



## Modeling and Simulation of Sensorless Speed Control of a Buck Converter Controlled Dc Motor

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### Abstract

This paper investigate a sensorless speed control of a separately excited dc motor fed from a buck type dc-dc converter. The control system is designed in digital technique by using a two dimension look-up table. The performance of the drive system was evaluated by digital simulation using Simulink toolbox of Matlab.

**Keywords:** DC motor, speed control, buck converter.

### 1. Introduction

In speed control of the dc motor, high frequency output voltage ripple is achieved using dc chopper where the average voltage across the motor terminals can be controlled by using the duty ratio of power switching device [Sen]. Different control methods have been used to regulate the motor speed like PI controller [Gurbuz] and fuzzy logic control [Tipsuwanporn]. In much application the use of speed sensors like tachogenerator or shaft encoder will add a significant cost and weight to the drive system.

In this work, high chopping frequency is achieved using a MOSFET as a switching device and a smooth dc output voltage and current are generated using a buck type dc-dc converter with sensorless speed control technique to reduce the cost and weight of the drive system. The control method is simple and reliable and does not need exact system parameters measurement when implemented practically.

The buck converter circuit design is presented in section II, while section III explains the proposed control technique with a two dimension look-up table which is used in speed control of induction machines [Jefstenic]. The complete system is modeled in section IV, and then

simulated using Simulink toolbox of Matlab in section V. Finally section VI presents the simulation results and conclusion for the proposed control system for both step change in reference speed and motor load.

### 2. Buck Converter Design

The buck converter circuit diagram is shown in Fig.1, where the steady state output voltage depends linearly on the duty ratio D where:

$$V_a = D.V_s \quad 0 \leq D \leq 1 \quad \dots(1)$$

The buck converter modes of operation are explained in details by [Mohan].

The converter switching frequency is 20 KHz, and the input voltage is 240V.

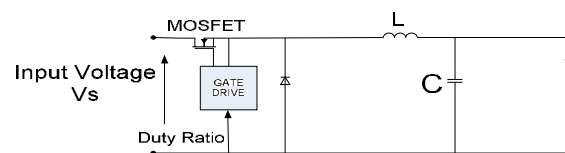


Fig.1. Buck Converter Circuit Diagram.

**2.1. Inductor design**

The inductor value depends on the admissible current ripple  $\Delta iL$  which is given by the following relation [Mohan]:

$$\Delta iL \equiv \frac{1}{L} (Vs - Va) \cdot \frac{D}{fs} \quad \dots(2)$$

The continuous conduction mode of the converter is ensured by making the minimum output current equal to the motor no load current which is about 2A for the used motor in this work. Therefore  $\Delta iL = 4A$  is the maximum admissible value. Solving Eq. (2) for  $L$  yields:

$$L = \frac{(Vs - Va) \cdot D \cdot Ts}{\Delta iL} \quad \dots(3)$$

Where:  $Ts = \frac{1}{fs}$

Substituting Eq.(1) by Eq.(3) gives:

$$L = \frac{Vs(1 - D)D \cdot Ts}{\Delta iL} \quad \dots(4)$$

Clearly the maximum value of the right hand side of Eq. (4) occurs at  $D = 0.5$ ; thus the value of the inductor becomes:

$$L = \frac{Vs \cdot Ts}{4\Delta iL} \quad \dots(5)$$

Taking  $\Delta iL = 2A$  to ensure more smoothness, the value of the inductor will be  $1.5mH$ .

**2.2. Capacitor Design**

The output voltage ripple can be minimized by making the corner frequency  $fc$  of the output LC filter as  $fc \ll fs$ ; also a rule of thumb of  $300\mu f / A$  minimum at  $20KHz$  is more realistic when electrolytic capacitors are used[Chrysis] and accordingly for the  $20A$  rated armature current, the capacitor selected to be two of  $4700\mu f$  connected in parallel is to reduce the equivalent series resistance of the capacitor.

