

Dynamic Modeling of Flyback Switching Power Supplies Using Graph Modeling: Case Study in Variable Speed DC Drives

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Abstract: In this paper, first, DC speed motor control by flyback switching power supply has been reviewed and Optimum Symmetric Controlling Method (Kessler Method) has been utilized to control converter's switch-on and switch-off time. Converter simulation and designed controller is required to assure design accuracy. Despite using powerful simulation software, simulation is seen to be very time-consuming. Therefore, a model is required to decrease the simulation time considerably and yet keep precision. Graph Modeling has been used as a precise, simple, and efficient, method to model DC-to-DC converters. Thus, flyback DC-to-DC converter was modeled by employing this method and the rendered model was simulated. A comparison between results of the converter's own simulation and that of the rendered model show that, using the rendered model has decreased the time of simulation to a considerable extent, while keeping the precision.

Keywords - Graph model, Flyback converter, Kessler Method, Chopper converter, DC Drive.

I. Introduction

Power Electronics is, in fact, processing of electrical power by electronic devices. Switching converters are comprised of three parts of power inputs, control inputs, and power outputs. Input power is processed by controller and is delivered to power output terminals. [1.7]

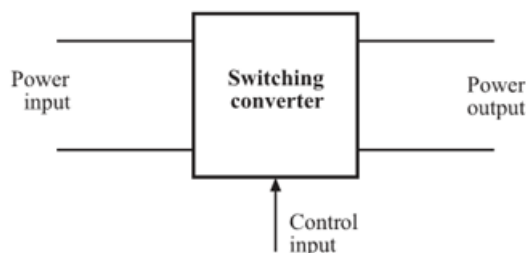


Fig. 1: Switching converter, a general block of power processing [8]

Controller should be in place in all mentioned converters, since almost always output needs to be adjusted properly and be independence of input voltage and load current.

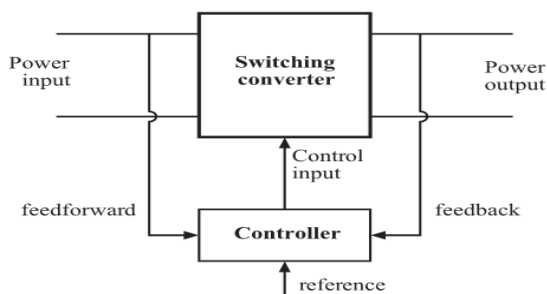


Fig. 2: Centrality of controller in electronic power devices

II. Graph Modeling

Graph Modeling is used to gain various convert functions such as input and output impedance, etc. A graph comprised of a number of loops, feed forewords, and nodes, in which the relationship between different voltages and currents have been specified. In a time-invariant linear circuit, a graph is obtained using circuit analysis principles such as KVL and KCL. In the first phase, based on the order of circuit element, different voltages and currents are specified by nodes. Then, connection of each node with other nodes is marked through

KVL and KCL. Using the specified connections, the connection of this node with other nodes is marked by directed arrows in the final phase. DC-to-DC converter modeling through Graph Modeling is explained in the following section.

A DC-to-DC converter changes between two different modes in a switching period and acts in a total non-linear manner due to non-linear elements such as transistor and diode. However, it is evident that equivalent circuits, created between two switch-on and switch-off modes, are time-invariant and linear. Therefore, each equivalent circuit can be modeled by a graph. On the other hand, the converter is in the switch-on mode for kT second and in switch-off for $(1-k)T$ second. Hence, the graph modeling of a DC-to-DC converter with the combination of equivalent graphs, created in switch-on and switch-off modes, is stated as follows:

$$G = kG_{on} + \bar{k}G_{off} \quad (1)$$

In the above equation, G_{on} and G_{off} are the graphs of converter circuit in the switch-on and switch-off modes, respectively. Therefore, in a DC-to-DC converter modeling via graph modeling, first, different voltages and currents of converter circuit are specified in order, from input voltage supply to load resistor by nodes. Then, considering the converter equivalent circuit in switch-on and switch-off modes, graph modeling of each mode is obtained. Subsequently, two graphs created from Equation (1) are combined. The lines which exist in switch-on mode, but not in switch-off mode, are specified by a line with gain “ k ” in combination of these two graphs. Similarly, lines which are in place in the switch-off mode, but not in switch-on mode, are marked with a line with gain “ \bar{k} ”.

In the following section, a simple technique is discussed for DC-to-DC converter modeling using graph modeling. This technique was introduced by Veerachary (2004) in [9].

