid of simulations. The same is true for DC motor drives. The software used to conduct simulations is usually a general simulation software that doesn't simulate the drive as an electronic circuit, at least not as precisely as a software designed specially for electronic circuit analysis would. This paper tries to show the opposite of that: to simulate the drive, the motor (DC motor in our example) and the mechanical system driven by the motor in an electronic circuit simulation software. This way, the driving circuit can be analyzed to the tiny details, whereas the accuracy of the modeling of the mechanical parts is not compromised in any way.

The benefit from a modeling in such manner is that the driving circuit is not limited to a few switches driven by a regulator. The circuit can be made of real transistors or mosfets which can be controlled by a real electronic circuit identical to the one that is finally going to be implemented. The real currents, voltages, dissipated powers can be examined, even Fourier analysis is possible. All electronic components are at our disposal which can be supported by the software we use. For the purposes of this paper, our choice was MicroCap.

2. THE MODEL

The system that will be analyzed in this paper is presented in Fig. 1. The model can be split into three parts marked with A, B and C. Part A represents the DC motor without its details. Part C is the driven mechanical system and it is not actually shown in the figure, only the point where it is supposed to be connected is marked. Part B is the frictional transmission mechanism. Its model will be explained further.

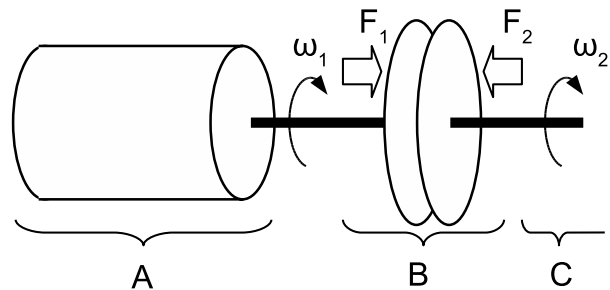


Fig. 1. The modeled system

2.1 The DC Motor (Part A)

Fig. 2 shows all the elements usually found in a DC motor model [1]. The left-hand part is a pure electrical system and as such it needs no transformation to be modeled in an electrical circuit simulator. The right-hand part though, is purely mechanical and cannot be directly modeled in the circuit simulator. There are known analogies between electrical and mechanical systems. Taking advantage of that, the mechanical part of the motor (and also the rest of the system presented in this paper) can be converted to a form easily modeled in the electrical circuit simulator. M_L is an additional load torque coming from the system driven by the motor (the frictional transmission in this case).

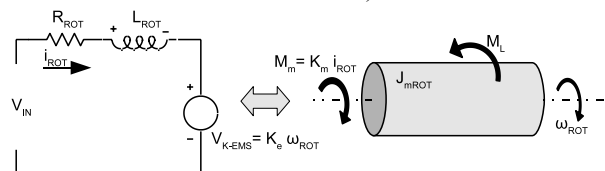


Fig. 2. The usual model of the DC motor

The model of the DC motor, ready to be analyzed as a completely electrical circuit is given in Fig. 3. The left-hand side is unchanged, as it was already an electrical circuit. According to the electro-mechanical analogies, current is analogous to torque and voltage (V_{ROT}) is analogous to angular velocity. Since the torque generated by the motor depends on the rotor current, the rotor current controls the dependant current source F_1 that

belongs to the mechanical part of the model. Similarly, the counter-EMS generated, depends on the angular velocity of the rotor. To model this, the voltage V_{rot} controls the dependant voltage source E_1 , which represents the counter-EMS. The rotor's moment of inertia is represented by a capacitance J_m . Viscous friction can also be present (in the rotor bearings) and can be taken into account by the resistor R_B ($R_B=1/B$, where B is the coefficient of viscous friction).

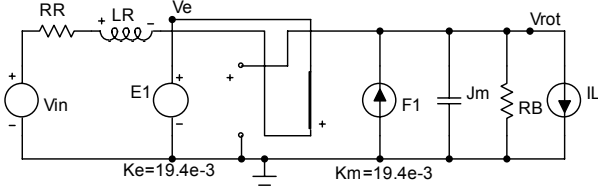


Fig. 3. The DC motor modeled for simulation

The current I_L , represents the current analogous to the torque M_L that is being transferred to the driven system. Actually, the current generator can be considered a placeholder for some more complex electro-mechanical system.

2.2 The Frictional Transmission (Part B)

This part is purely mechanical, thus it will be modeled via electro-mechanical analogies. It consists of two discs which are pressed against each other with a force that can be controlled. The torque transmission is accomplished by dry friction between the discs. Slipping is considered normal condition, and happens when the torque that is being transferred exceeds the torque of the dry friction. The forces F_1 and F_2 (Fig. 1), according to the action-reaction force equality, must be of equal intensities.