**3. The Proposed Control Concept**

The well known equation of the dc motor is:

$$Va = Eg + Ia \cdot Ra \quad \dots(6)$$

Where:  $Eg = Ka\Phi \cdot n \quad \dots(7)$

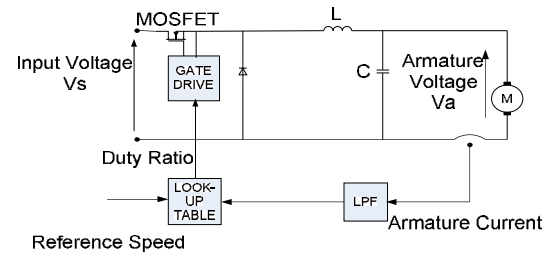
Using the last two equations with Eq.(1), yields:

$$D = \frac{Ka\Phi \cdot n + Ia \cdot Ra}{Vs} \quad \dots(8)$$

Then:  $D = f(n, Ia) \quad \dots(9)$

The proposed algorithm assumes that the reference speed is equal to the actual speed, so if there is a two dimension look-up table in which the first field represents motor speed, the second field represents the armature current and the third one represents the duty ratio; then the required duty ratio can be calculated for a given reference speed and motor load which is estimated by the armature current. The schematic of the drive and control system is shown in Fig.2. For operating points not included in the table, cubic spline interpolation and extrapolation is used to calculate the required duty ratio.

The two dimension look-up table can be formed in two ways. The first method uses simple measurements for small number of operating points while in the second method, the steady state dc motor equivalent circuit is used to calculate the required armature voltage and then the duty ratio for a given reference speed and motor load.



**Fig.2. Buck Converter Controlled dc Motor**

Fig.3 shows the calculated function  $D = f(nref, Ia)$ , from which the required duty ratio is calculated for a given reference speed and armature current, therefore, the speed can be controlled using only the armature current signal.

A current limiter is used to protect the system from the large starting and transient currents, which can damage the converter and possibly the motor.