A DC-to-DC converter is comprised of a number of active and passive switches, resistor and energy saving elements. In most cases, there are a large number of energy saving elements which cause converter’s temperature rise. For example, buck-boost converters can connect in a cascade manner. This cascade junction in telecommunication and aerospace systems are frequently used to reach to high or low voltage levels. The following method is a general method to draw graph modeling of a DC-to-DC converter:

1. Nominate the graph nodes based on deployment order of feed supply, inductances, capacitors, and load resistor. Inaccurate nomination of the nodes will lead to incorrect result.
2. If the element is an inductance, nodes should precede inductance current in the nomination.
3. If the element is a capacitor, capacitor current should precede capacitor voltage in the nomination of nodes.
4. KVL equations are written for inductances’ voltage. These equations should be a function of input voltage and capacitors’ voltage. The line which is connected only when the switch is connected to inductance voltage node has the gain of “ d ”. Similarly, the line which is connected only when the switch is disconnected from inductance voltage node has the gain of “ \bar{d} ”, and the line which is always connected to inductance voltage node has the gain of +1 or -1 depending on capacitor current direction.
5. KCL equations are written for capacitors’ voltage. These equations should be a function of inductances’ current. The line which is connected only when the switch is connected to capacitor current node has the gain of “ d ”. Similarly, the line which is connected only when the switch is disconnected from capacitor current node has the gain of “ \bar{d} ”, and the line which is always connected to capacitor current node has the gain of +1 or -1 depending on capacitor current direction.
6. Inductance current node is connected to its voltage node with the gain of $1/SL$.
7. Capacitor voltage node is connected to its current node with the gain of $1/SC$.

III. Modeling Fly back Dc-To-Dc Converters With Graph Modeling

Flyback is designed based on a buck-boost converter. This derivation is shown in Figures 3 to 6. Figure 3 shows a simple buck-boost converter whose switch has been designed by a MOSFET and diode. In Figure 4, an ordinary inductance has been replaced by a two-winding inductance with a 1:1 proportion. In this way, no change is occurred in the inductance’s main performance and parallel windings will perform together as a one-winding inductance. In Figure 5, two windings have been disconnected. One of the winding works when the Q1 transistor conducts and the other works when diode conducts. Although the final current has not changed compared to Figure 4, however, the current between two windings is distributed in a different way. Magnetic field of both windings is the same. Although each element with two magnetic fields is shown by a symbol similar to transformer, it is more appropriate if it is called two-winding inductance. This element is usually referred to as flyback. In contrast to ideal transformer, the current is not in line simultaneously between flyback transformer’s primary and secondary sides. Figure 6 shows a flyback DC-to-DC converter. MOSFET source is connected to primary winding. The polarity of transformer can be changed to reach a positive voltage in output. Windings with 1:n proportion can also be used to improve converter’s performance.

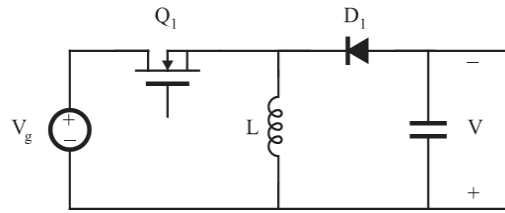


Fig. 3: Buck-boost converter

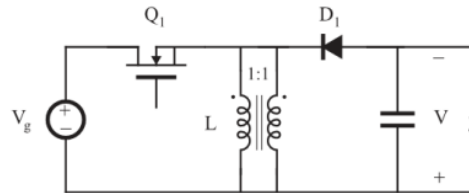


Fig. 4: Replacing an ordinary inductance with a parallel two-winding inductance

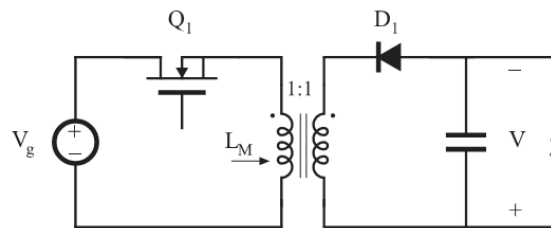


Fig. 5: Using an isolated inductance, flyback converter

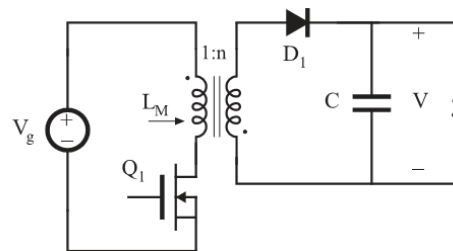


Fig. 6: Flyback converter with 1:n winding proportion and positive output

Flyback converter can be replaced as shown in Figure 7 for analyzing flyback converter. Magnetic inductance L_m has a similar performance as inductance L in buck-boost converter. When Q_1 MOSFET conducts, energy flows to L_m through V_g source and when D_1 diode conducts, this energy flows to load from L_m . It might be noted that voltage and load current follow 1:n winding proportion.