Let's consider, how the torque transferred by the frictional transmission depends on the relative angular velocities of its two ends. The graphical representation of this relationship is given in Fig. 4.

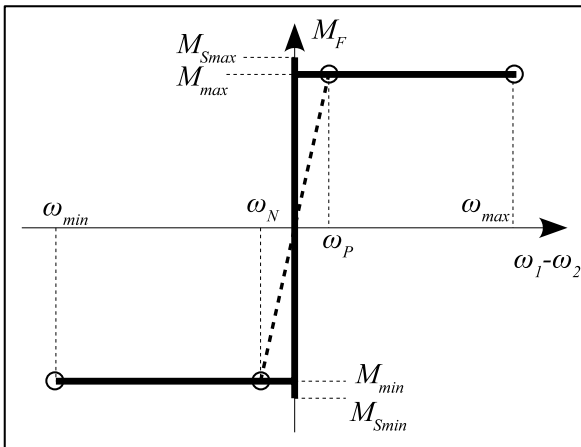


Fig. 4. The frictional transmission characteristic

The real case is drawn with a solid line. When the discs don't move with respect to each other, it's the case of static dry friction: any torque is transferred that is less than the maximal value M_{Smax} (or mathematically greater than M_{Smin} in the opposite direction) without slippage between the discs. If the torque being transferred exceeds any of its static limits, slippage begins (the angular velocities of the two disks do not coincide anymore) and

the maximum torque transferred becomes a bit less than the exceeded static maximum – M_{max} (or M_{min}). When slippage starts, the static friction becomes Coulomb friction. One part of the characteristic is vertical, which can cause modeling and simulation difficulties. That's the reason, why it is convenient to find a reasonable approximation of this characteristic. Our choice is shown in the same figure, drawn with a dashed line. The vertical part is substituted with a very steep part. Actually, this models the static dry friction case as a high viscous friction when the velocity difference between the discs is not greater than ω_P (or less than ω_N). The fact that the maximum static torque is greater than the torque when slippage exists is neglected, considering that M_{Smax} and M_{max} are close values (though examples can be found where that is not the case).

Another question is how to calculate the M_{max} value when the friction coefficient μ for the two surfaces and the force that pushes the disks together are known. In this paper, we will not go further in this analysis. The values for M_{max} (and similarly M_{min}) can be found experimentally for a given system.

The electrical circuit analogous to the presented mechanical system is given in Fig 5. This picture shows both the transmission and the driven mechanical system that will be further analyzed in the next section. The main part is a voltage controlled current source [2]. The controlling voltage is the potential difference between the node which represents the motor angular velocity and the node representing the load angular velocity. The dependency of the current from the controlling voltage is not linear, but part-by-part linear function defined by Fig. 4. The hollow circles along the characteristic represent the points that define this part-by-part linear function. The coordinates of these points can be easily defined by 4 parameters: M_{max} , M_{min} , ω_P , ω_N . The rightmost and the leftmost points should be far enough to have an absolute value greater than any angular velocity that occurs in the simulation.

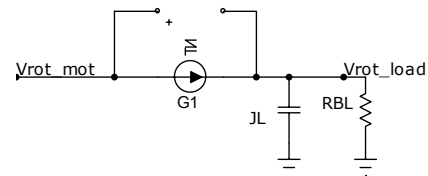


Fig 5. The electrical model of the frictional transmission together with the load

One question remains – the slope of the characteristic around the zero velocity difference. For a good approximation of the dry friction model, ω_P and ω_N should be significantly less than the angular velocities the system components achieve.

2.3 The Driven System (Part C)

This part is the useful load, the reason the motor drive and the frictional transmission are built. In this paper, we will focus on the transmission, not on the load. Therefore, only a simple load will be added – a rotating mass with a viscous friction in its bearings. For the sake of simplicity it will be exactly the same as the DC motor's rotor. They are represented by the capacitor J_L and the resistor R_{BL} .

3. EXAMPLES

To illustrate the possibilities of the model, two examples will be presented.

3.1 Motor Start/Stop

In this example, the DC motor is connected to an impulse generator. The motor starts when a 12V high, 2 seconds wide impulse appears at its input. Because of the dynamical characteristics of the system, the final angular velocities are reached in less than 2 seconds, therefore the whole simulation lasts 3.5 seconds. Slippage at the frictional transmission is easily noticeable, so the example shows many features of the system.

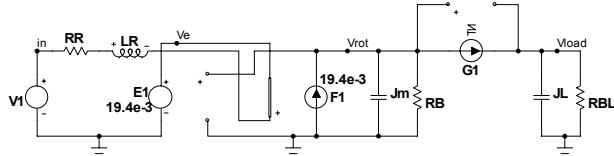


Fig. 6. The system from the start/stop example

In Fig. 6 the complete system is shown. All the results of this example were obtained from it. V1 is an impulse generator that generates 12V impulses 2s wide. The period of the impulses was set to a value longer than the simulation, thus only one impulse is visible. Fig. 7 shows the input signal.