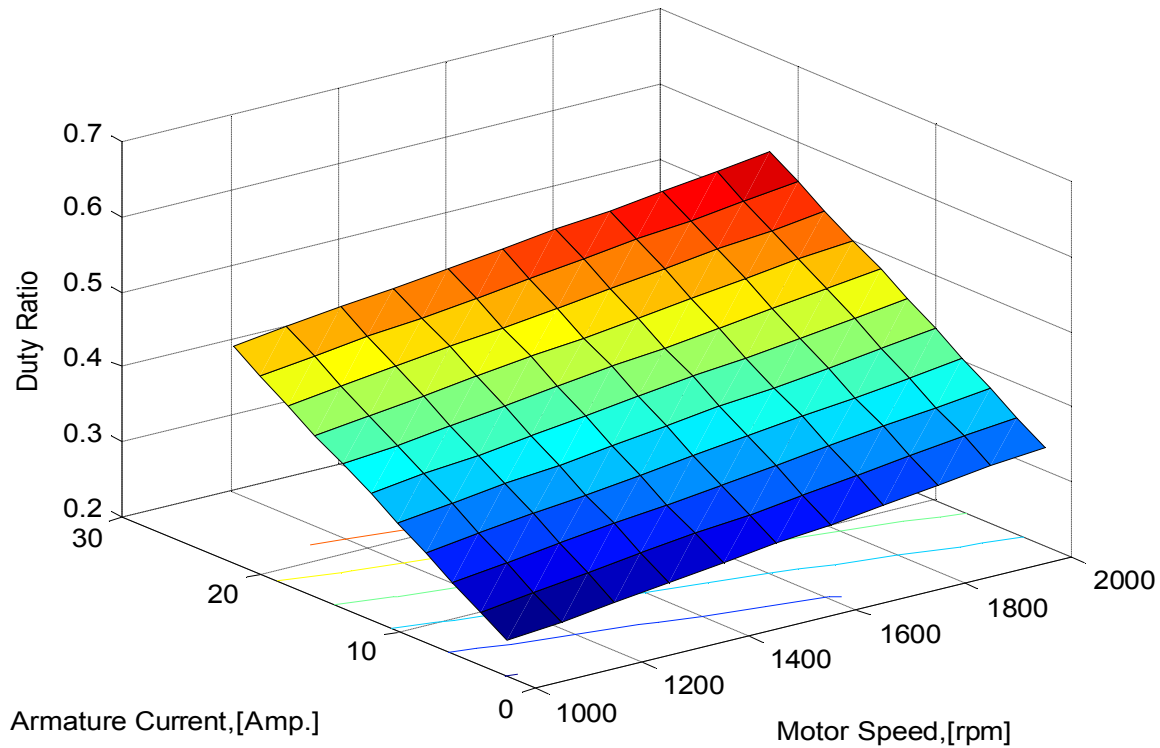


Fig.3. The Duty Ratio Vs. the Armature Current and Motor Speed

#### 4. System Modeling and Simulation

This section includes the modeling of the dc motor and the buck converter, and then the overall system is simulated using Simulink toolbox of Matlab.

##### 4.1. DC motor Modeling

A separately excited dc motor is modeled by the equations below [Tipsuwanporn]:

$$v_a = e_g + R_a i_a + L_a \frac{\partial i_a}{\partial t} \quad \dots(10)$$

Where:

$$e_g = K_a \Phi \cdot n$$

The torque balance equation is:

$$t = T_l + B \cdot n + J \cdot \frac{\partial n}{\partial t} \quad \dots(11)$$

Where:

$$t = K_a \Phi i_a$$

##### 4.2. Buck Converter Modeling

The buck converter is modeled using the equations [Chrin]:

$$\frac{\partial i_L}{\partial t} = \frac{1}{L} (d \cdot v_s - i_L \cdot R_l - v_o) \quad \dots(12)$$

$$\frac{\partial v_c}{\partial t} = \frac{1}{C} (i_L - i_o) \quad \dots(13)$$

$$v_o = v_c + R_e s r (i_L - i_o) \quad \dots(14)$$

Where:

$$d = 1 \quad \text{When the switch is on.}$$

$$d = 0 \quad \text{When the switch is off.}$$

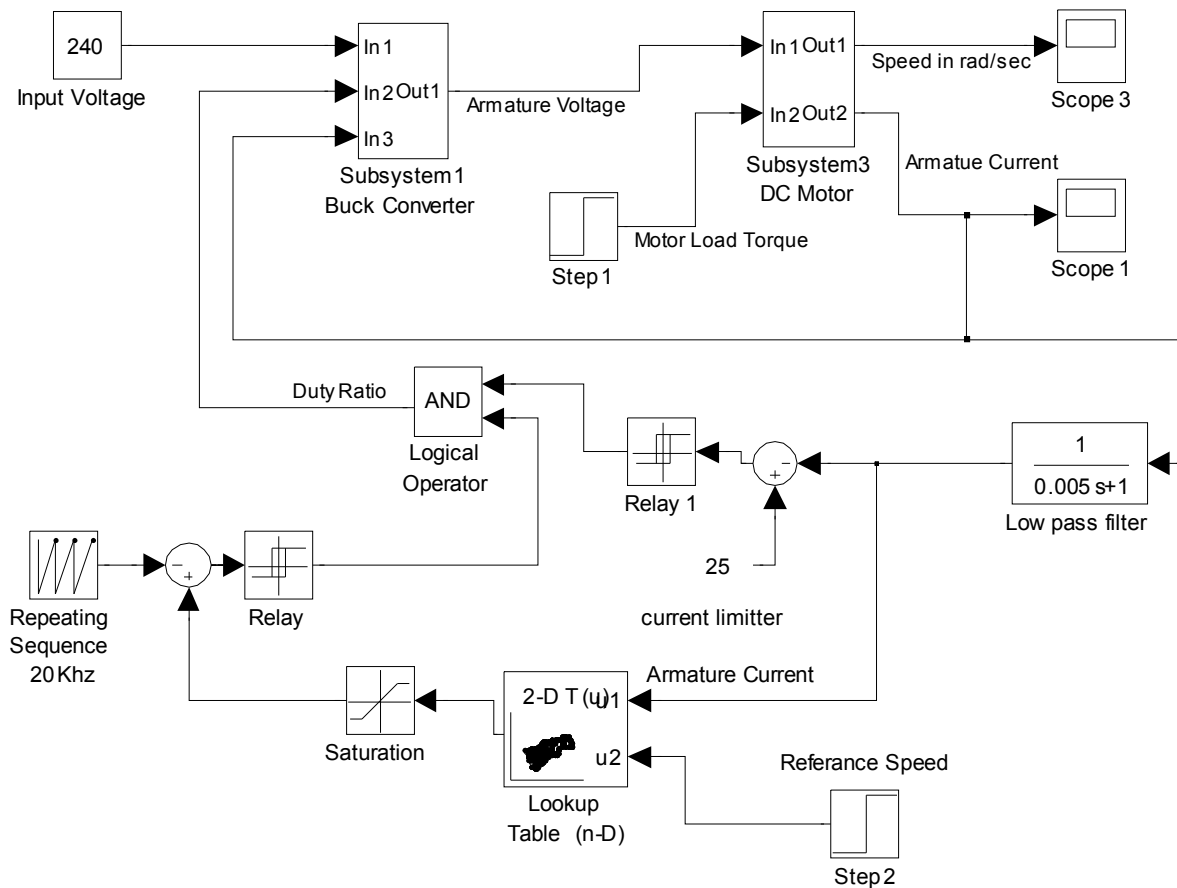
Using the equations (10-14) with the look-up table, Fig.4 shows the overall system simulation while Fig.5 and Fig.6 are the simulation of the dc motor and the buck converter respectively using Simulink toolbox of Matlab.

**5. Simulation Results and Conclusion**

Based on the system model, the motor parameters, and the converter parameters shown in the appendix, Simulink is used to simulate the system under consideration.

Simulation results are shown in Fig.7 and Fig.8 for step response for speed change from 1000 rpm to 1800 rpm ( 104.7 rad/sec to 188.5 rad/sec) and from 1800 rpm to 1000 rpm at rated motor load, and for step change in motor load from 7 N.m to 11 Nm and from 11 Nm to 7Nm at rated speed respectively. These figures clarify the soft start of the motor and the operation of the current limit as well as the satisfactory transient response.

The results demonstrate the effectiveness of the proposed control scheme. One can conclude that the steady state accuracy depends mainly on the look-up table forming. The experimental method for producing a look-up table will lead to more accurate results than that of the method of calculation used in this work since it takes into account some effects, like the parasitic elements not considered in the model. Practical implementation of this proposed control method doesn't require exact motor parameters measurement and lookup table can be changed easily without any hardware modification to take into account the mechanical status of the motor which is changed after a long period of operation.



