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Cuk Converter Fed Open-Loop Speed Control of Separately Excited DC Motor

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Abstract: This paper describes the study and application of DC-DC converters for controlling the speed of a DC motor. It highlights open-loop speed control of a separately excited DC motor by using a Cuk converter. This has been achieved by employing the Cuk converter for controlling the motor speed by varying the armature voltage, which is the output voltage of the Cuk converter based on the PWM (Pulse Width Modulation) technique. The speed control of DC motor is being done for both its: a) rated and b) below rated speeds, and a simulation analyzed in MATLAB using a Simulink model for open loop speed control. The performance metrics were also studied through a hardware setup for implementing control on DC motor.

Keywords: Cuk converter, separately excited DC motor, speed control, PWM (Pulse Width Modulation).

I. INTRODUCTION

D.C. motors are one of the most important kinds of electrical machines which find extensive applications in the industry due to their low cost, simpler control structure, wide range of operating speeds, high starting torque and are free from harmonics. The basic electrical DC drive comprises of controller, converter and DC motor. Here, the DC-DC Cuk converter is used to control the armature voltage. The Cuk converter is a type of dc-dc converter that has an output voltage magnitude that is either greater than or less than the input voltage. The polarity of the output voltage of a Cuk converter is opposite with reference to the input voltage,just like ina buck-boost converter, with inductors present both on the input and the output terminals. Traditionally, MOSFETshave been used as switching devices in low power and high frequency applications. Moreover, as the turn-on and turn-off times of MOSFETs are lower as compared to other switching devices like IGBT,this in turn reduces the switching losseshence making them efficient for such applications. Besides, using MOSFETsforhigher frequency applications further reduces the size of the filter components in a Cuk converter [1]. Also, Cuk convertershave excellent properties like capacitive energy transfer, full transformer utilisation, good steady-state performances and filtering of input and output currents due to the presence of inductors on both sides[1]. Closed-loop speed control of DC motors for various applications requires identification of the exact parameters for finding the gains in order to select the most efficient controllers [2].There are various methods of speed control of DC drives such as armature voltage control, field flux control and armature resistance control.

II. BACKGROUND

The following figure shows the schematic circuit diagram of Separately Excited DC motor:

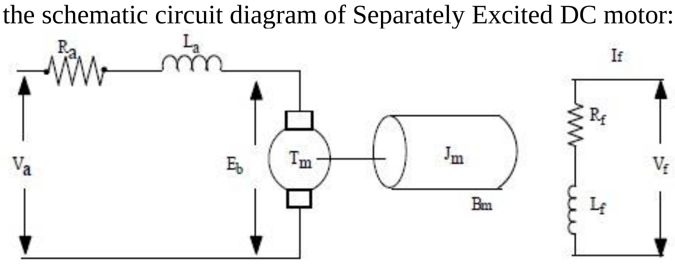

Figure 1: Schematic Circuit Diagram of a Separately Excited DC Motor.

A separately excited DC motor has separate armature and field windings, with the field winding supplying field flux to the armature. When a variable DC voltage is applied to the armature terminal of a separately excited DC motor, an armature current I_a flows in the circuit. As a result, a back EMF (electromotive force) E_b is developed in the motor causing its rotation and an electrical torque is developed to balance the load torque at a specific speed.
The various parameters of the separately excited DC motor are shown below:

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T_m= Motor torque or electrical torque.
B_m= Viscous friction coefficient.
J_m= Total inertia of the motor.
V_f= Field excitation of the motor.
R_f= Field resistance.
I_f = Field current.

At the steady-state, the voltage equation of separately excited DC motor is given by [2],

$V_a = I_a R_a + E_b$ (1)

Where, V_a = Armature voltage in volts.
I_a = Armature current in Amperes.
R_a = Armature resistance in Ohms.
E_b =Back EMF (Electromotive Force).

The back EMF equation is further given by,

$E_b = k\emptyset N$ (2)

Where, k is a constant decided by the design of the machine (total no. of conductors, no. of parallel paths and no. of poles) and $\emptyset$ is the field flux and N is the speed of DC motor in rpm.Using equations (1) and (2), the speed equation for separately excited DC motor is given by,

$V_a = I_a R_a + k\emptyset N$ (3)

Simplifying further,

$N = (V_a - I_a R_a)/k\emptyset$ (4)

The speed control of a separately excited DC motor using armature voltage control technique can be done only for a speed below and till the rated speed. The rating of the separately excited DC motor chosen is 1HP, 220V, 1500rpm and field 220V, 0.25A.