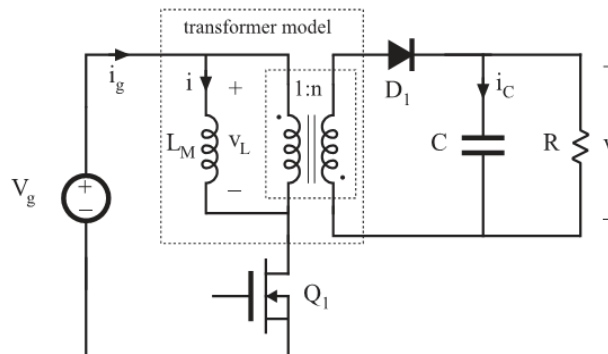


Fig. 7: Flyback converter with transformer equivalent circuit

During time interval 1, when Q_1 switch conducts, converter model would be as Figure 8 and inductance voltage V_L and capacitor current i_c and DC current of i_g source would be set as follows:

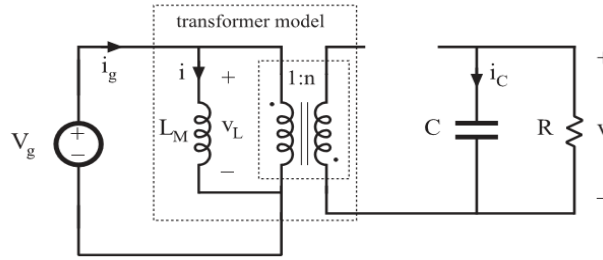


Fig. 8: Time interval 1

$$v_L = V_g \tag{2}$$

$$i_C = -\frac{v}{R} \tag{3}$$

$$i_g = i \tag{4}$$

Assuming converter works in Continuous Conducting Mode (CCM) and ripples of inductance current and capacitor voltage are negligible, inductance current and output capacitor voltage can be replaced by DC elements. Thus, equation (2) to (4) will be as follows:

$$v_L = V_g \tag{5}$$

$$i_C = \frac{-V}{R} \tag{6}$$

$$i_g = I \tag{7}$$

During the second time interval, Q_1 switch is off and diode conducts. This circuit is shown in Figure 9. The primary voltage of magnetic inductance V_1 and capacitor current i_C and DC current of i_g source would be:

$$v_L = \frac{-v}{n} \tag{8}$$

$$i_C = \frac{i}{n} - \frac{v}{R} \tag{9}$$

$$i_g = 0 \tag{10}$$

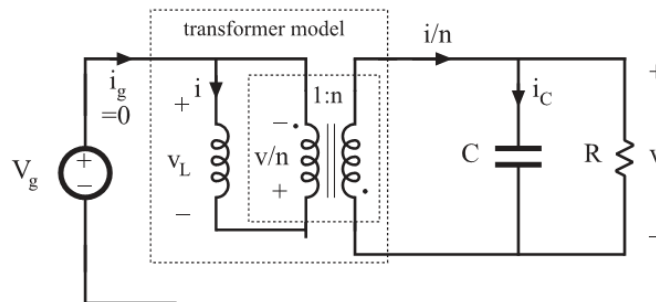


Fig. 9: Time interval 2

Ignoring ripples, Equations (11) to (13) are obtained:

$$v_L = -\frac{v}{n} \tag{11}$$

$$i_C = \frac{I}{n} - \frac{V}{R} \tag{12}$$

$$i_g = 0 \tag{13}$$

$V_L(t)$, $i_C(t)$, and $i_g(t)$ are shown in Figure 10.