**Fig. 4. Simulink of a Sensorless Buck Converter Controlled dc Motor.**

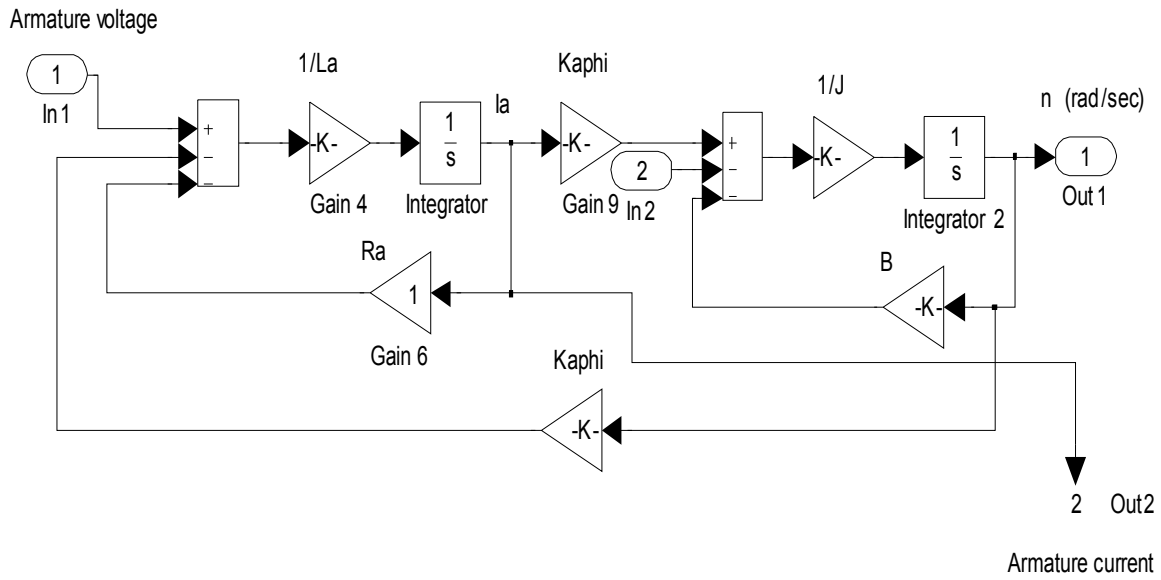


Fig. 5. Simulink of a Separately Excited dc Motor.

