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Advanced Control Method for DC Motor Drives

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Abstract— **In this research work, trajectory tracking of DC motor is established. A hierarchical controller with the dc motor based on differential flatness and the dc/dc Buck converter is designed. In dc motor, angular velocity tracked from a desired velocity trajectory from the desired voltage profile. The inner current loop and the outer voltage loop of cascade control is modelled. The desired angular velocity trajectory is well tracked and the controller is robust in such dynamic operating conditions. The actual value follows the trajectory with time delay and reduced magnitude in simulation. So controller gains are introduced to overcome these issues. Along with that, hardware is to be implemented for the simulation model of overall system. It is important that these types of abrupt variations do not happen in practice at the same time, or with such large variations regarding their nominal values.**

Index Terms— **cascade control, dynamic operating conditions, hierarchical controller, trajectory tracking**

I. INTRODUCTION

DC motors are widely used in systems with high control requirements. Thus, rolling mills, double-hulled tankers, and high-precision digital tools can be mentioned as examples of such systems. Generally, to control the stepless velocity and smoothness, adjustment of the armature voltage of the motor, applying pulse width modulation (PWM) signals with respect to the motor input voltage is one of the methods most employed to drive a DC motor.

The angular velocity trajectory tracking task using proportional-integral (PI) controllers for the regulation of the motor angular velocity were designed. The numerical simulations for the performance of both PI and back stepping controllers associated with the regulation of the angular velocity of the aforementioned system. It allows the DC motor and controller parameters to be changed, and the system's reaction under various operational conditions to be monitored by means of a graphical user interface. The active disturbance rejection control and flatness-based control, for unknown time-varying load, two set of combinations namely DC/DC Buck converters and DC motors. The proposed control scheme effectively provides robustness to the tracking performance when parametric uncertainties related to the system appear which is associated with the DC/DC Buck converter–DC motor system, task enabled by below steps,

i) By employing a fourth-order mathematical model that, generally, leads to long controllers, whose implementation is usually complex.

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ii) By using a second-order model, obtained by ignoring some parameters or states of the system, which is inconvenient for low- and medium-power applications.

On the other hand, performance of the controllers designed, for the angular velocity regulation and trajectory tracking tasks, experimental validation has not been reported where multiple parametric uncertainties have been considered, for either the converter or the motor, nor when the parameters' nominal values are subjected to major variations. To achieve this, as a variation of two independent controllers are designed; one for the DC motor (via differential flatness) and another via the *cascade* scheme (through the SMC and PI control) for the Buck converter, which are then interconnected in order to work as a whole. Additionally, experimental validation of the proposed hierarchical controller's performance is included, showing how the trajectory tracking task is successfully accomplished, even when abrupt variations of the system parameters appear, so exhibiting the robustness of the controller is presented. The design and analysis of a cascade control has been reported, for the voltage regulation task of the Boost, Buck–Boost, noninverting Buck– Boost, and Cuk converters, respectively, while for the voltage trajectory tracking task of the DC/DC Buck converter, a cascade control has not been proposed.

II. CASCADE CONTROL SYSTEM

A) Control of A DC/DC Buck Power Converter

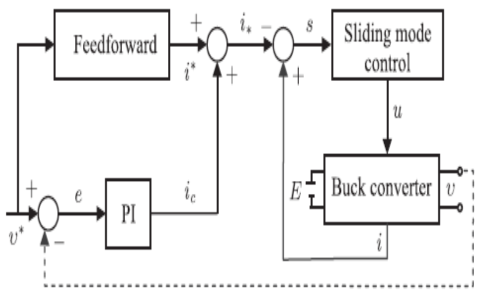

Fig 3.1 Cascade control for the Buck power converter

The voltage profile ϑ is required by the DC motor to track the desired angular velocity trajectory. It must be remembered that ϑ is produced by a Buck power converter. Therefore, it naturally arises the need to develop a control scheme for the converter that allows to reproduce the desired voltage profile ϑ. Thus, the purpose of this section is to present a cascade control for the Buck converter similar to those presented for Boost, Buck–Boost, non-inverting Buck–Boost, and Cuk converters respectively. It is important to mention that those controllers were only designed for the regulation task. In contrast to those controllers, this section gives the solution for the voltage trajectory tracking task of the Buck converter output.