A. Parameter Identification of Separately Excited DC Motor:

Some experiments that have been performed for the identification of above-mentioned DC motor parameters [3]:

Armature resistance, R_a =9Ω
Armature inductance, L_a=0.335H
Field resistance, R_f =857Ω
Field inductance, L_f =2.1227H
Field armature mutual inductance, L_{af} =5.068H
Total inertia, J_m=0.01Kgm^2
Viscous friction coefficient, B_m =0.013Nms.

Considering the load applied to the motor to be 500Watts for a DC machine of 1HP, the output power in Watts is given by,

$P_{out} = T.\omega$ (5)

Where, ω is the motor speed in rad/s. The speed of DC motor in rad/s is given by,

$\omega = (2\pi N)/60$ (6)

Using equations (5) and (6), the load torque applied to the motor is found to be 2.54 Nm.

B. DC-DC Cuk Converter

Figure 2 shows the schematic circuit diagram of a DC-DC Cuk converter fed DC motor. There are two operating states of a non-isolated DC-DC Cuk converter. In the first state, when the switch is turned ON, the diode gets reversed biased by the large voltage across the coupling capacitor C_1 and the switch is short circuited.

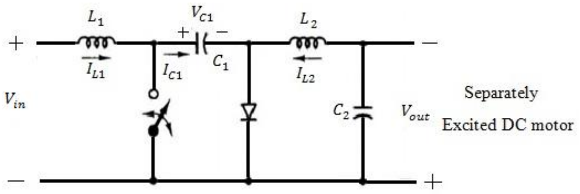

Figure 2: Schematic circuit diagram of a DC-DC Cuk converter.

The current through the inductor L_1 rises and flows through the switch. In the second state, when the switch is turned OFF, the currents through the inductors L_1 and L_2 force the diodeto forward bias and become short circuited and the

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switch is open circuited. Both the inductor currentsI_{L1} and I_{L2} flow through the diode and in the mean time I_{L1}charges the coupling capacitorC_1 andI_{L2} flows through the output capacitor and the motor load.

The DC-DC Cuk converter has to be operated in CCM (Continuous Conduction Mode). So, the various design equations for DC-DC Cuk converter in CCM are as follows [4]:

$$V_{out} = D\,V_{in}/(1-D) \qquad (7)$$

$$L_1 = DV_{in}/(\Delta I_{L1})f_s \qquad (8)$$

$$L_2 = V_{out}(1-D)/(\Delta I_{L2})f_s \qquad (9)$$

$$C_1 = D/\{(Zf_s)(\Delta V_{C1}/V_{out}) \qquad (10)$$

$$C_2 = (1-D)/\{(8L_2 f_s^2)(\Delta V_{C1}/V_{out}) \qquad (11)$$

Where, f_s = Switching frequency.
V_{in} = Input voltage.
V_{out}= Output voltage.
D = Duty ratio.
ΔI_{L1} = Peak to peak ripple current of I_{L1}.
ΔI_{L2} = Peak to peak ripple current of I_{L2}.
ΔV_{C1} = Voltage ripple.

The constant input voltage given to the Cuk converter is 110V andthe switching frequencyf_s=25KHz. The output voltage is variable from 0 to 220V by changing the duty cycle for obtaining variable speed of the DC motor. The assumed values of peak to peak ripples values of inductor current are L_1= 0.16A and L_2= 0.19A. The values of components of the Cuk converter calculated using above data are L_1 = 18 mH, L_2 = 15 mH, C_1 = 200μF , and C_2 = 230μF.

III. PROPOSED MODEL

Modeling of DC drives on Graphical user Interface (GUI) based platforms like Simulink allow study of wide parameter variations in control of such systems [5]. Here, a simulation model of the proposed setup has been developed on MATLAB (Simulink) and is being shown here. An experimental setup consisting of components as depicted in figures 1 and 2 mentioned earlier was also setup for gaining a better understanding of the control mechanism and the possible outcomes [6, 7]. The first stage in the model corresponds to the Cuk converter, the second step relates to the DC machine and the final stage models the signal generator along with different visual devices to provide information related to the experiment.