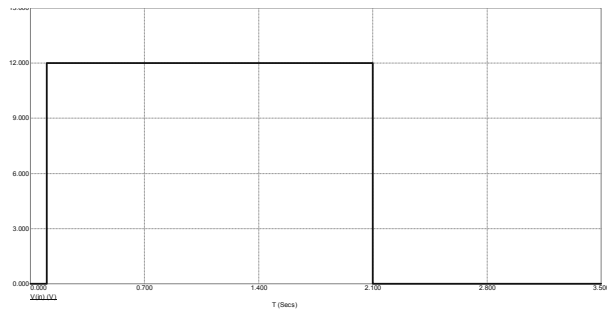


Fig. 7. The input voltage

Maybe the most important thing is to see the angular velocities of the motor itself and the load attached through the frictional transmission. Both of them are shown in Fig. 8.

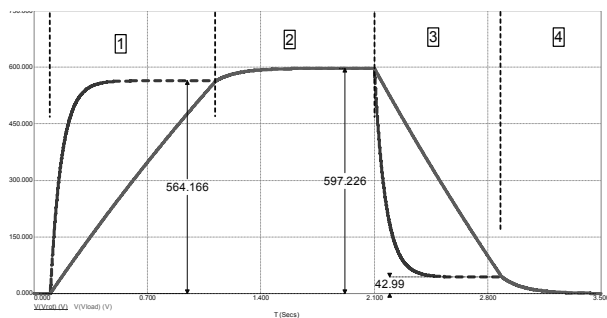


Fig. 8. The angular velocities of the motor and the load attached. (Motor – dashed line, load – solid line)

There are easily noticeable zones in the response. In zone 1, the motor driving torque is higher than the frictional transmission can transfer, so slippage is present. The motor accelerates quickly to some constant value, while the load is accelerated with a constant torque (M_{\max}) and hence, its angular velocity increase is

linear. Zone 2 begins when the speeds of the motor and the load equal out, i.e. when the torque to be transferred by the frictional transmission becomes less than M_{\max} .

In zone 3, the electrical inputs of the motor are short circuited and it starts to decelerate. Driven by its own inertia and the inertia of the load delivering its torque through the frictional transmission, the motor acts as a generator. Since only M_{\min} of torque can pass through the transmission the motor decelerates quickly to some constant value, while the load changes its angular velocity linearly. Zone 4 starts when their angular velocities equal out.

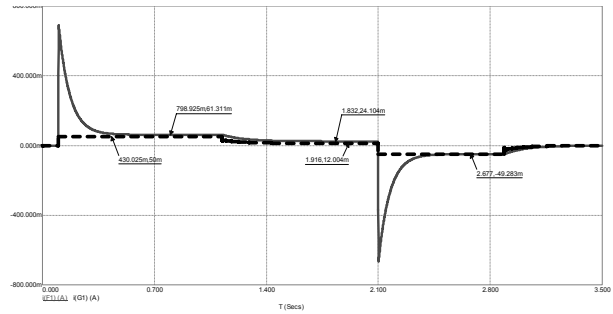


Fig. 9. The torques. (solid - generated by the motor, dashed - transferred by the transmission)

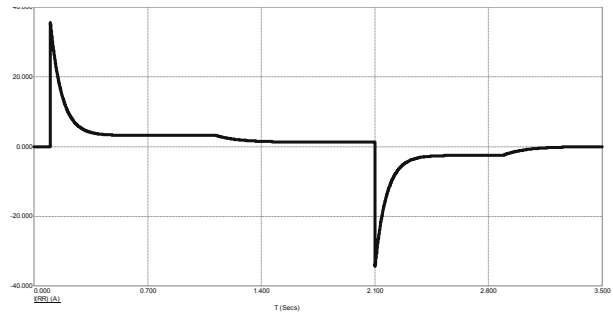


Fig. 10. The current flowing through the rotor windings

The parameters of the system analyzed are gathered in Table 1.

Table 1. System parameters

Par.	Parameter explanation	Value
R_R	Rotor resistance	0.334Ω
L_R	Rotor inductance	$85\mu\text{H}$
K_e	Electrical motor constant	19.4mVs/rad
K_m	Mechanical motor constant	19.4mNm/A
J_m	Moment of inertia – rotor	80gcm^2
R_B	Viscous friction coeff. - rotor	$50\text{k}\Omega$
J_L	Moment of inertia – load	80gcm^2
R_{BL}	Viscous friction coeff. – load	$50\text{k}\Omega$
$M_{\max} = -M_{\min}$	Maximum torque the transmission can transfer	50mNm

In Fig. 9, the torques can be seen. As previously mentioned, the motor immediately after start, generates a very high torque (the positive peak). The transmission puts through only a part of it – M_{\max} (the positive level part). When the slippage stops, the rotor of the motor and the load share the generated torque. Exactly the opposite happens when decelerating.