$L\frac{di}{dt} = -v + Eu$ (1)

$C\frac{dv}{dt} = i - v/R$ (2)

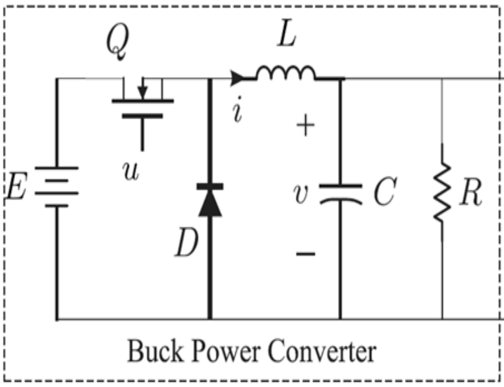

Fig 3.2 DC/DC Buck power converter

This switched converter is associated with the following Model where i represent the inductor current and υ is the capacitor output voltage. The control input u, which represents the switch position function, is a signal that can take values in the discrete set {0, 1}. The system parameters and R, the output load, assumed that the circuit operates in continuous conduction mode, which implies inductor current lower than zero due to load variations.

U=$\frac{1}{2}$[1-sign(s)] (3)

S=i-i_*, (4)

Sign(s)=+1,s≥0 Sign(s)=-1 ,s<0

$i_* = i^* + i_c$ (5)

$= C\frac{dv^*}{dt} + \frac{v^*}{R} + k_p e + k_i \int_0^t e(\tau)d\tau$ (6)

e=$v^* - v$ (7)

Considering, for the Buck converter, the cascade control scheme is proposed, where i *is the feedback reference current, υ*is the reference voltage, E, υ, i, and u are as defined previously, and the voltage error, e, is defined by e = υ*− υ. The Buck converter considers 2 loops for control of the current i and another one for the voltage υ*. The inner current loop uses SMC and the outer voltage loop uses a PI control. The following proposition summarizes the proposed controller .Consider the Buck converter system in a closed-loop with the following controller where υ is the time varying desired voltage at the converter output. K_p and K_e exist such that the origin of the closed-loop system is asymptotically stable whenever the time derivative is the positive definite for radially unbounded scalar function .Finally, from the sliding condition s˙ = 0 and using it is found that the equivalent control satisfies the following bound which means that the sliding regime is possible. On the other hand, ensures that the sliding surface s = i− i*= 0, is reached, that is i= i* for any future time.It only remains to study the stability of the dynamics , when evaluated at i=i-i*, in closed loop. Using *i*= *i**and in yields is positive definite and radially unbounded if K_e>0.It is straightforward to find that the time derivative along with the trajectories of the closed-loop dynamics on the sliding surface *s* = 0, which ensures convergence of model.

III. HIERARCHICAL CONTROL SYSTEM

A) Hierarchical Control For A Dc/Dc Buck Power Converter Dc Motor System

The angular velocity trajectory tracking task for the DC/DC Buck power converter-DC motor system, which is designed with step wise control as given below

1) A control based on differential flatness corresponds to the desired voltage profile that the output voltage of the Buck converter has to track.
2) In order to assure that the converter output voltage, *υ*, tracks *ϑ*, a cascade control is developed in the low hierarchy level.In this control, the inner current loop uses SMC, while the outer voltage loop uses a PI control.
3) Finally, by means of the hierarchical control approach, the controllers developed in 1) and 2) are interconnected to carry out the angular velocity trajectory tracking task of the system.