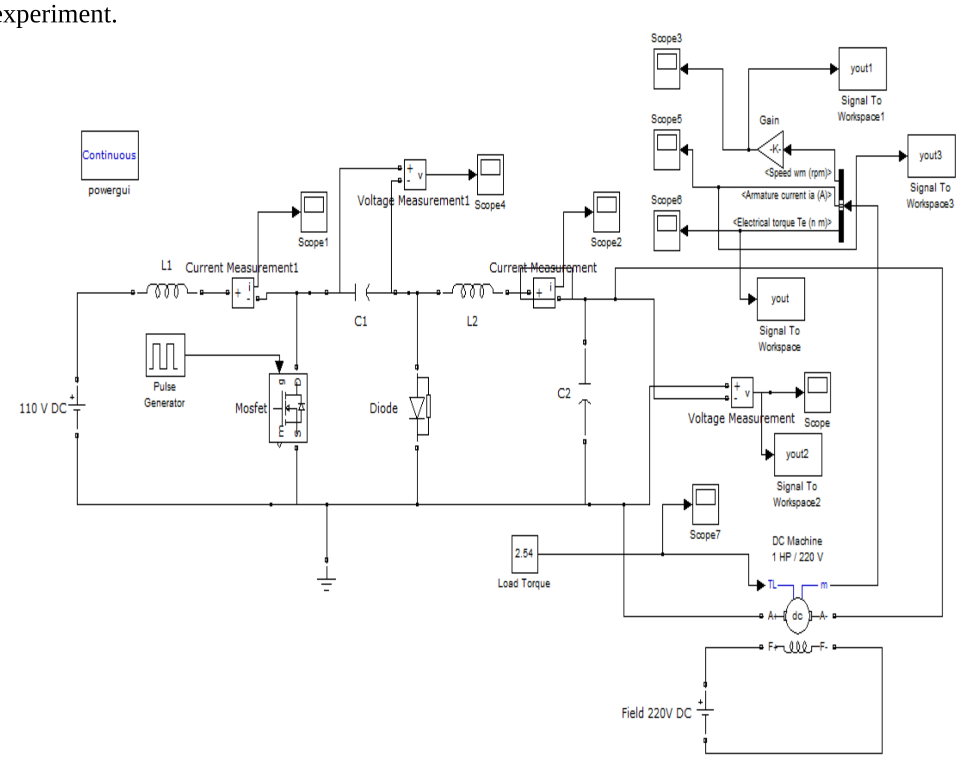

Figure 3: Open-Loop Speed Control of Separately Excited DC Motor Using Cuk Converter.

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IV. RESULTS

A. Simulation Results:

The load torque applied to the separately excited dc motor is 2.54Nm. The various simulation results and plots obtained from the open-loop speed control tests are as shown below:

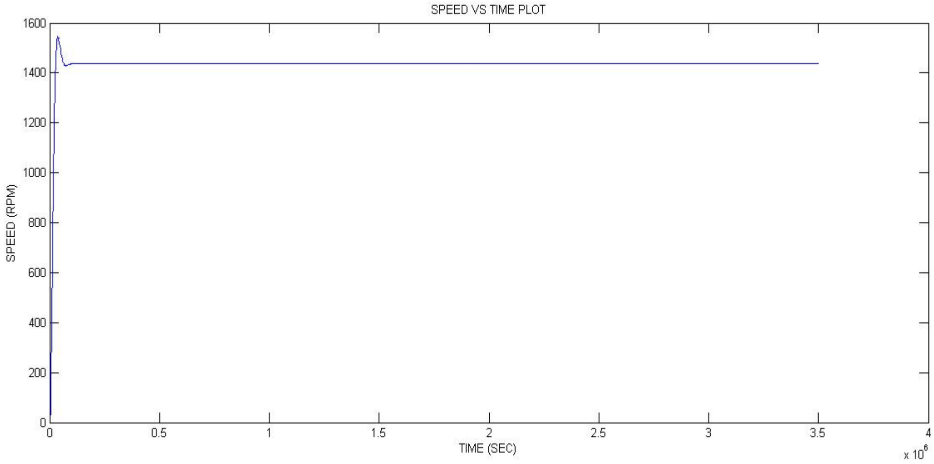

Figure 3.1 (a) : Motor speed = 1437 rpm.