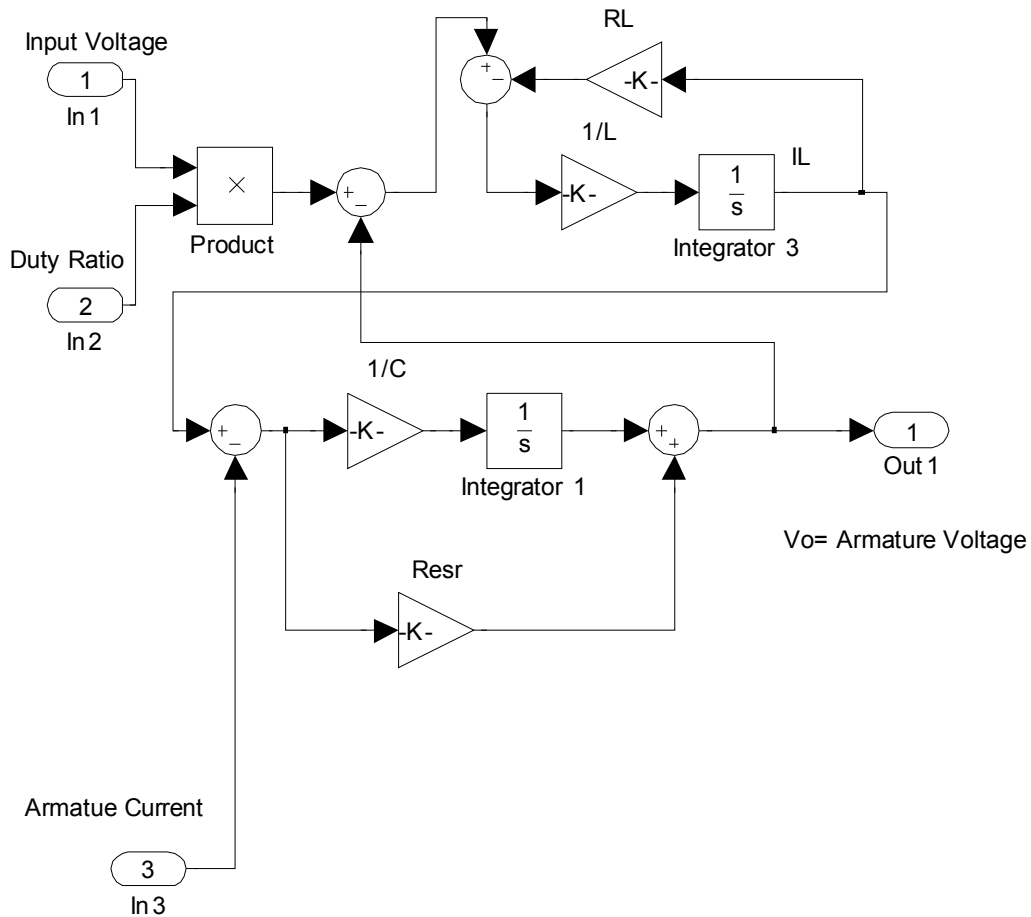


Fig. 6. Simulink of Buck Converter.

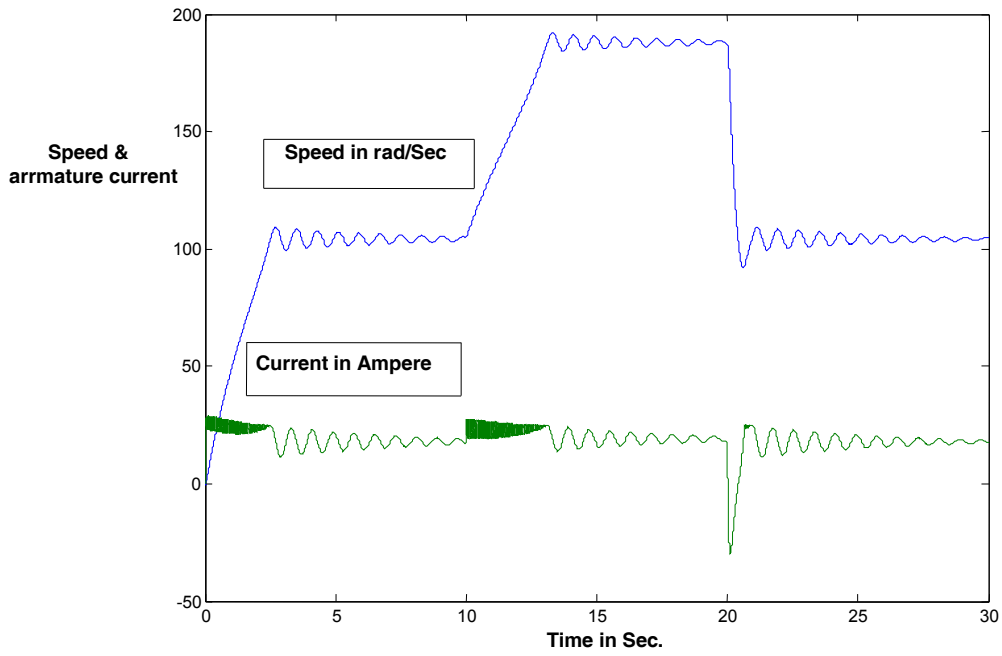


Fig.7. Transient Response due to Step Change in Speed.