The current flowing through the rotor windings is shown in Fig. 10. It's easy to see, how the motor torque is actually proportional to the rotor current.

3.2 PWM Controlled Motor Start

In the next example the same electro-mechanical system is used as in the previous. The only difference is in the rotor inductivity which is increased to 1mH in order to reduce the rotor current ripple when a PWM drive is used. Only the acceleration is analyzed, the simulation is stopped as soon as the velocity asymptotes are reached.

The circuit used in this analysis is the same as the one shown in Fig. 6, except that the voltage generator is replaced with a very simple PWM drive circuit shown in Fig. 11. S_1 is a voltage controlled switch, D_1 acts as a freewheeling diode. The impulse generator V_1 generates the actual PWM signal whose duty-cycle controls the current through the motor windings. In this example, the duty-cycle is constantly 50%. The system is powered from a DC voltage source (battery) V_{DC} of 12V.

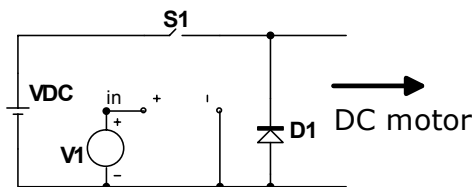


Fig. 11. The simple PWM drive

Fig. 12 shows the angular velocities of the rotor and the load. The result is very similar to the result of the previous example. The maximum angular velocities differ however, which is expected since the duty cycle of the PWM is 50% giving an average voltage value of 6V. The smaller voltage results in smaller rotation speed.

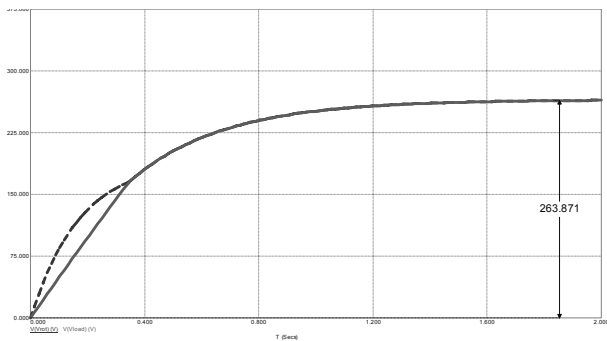


Fig. 12. The angular velocities (dashed - rotor, solid - load)

Important are the currents through the switching components (Fig. 13) and the motor windings (Fig. 14). Together with the motor windings current, the PWM signal is also shown. Only a small fragment of these signals is presented because of their high frequency.

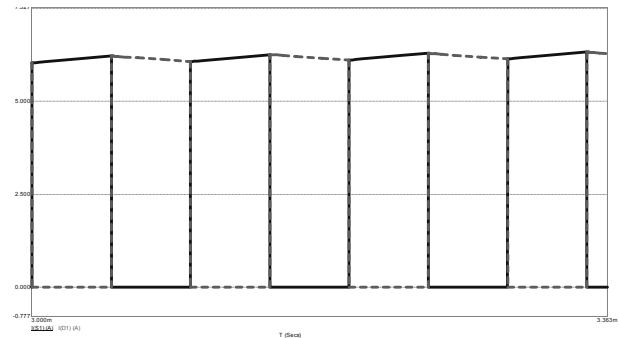


Fig. 13. The currents of the switching components (dashed - diode D_1 , solid - switch S_1)

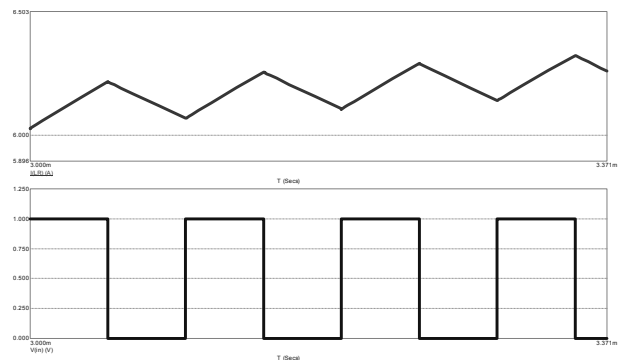


Fig. 14. The currents through the motor windings (upper) and the PWM signal (lower)

4. CONCLUSION

The possibilities of modeling electro-mechanical systems in simulator software for electronic circuits are explored in this paper. Electrical models for modeling DC motors and frictional transmissions are presented. Through examples, the possibilities of such approach are shown. The presented model of frictional transmission is an approximation and can be further refined to more closely model the finer aspects of such systems.

5. REFERENCES

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- [2] *Micro-Cap 9, Manual – help*, Spectrum Software, 2007.