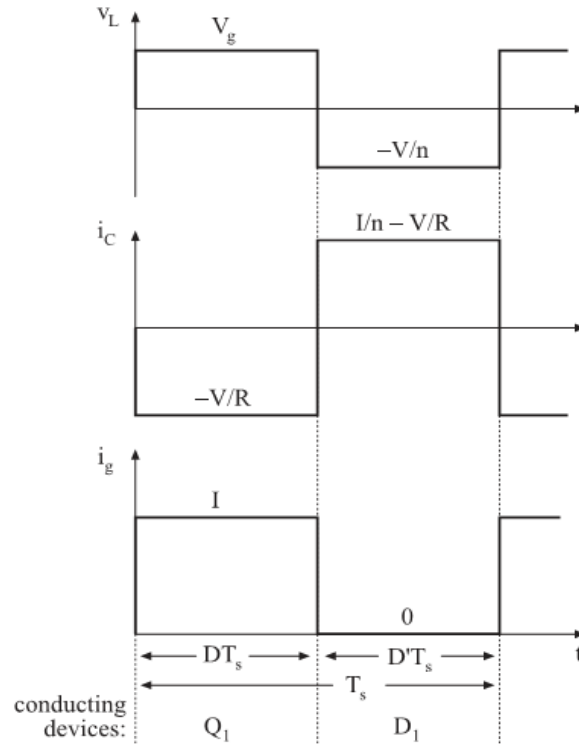


Fig. 10: Form of Waves $v_L(t)$, $i_C(t)$, and $i_g(t)$

Using volt-seconds balance principle in primary winding of magnetic winding, equation 14 is obtained:

$$\langle v_L \rangle = D(V_g) + D' \left(-\frac{V}{n} \right) = 0 \quad (14)$$

As a result, the transfer proportion of flyback converter would be:

$$M(D) = \frac{V}{V_g} = n \frac{D}{D'} \quad (15)$$

It is evident that the transfer proportion of flyback converter is the same as buck-boost converter; with the difference that coefficient “n” has been added to the former. Moreover, using electrical load balance principle, capacitor’s output current would be:

$$\langle i_C \rangle = D \left(\frac{-V}{R} \right) + D' \left(\frac{I}{n} - \frac{V}{R} \right) = 0 \quad (16)$$

Therefore,

$$I = \frac{nV}{D'R} \quad (17)$$

Additionally, DC element of i_g current source would be:

$$I_g = \langle i_g \rangle = D(I) + D'(0) \quad (18)$$

Now, a model of flyback converter can be obtained based on DC wave forms resulted from above equations.

IV. Designing DC Drive Using Fly back Converter

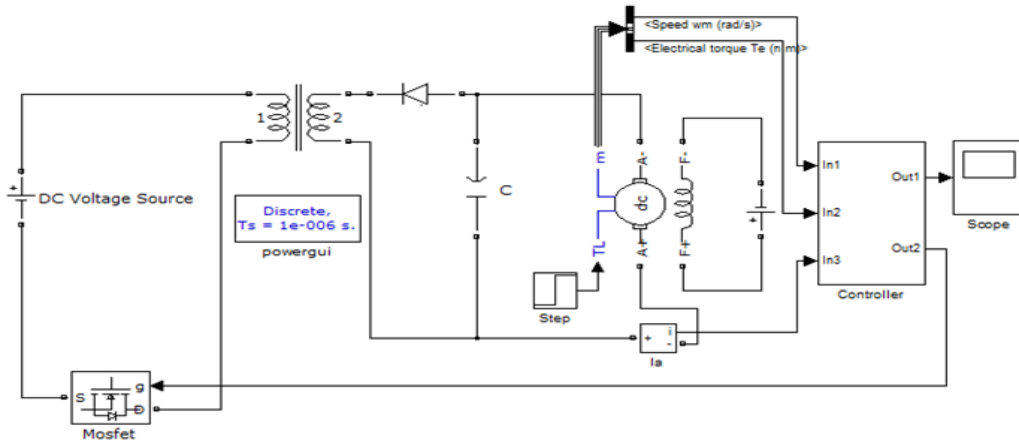


Fig. 11: Flyback converter with motor load

In Figure 11, a flyback DC-to-DC converter has been used as the power supply of separately excited DC motor. Also, a controller with three inputs (motor angular velocity, motor electrical torque, and motor current) and two outputs (one for controlling the flyback converter task time and the other for display of motor speed changes) has been designed.

Switching frequency of 5 kHz is selected and, in Figure 11 converter, L_m is obtained from following equations [10]:

$$f = 5 \text{ kHz} \Rightarrow T = 2 \times 10^{-4} \text{ S} \quad (19)$$

$$L_m = \frac{R_{eq} T D^2}{2} \quad (20)$$

$$R = 4 \Omega, D = 0.7 \Rightarrow L_m \cong 2 \times 10^{-4} \text{ H} \quad (21)$$

Moreover, in Figure 11, DC motor No. 5 MATLAB/ Simulink with following specifications has been used:

$$P = 10 \text{ hp}, V = 500 \text{ V}, \text{Speed} = 1750 \text{ rpm}, V_f = 300 \text{ V}$$

And using Optimum Symmetric Method (Kessler), the controller shown in Figure 11 has been designed as shown in Figure 12.