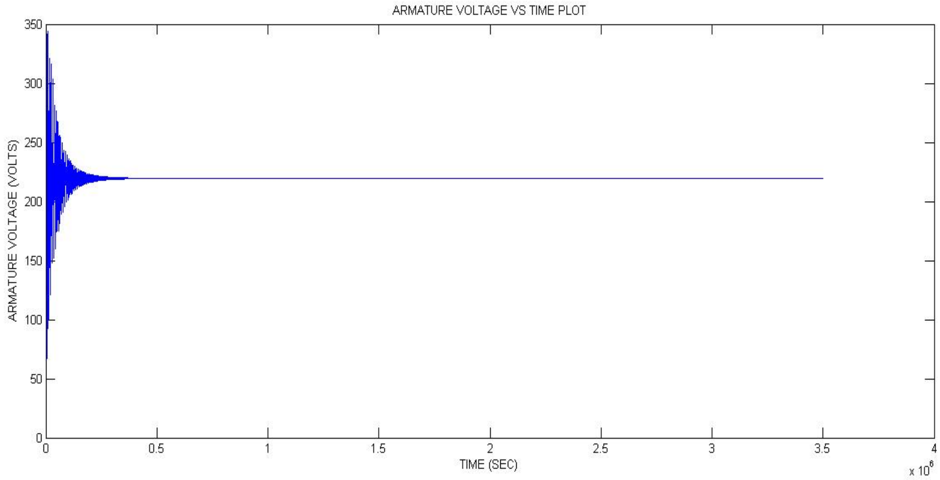

Figure 3.1 (b) : Armature Voltage = 219.4V

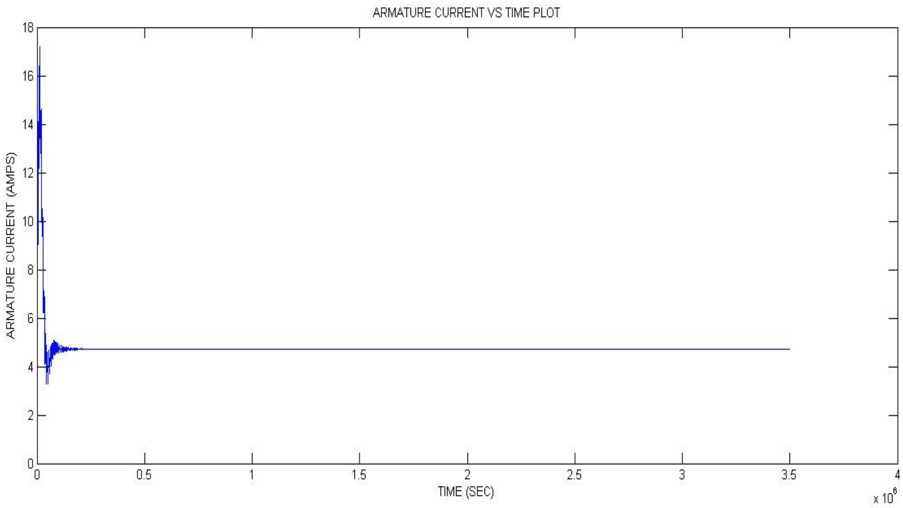

Figure 3.1 (c) : Armature current = 4.71A.