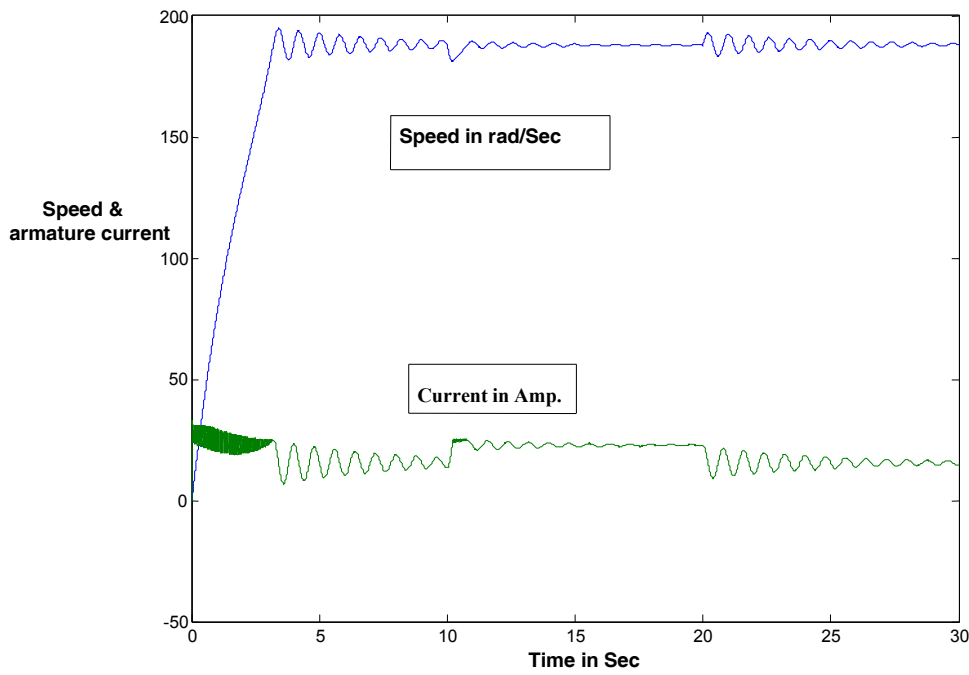


Fig.8. Transient Response due to Step Change in Load.

**Notation**

$eg$	Motor generated voltage (or back emf).
$fs$	Converter switching frequency.
$ia$	Motor armature current.
$iL$	Converter inductor current.
$io$	Converter output current.
$n$	Motor speed.
$nref$	Motor reference speed.
$t$	Developed torque.
$va$	Motor armature voltage.
$vc$	Converter capacitor voltage.
$vo$	Converter output voltage.
$A$	Ampere
$B$	Friction coefficient.
$C$	Converter capacitance.
$D$	Duty ratio
$Eg$	Average motor generated voltage.
$Ia$	Average armature current.
$J$	Moment of inertia.
$Ka\Phi$	Back emf and torque constant.
$L$	Converter inductance.
$La$	Motor armature circuit inductance.
$Ra$	Motor armature circuit resistance.
$Re sr$	Capacitor equivalent series resistance.
$Rl$	Converter inductor internal resistance.
$Tl$	Load torque.
$Va$	Average motor armature voltage.
$Vc$	Average capacitor voltage.
$Vo$	Average converter output voltage.
$Vs$	Converter input voltage.
$\Delta iL$	Inductor current ripple.

**Appendix**

The dc motor used has the following specifications:

DC motor, 110V, 2.5 hp, 1800rpm,  $Ia = 20A$   
 $Ra = 1\Omega$ ,  $La = 46mH$ ,  $J = 0.093Kg - m^2$   
 for the motor and its connected load,  
 $B = 0.008N.m.sec/rad$ . for the motor and its  
 coupled load.,  $Ka\phi = 0.55V.sec/rad$ , which is  
 the back emf and torque constant.

The buck converter specifications are:

Input voltage  $Vs = 240V$ .

Output voltage  $Vo = Va$  is adjustable according  
 to required speed and load.

Output current  $Io = Ia$ .

$L = 1.5mH$ , with internal resistance  
 $Rl = 0.017\Omega$ ,  $C =$  two capacitors connected in  
 parallel each of  $4700\mu f$ . with  $Resr = 0.25\Omega$ ,  
 switching frequency  $fs = 20KHz$ .

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## نمذجة ومحاكاة محرك تيار مستمر مسيطر عليه بواسطة مغير تيار مستمر خافض للفلتية وبدون متحسس سرعه

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### الخلاصة

تحقق هذه الورقه البحثيه في امكانيه السيطرة على سرعه محرك تيار مستمر منفصل الاثاره بواسطة محول تيار مستمر خافض للفلتية من نوع ( Buck ) وبدون استخدام متحسس سرعه وباستخدام تقنيه رقميه من خلال استخدام جدول اثنائي الابعاد ثم تم تقييم مواصفات النظام من خلال محاكاة النظام باستخدام مايسمى بالـ (Simulink toolbox).