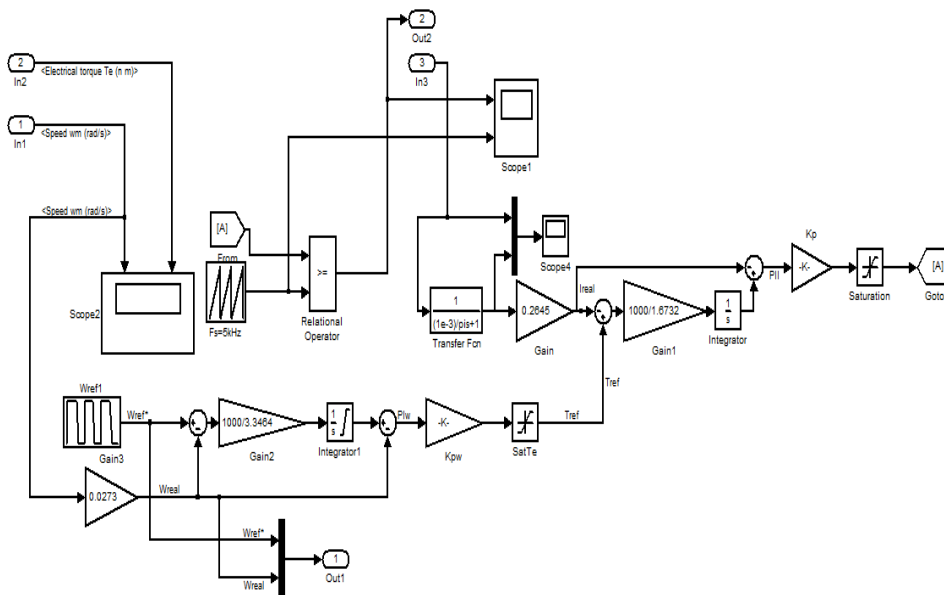


Fig. 12: Controller

Using the designed drive, controller's desired angular velocity shape and motor's angular velocity shape can be shown in Figures 13 to 15 after simulation by MATLAB/Simulink software.

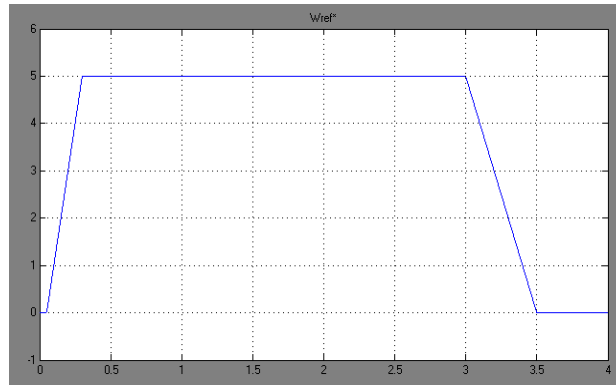


Fig. 13: Controller's desired angular velocity wave

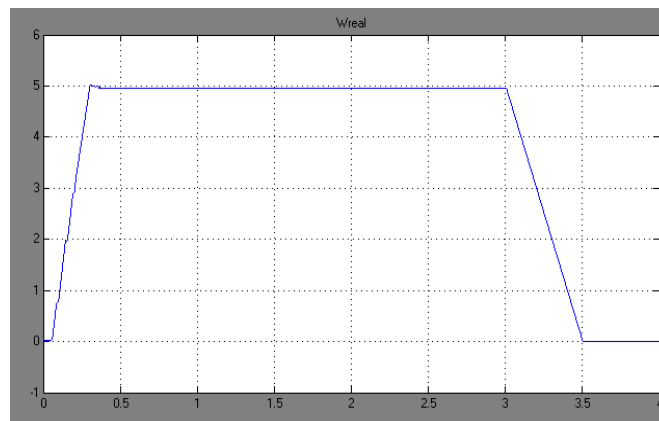


Fig. 14: Motor's angular velocity wave

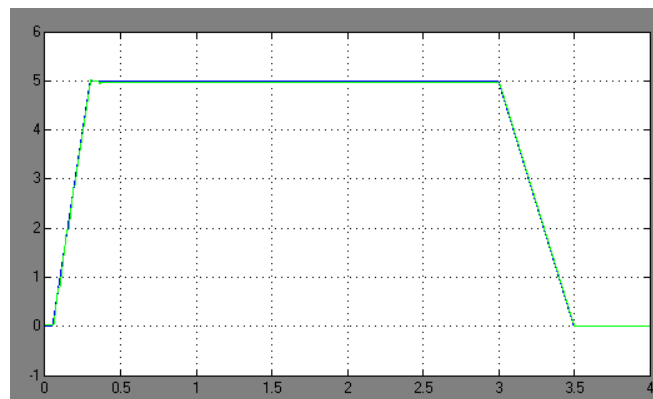


Fig. 15: Comparison of controller's desired angular velocity wave and motor's angular velocity wave on a graph.