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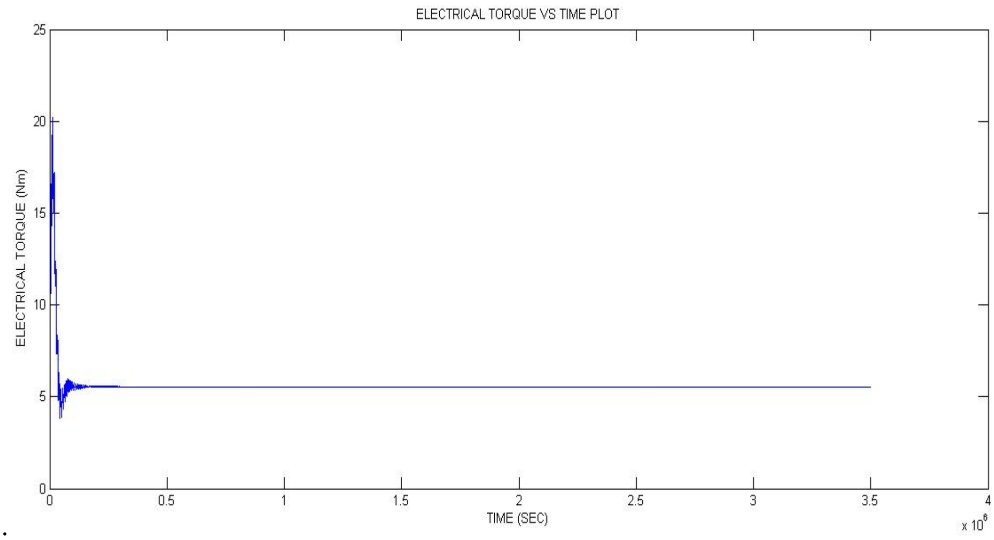
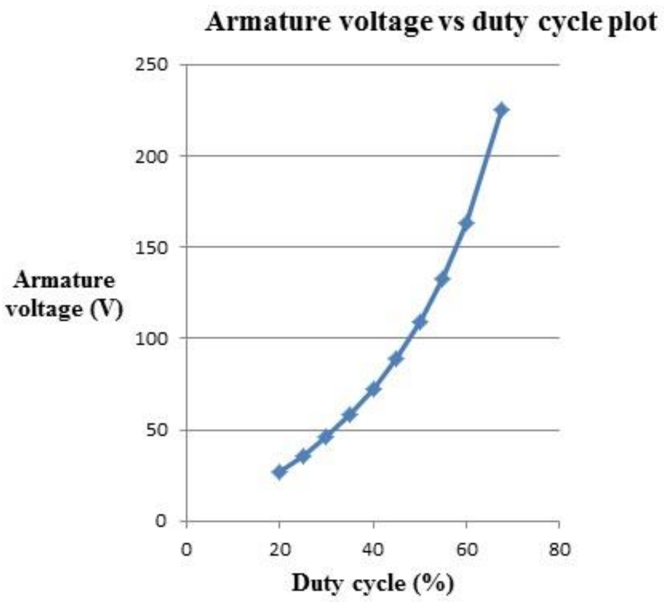


Figure 3.1 (d) : Electrical torque = 5.6Nm.

Table 3.1: The various output parameters with respect to duty ratio obtained from the simulation plots are shown below in the table:

Sl. No.	Duty Cycle (%)	Armature Voltage(V)	Motor speed (RPM)	Armature Current(A)	Electrical Torque(Nm)
1.	20	26.6	63	2	2.62
2.	25	36	126	2.05	2.67
3.	30	46.5	200	2.11	2.75
4.	35	58.5	280	2.185	2.836
5.	40	72	380	2.26	3
6.	45	88.8	500	2.35	3.1
7.	50	108.8	635	2.45	3.2
8.	55	133	800	2.6	3.4
9.	60	163	1000	2.77	3.6
10.	67.7	225	1449	3.15	4.1



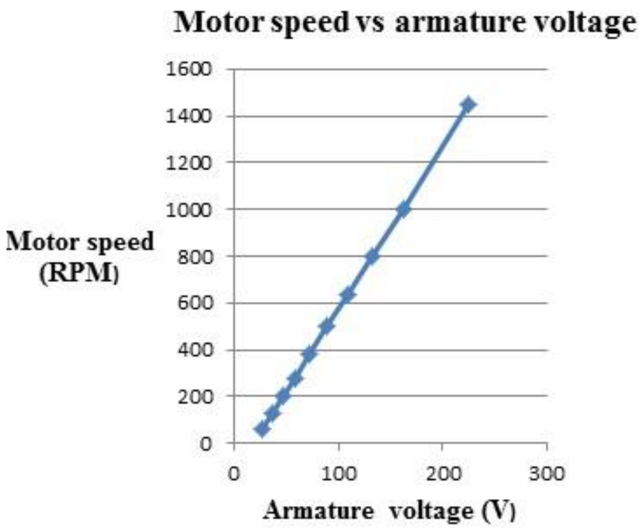


Figure 3.1(e): Armature voltage versus duty cycle plot.

Figure 3.1(f): Motor speed versus armature voltage plot.

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B. Hardware Experimental Results:

The DC-DC Cuk converter has been tested for an input DC voltage of 60V and has been operated under the buck mode. The various results obtained from the hardware results are shown below:

(i) At duty cycle 12.13% as shown in the figure below, the corresponding value of speed is coming out to be 238 rpm with the output voltage of 19V.
(ii) At duty cycle 31% as shown in the figure below, the corresponding value of speed is coming out to be 425 rpm with the output voltage of 36V.
(iii) At duty cycle 46% as shown in the figure below, the corresponding value of speed is coming out to be 538 rpm with the output voltage of 52V.