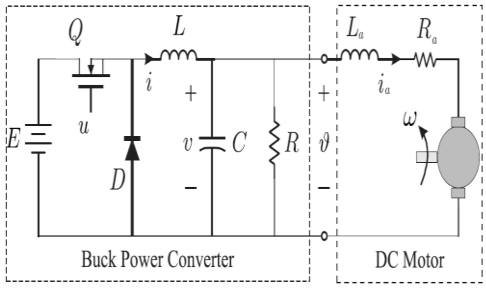

Fig 4.1 DC/DC Buck power converter –DC motor system

B) Control of a DC Permanent Magnet DC Motor

The design of a controller by applying the differential flatness concept for a DC motor is introduced. For the design, the motor inductance is considered different to zero and a DC motor mathematical model expressed in terms of the angular velocity, *ω* where *ϑ* is the applied voltage in the motor armature terminals ,Ia is the armature current, Ke is the counterelectromotive force constant, Km is the motor torque constant, La is the armature inductance, Ra is the armature resistance, J is the moment of inertia of the rotor and motor load, and b is the viscous friction coefficient of the motor.

$L_a\frac{di_a}{dt} = v - R_a i_a - k_e\omega$ (8)

$J\frac{d\omega}{dt} = -b\omega + k_m i_a$ (9)

F=ω (10)

With the intent of synthesizing the control strategy, it is observed that the system is controllable and therefore differentially flat. The angular velocity variable is taken as flat output. Thus, the differential parameterization of the system variables in terms of *F* and its derivatives which give the trajectory tracking task of the angular velocity is reduced to control the following system.

$V = \frac{JL_a}{k_m}\ddot{F} + \frac{1}{k_m}(bL_a + JR_a)\dot{F} + \left(\frac{bR_a}{k_m} + k_e\right)F$ (11)

$V = \frac{JL_a}{k_m}\mu_m + \frac{1}{k_m}(bL_a + JR_a)\dot{F} + \left(\frac{bR_a}{k_m} + k_e\right)F$ (12)

$\ddot{F} = \mu_m$ (13)

$\dddot{e}_\omega + \gamma_2\ddot{e}_\omega + \gamma_1\dot{e}_\omega + \gamma_0 e_\omega = 0$ (14)

P(s)= $s^3 + \gamma_2 s^2 + \gamma_1 s + \gamma_0$ (15)

$$P_d(s) = (s+a)(s^2 + 2\zeta\omega_n s + \omega_n^2) \quad (16)$$
$$\gamma_2 = a + 2\zeta\omega_n \quad (17)$$
$$\gamma_1 = 2\zeta\omega_n a + \omega_n^2 \quad (18)$$
$$\gamma_0 = a\omega_n^2 \quad (19)$$
$$V = \frac{JL_a}{k_m}\mu_m + \frac{1}{k_m}(bL_a + JR_a)\dot{\omega} + \left(\frac{bR_a}{k_m} + k_e\right)\omega \quad (20)$$

Where

$$,\mu_m = \ddot{\omega}^* - \gamma_2(\dot{\omega} - \dot{\omega}^*) - \gamma_1(\omega - \omega^*) - \gamma_0\int_0^t(\omega - \omega^*)\,d\tau \quad (21)$$

If F^* is the desired angular velocity trajectory, then as $F \rightarrow F^*$ when t→∞.The integral-differential expression, defining $e_\omega = F - F^*$, then the closed-loop tracking error dynamics is obtained when error function is a Hurwitz polynomial. For Hurwitz polynomial parameters limitations as follows ,a >0, ζ >0, ω_n>0,and the controller gains, γ2, γ1 , and γ0 are defined. Finally, the control based on differential flatness is as follows:

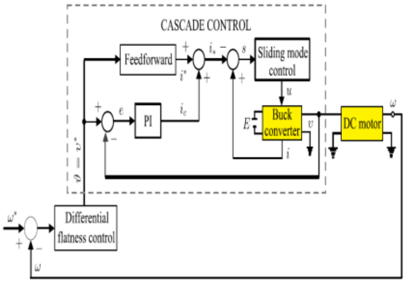

Fig 4.2 Hierarchical block diagram of the system.