V. Modeling The Designed Drive Using Graph Modeling

Now, converter modeling is done and, in so doing, the circuit is divided into two time intervals:

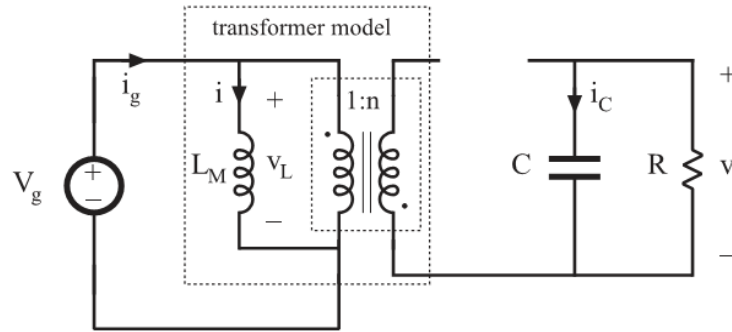


Fig. 16: Time interval 1

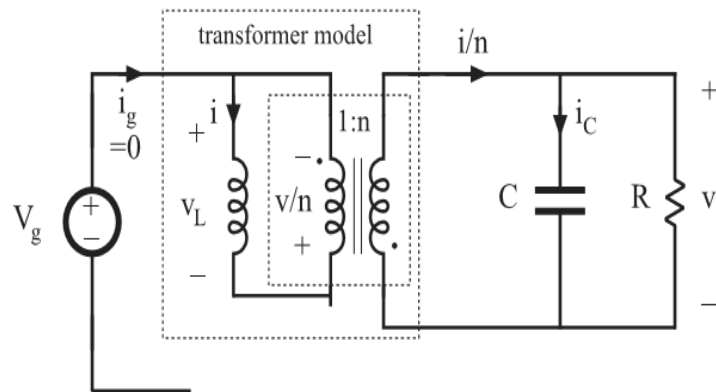


Fig. 17: Time interval 2

Considering the above explanations, graph modeling for time interval 1 would be represented by Figure18:

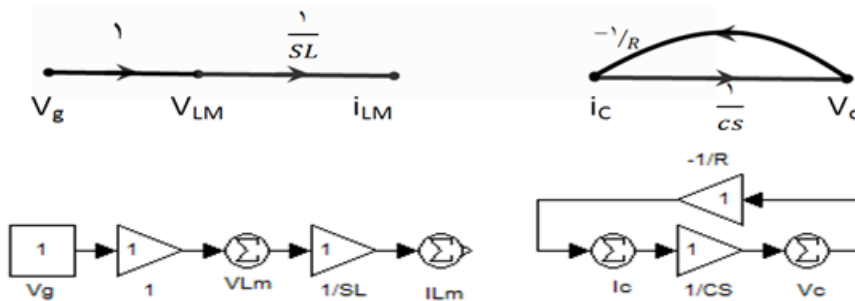


Fig. 18: Graph modeling for time interval 1 (D=0.7)

And graph modeling for time interval 2 would be represented as follows:

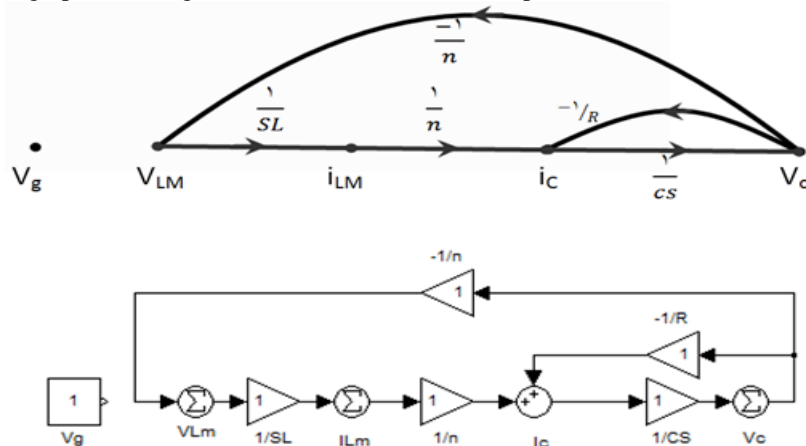


Fig. 19: Graph modeling for time interval 2 (D'=0.3)

Merging Figure 18 and Figure 19 would render the flyback converter graph modeling.