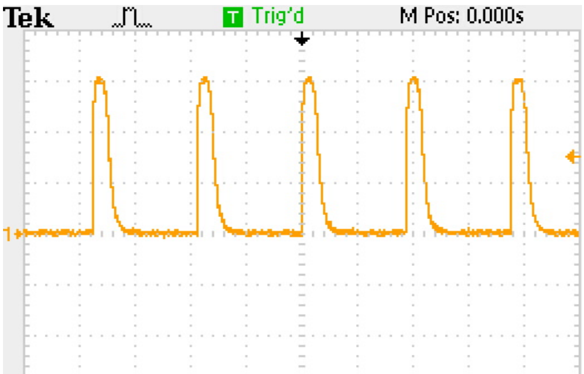

Figure 3.2(a): PWM pulse waveform at 12.13% duty cycle.

Figure 3.2(b): PWM pulse waveform at 31% duty cycle.

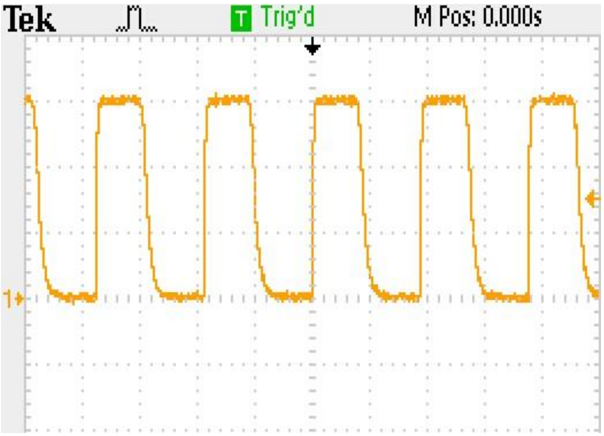

Figure 3.2(c): PWM pulse waveform at 46% duty cycle.

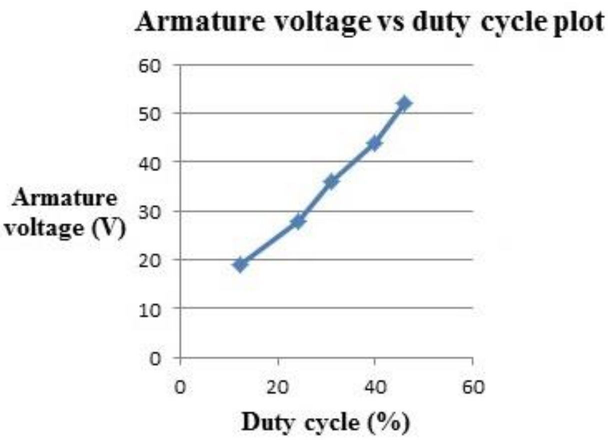

Figure 3.2(d): Armature voltage versus duty cycle plot

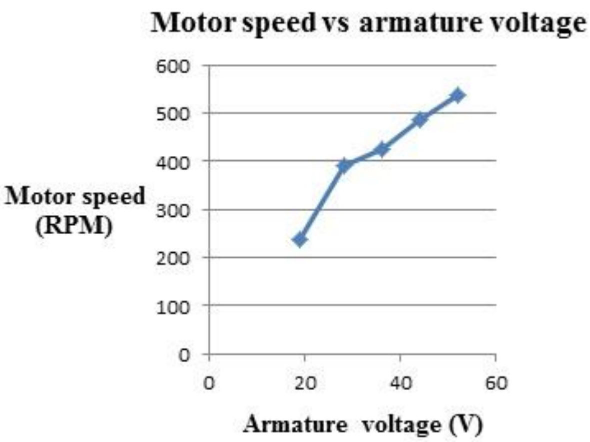

Figure 3.2(e): Motor speed versus armature voltage plot.

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V. CONCLUSION

Simulations were carried out on a Simulink model of the proposed experimental setupwhich was correlated with a hardware implementation of the model being studied for an input DC voltage of 110Vfor an input voltage of 60V in the buck mode both for open-loop speed control. The simulation and experimental data obtained have provided information regardingvariation of armature voltage with duty cycle plot and relation of motor speed as a function of armature voltage. An analysis of the results obtained, both for simulated and experimental data, indicate that the duty cycle of the PWM pulse is directly proportional to the armature voltage and the motor speed. Further, closed-loop speed control can be achieved by designing a controller in the feedback loop. As a further scope for work, other DC-DC converters can also be employed and efficient controllers designed for the same application and their overall results compared for better understanding [8].

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