C) Control Laws Integration

$$.V = \frac{JL_a}{k_m}\mu_m + \frac{1}{k_m}(bL_a + JR_a)\dot{\omega} + \left(\frac{bR_a}{k_m} + k_e\right)\omega \quad (22)$$

$U=\frac{1}{2}[1\text{-sign}(s)]$ (23)

$S=i-i_*$, (24) Sign(s)=+1,s>=0;

Sign(s)=-1,s<0;

$v^* = v$ (25)

Therefore, connection of the controllers proposed and connection of the controllers to the DC motor, via the DC/DC Buck converter, accomplishes the angular velocity trajectory tracking task. The control associated with the DC motor is given in expression, where μ_m is determined.The DC motor is driven by a Buck converter, it was found that *u* is Pulse given to the desired voltage for the Buck converter. The voltage profile ϑ obtained from controlling the DC motor, which allows the angular velocity trajectory tracking task for the DC/DC Buck converter–DC motor system.

IV. SIMULATION AND RESULTS

In order to test the performance of the hierarchical controller,the DC/DC Buck power converter-DC motor system in closed-loop,which results in the parametric uncertainties of the system. In the synthesized controller, the nominal values used for the Buck converter parameters.AGNM5440E DC Engel motor (24V, 95W) Such a DC motor has the nominal parameters in given table. Regarding the real-time implementation of the hierarchical controller, a MATLAB-Simulink were used. Since the optoisolator provides an inverter signal in its output with regard to a logical input signal, it is necessary beforehand to invert the control signal u in the Control Block, developed via MATLAB-Simulink, to generate u. The control gains associated with the DC motor (γ2, γ1, γ0), which are determined, and following parameters a = 15, ζ= 2, ω_n= 120 are selected. Whereas the gains for the converter are Kp= 0.001,Ki= 50.Furthermore, the desired angular velocity trajectory was proposed as follows:

$$\omega^* = 2 + 1.75\pi[(1 - e{-}2t^3)(1 + \sin(2.5t))]$$

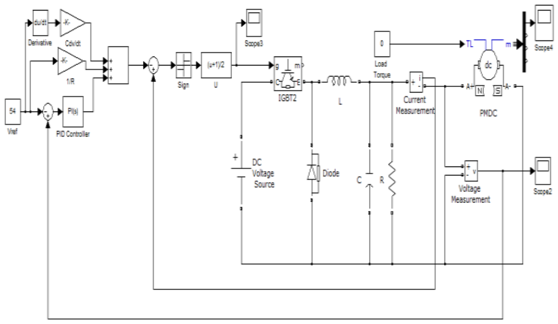

Fig 5.1 Simulink Model of DC/DC Buck power converter (Vref>Vdc)

The Matlab-Simulink Model of DC/DC Buck Power Converter presented above (Fig 5.1) has several blocks such as gain, constant, summer, function block, and circuit parameters like DC Source, Resistor, Inductor, Capacitor, Power Electronics Devices, Measuring Devices and PMDC Motor. Scope is used to display Output Waveforms.

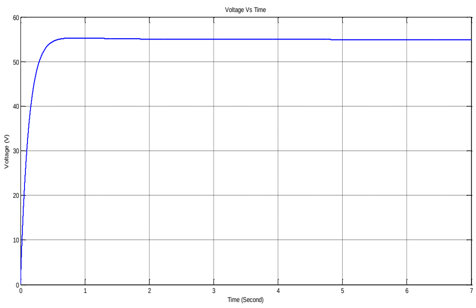

Fig 5.2 Simulation Result of Voltage Vs Time

The Fig 5.2 shows the Simulation results of Voltage Vs Time and describes the relationship between Voltage applied across PMDC Motor and Time. The Simulation run time is set to 7 seconds. The Solver used for this simulation is “ode45”.Due to V* >V the Sliding Mode Control Block is Switched on Continuously, Hence Voltage Reaches the Dc Source Voltage of Buck Power Converter in exponential form.