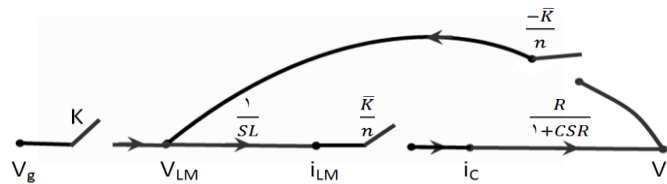
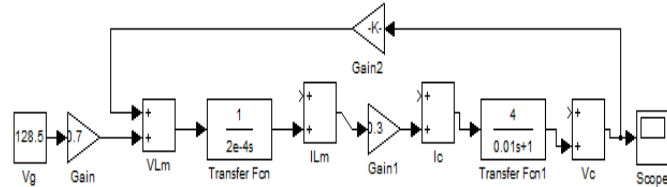


Fig. 20: Flyback converter graph modeling of Figure 11



Flyback converter graph modeling is shown in Figure 20. Being totally comprised of gain and transfer function, the controller’s graph modeling is identical to the controller itself. However, our intended DC motor should be replaced in a way to include transfer functions and gain. With respect to reference [11], Simulink motor No. 5 is modeled in the following way:

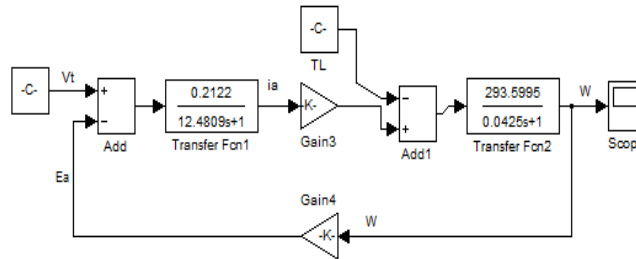


Fig. 21: The presented model for Simulink DC motor separately excited No. 5

In Figure 21, transfer function 1 is $\frac{1/R_a}{1+\tau_s}$, gains 3 and 4 are $k\Phi$ and transfer function 2 is $\frac{1/B}{1+\tau_m BS}$. Finally, the circuit would be as follows:

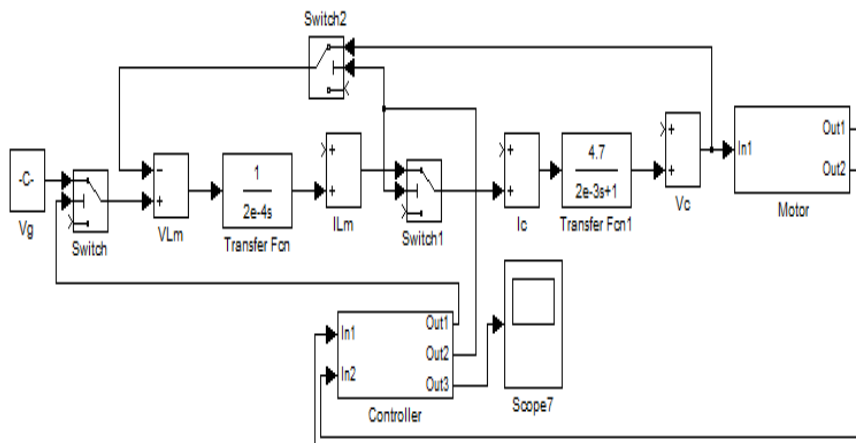


Fig. 22: Flyback convert circuit with motor, modeled through graph modeling

After simulation, controller’s desired angular velocity and motor angular velocity shapes are shown in Figures 23 to 25:

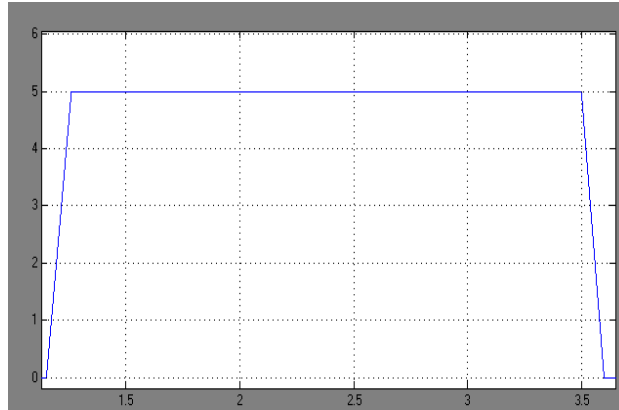


Fig. 23: Controller's desired angular velocity

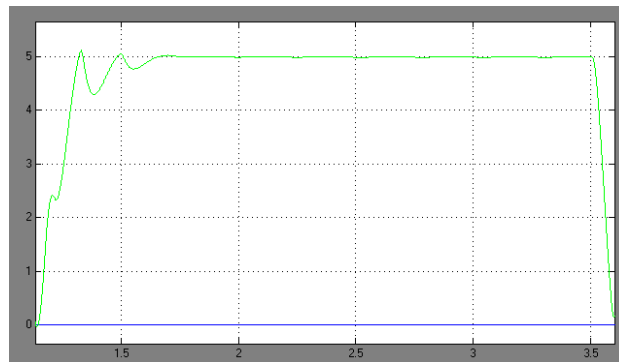


Fig. 24: Motor's angular velocity

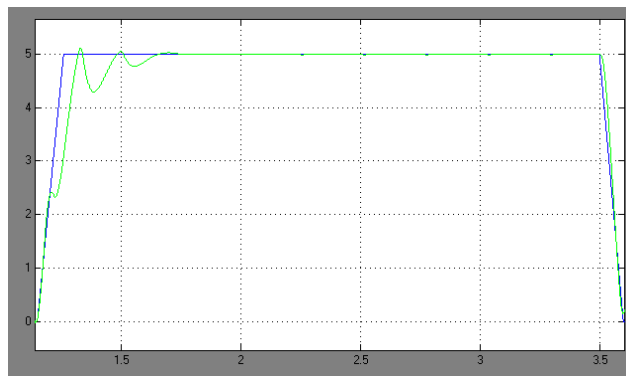


Fig. 25: Comparison of Controller's desired angular velocity wave with Motor's angular velocity wave on a graph.

VI. Conclusion

After designing a flyback DC-to-DC converter and the related controller, the converter was simulated by MATLAB/SIMULINK software and Controller's desired angular velocity wave with Motor's angular velocity were compared. Since this simulation is a very time-consuming process, any change in controller, motor, or converter and re-simulation requires a considerable waste of time. For example, doing this simulation with a DELL CORE i3 laptop with 2GB RAM in continuous time mode, takes several hours and in discontinuous time mode takes about 8 minutes; while simulation through the proposed graph modeling for this converter, controller and motor with the same laptop and software requires less than 10 seconds. Therefore, modeling the converter through graph modeling and its simulation, enable us to study the applied changes in the system within a much shorter time.

References

- [1] W. E. Newell, "Power Electronics-Emerging from limbo," IEEE Power Electronics Specialists Conference, 1973 Record, pp. 6-12
- [2] R. D. Middlebrook, "Power Electronics: An Emerging Discipline" IEEE International Symposium on Circuits and Systems, 1981 Proceedings, April 1981.
- [3] R. D. Middlebrook, "Power Electronics: Topologies, Modeling, and Measurement," IEEE International Symposium on Circuits and Systems, 1981 Proceedings, April 1981.
- [4] S. Cuk, "Basics of switched mode Power Conversion: Topologies, Magnetics, and Control," in Advances in Switched-Mode Power Conversion, vol.2, pp279—310, Irvine, Teslaco, 1981
- [5] N. Mohan, "Power Electronics Circuits: An overview," IEEE IECON, 1988 Proceedings, pp. 522-527
- [6] B. K. Bose, "Power Electronics-A Technology Review," Proceedings of the IEEE, vol. 80, no. 8, August 1992, pp, 1303-1334
- [7] M. Nishihara, "Power Electronics Diversity," International Power Electronics Conference (Tokyo), 1990 Proceedings, pp. 21-28
- [8] R. W. Erickson and D. Maksimovic, "Fundamental of Power Electronics," Massachussets, 2nd ed, MA, Kluwer, 2001
- [9] M. Veerachary. "General rules for signal flow graph modeling and analysis of DC-DC converter". IEEE Trans.Aerosp. Electron. Syst, vol 40, no 1, pp 259-271, Jan 2004.
- [10] COLONEL WM. T. MCLYMAN "TRANSFORMER AND INDUCTOR DESIGNHANDBOOK" Third Edition, Revised and Expanded, Kg Magnetics, Inc. Idyllwild, California, U.S.A. 2004
- [11] P.C. Sen "Principles of Electric machines and Power Electronics", John Wiley & Sons Inc 1989.