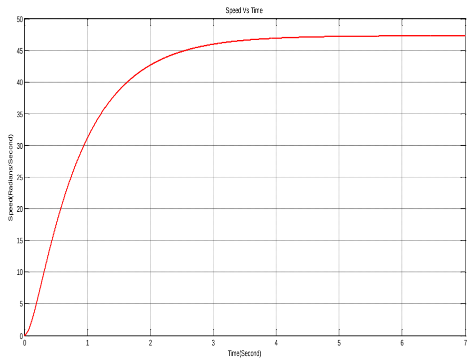

Fig 5.3 Simulation Result of Speed Vs Time

The Fig 5.3 shows the Simulation results of Speed Vs Time and describes the relationship between Speed applied across PMDC Motor and Time. The Simulation run time is set to 7 seconds. The Solver used for this simulation is “ode45”.Due to V* >V the Sliding Mode Control Block is Switched on Continuously, Hence Voltage Reaches the Dc Source Voltage of Buck Power Converter in exponential form. Thus Speed Follows the Voltage profile in same manner.

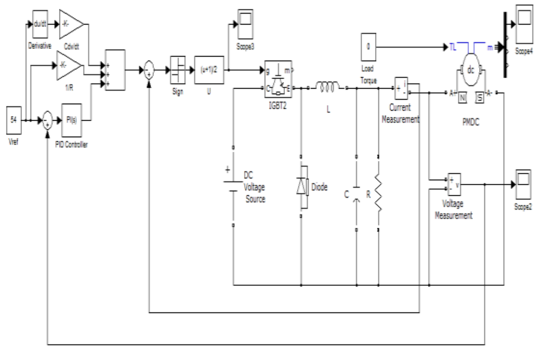

Fig 5.4 Simulink Model of DC/DC Buck power converter (Vref<Vdc)

The Matlab-Simulink Model of DC/DC Buck Power Converter presented above (Fig 5.4) has several blocks such as gain, constant, summer, function block, and circuit parameters like DC Source, Resistor, Inductor, Capacitor, Power Electronics Devices, Measuring Devices and PMDC Motor. Scope is used to display Output Waveforms.

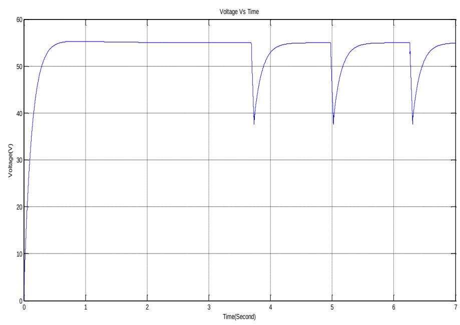

Fig 5.5 Simulation Result of Voltage Vs Time

The Fig 5.5 shows the Simulation results of Voltage Vs Time and describes the relationship between Voltage applied across PMDC Motor and Time. The Simulation run time is set to 7 seconds. The Solver used for this simulation is “ode45”.Due to V* <V the Sliding Mode Control Block is Switched on in pulsating manner, Hence Voltage Reaches the Dc Source Voltage of Buck Power Converter in exponential form followed by spikes as SMC starts pulsating.

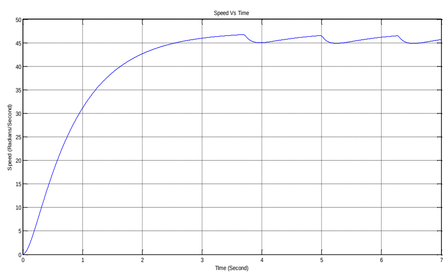

Fig 5.6 Simulation Result of Speed Vs Time

The Fig 5.6 shows the Simulation Results of Voltage Vs Time and describes the relationship between Voltage applied across PMDC Motor and Time. The Simulation run time is set to 7 seconds. The Solver used for this simulation is “ode45”.Due to V* <V the Sliding Mode Control Block is Switched on in pulsating manner, Hence Voltage Reaches the Dc Source Voltage of Buck Power Converter in exponential form followed by spikes as SMC starts pulsating. Thus Speed of Motor starts to pulsate when Voltage starts to pulsate.

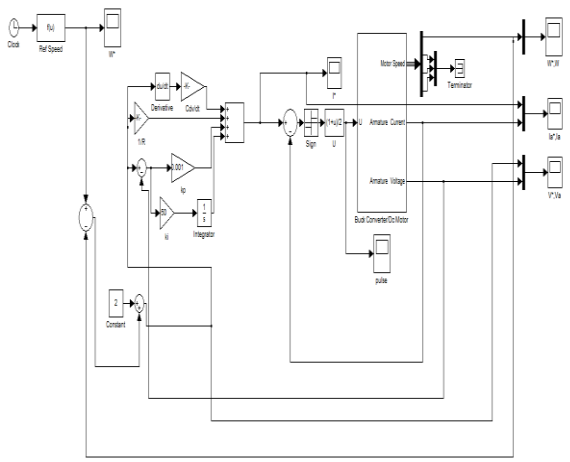

Fig 5.7 Simulink Model of Hierarchical Control of the system.

The Matlab-Simulink Model of Hierarchical Control of the entire system presented above (Fig 5.7) has several blocks such as gain, constant, summer, function block, and circuit parameters like DC Source, Resistor, Inductor, Capacitor, Power Electronics Devices, Measuring Devices and PMDC Motor. Scope is used to display Output Waveforms.

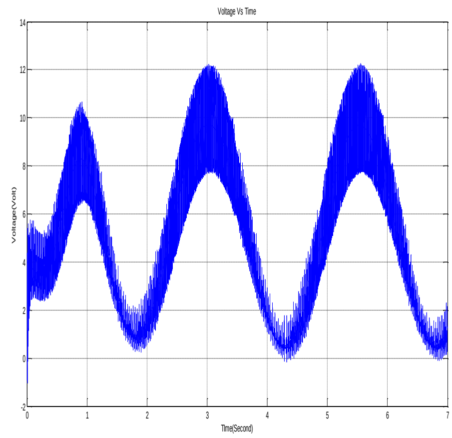

Fig 5.8 Simulation Results of Voltage Vs Time

The Fig 5.8 shows the Simulation Results of Voltage Vs Time and describes the relationship between Voltage applied across PMDC Motor and Time.The Simulation run time is set to 7 seconds. The Solver used for this simulation is “ode45”.Due to influence of the Sliding Mode Control Block, Feed Forward Block and PI Controller are controlling inner loop, mean while differential flatness control deduce Voltage Profile for Trajectory Tracking of PMDC Motor which is provided as input to Inner loop. Hence Trajectory of Speed of Motor tries to follow Reference Speed which yields Voltage

Profile but due to Controller and Loops, Oscillated Voltage Wave form presents within which Voltage Profile exist.

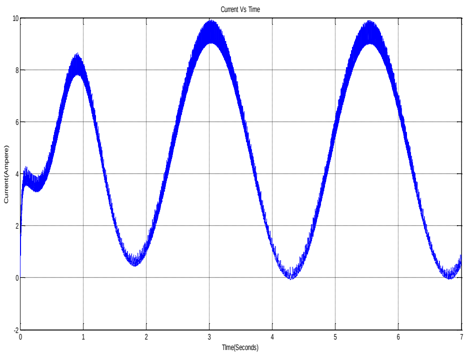

Fig 5.9 Simulation Results Current Vs Time

The Fig 5.9 shows the Simulation Results of Voltage Vs Time and describes the relationship between Voltage applied across PMDC Motor and Time. The Simulation run time is set to 7 seconds. The Solver used for this simulation is "ode45".Due to influence of the Sliding Mode Control Block, Feed Forward Block and PI Controller are controlling inner loop, mean while differential flatness control deduce Voltage Profile for Trajectory Tracking of PMDC Motor which is provided as input to Inner loop.Hence Trajectory of Speed of Motor tries to follow Reference Speed which yields Voltage Profile, which in turn yields reference current but due to Controller and Loops, Oscillated Current Wave form presents within which Actual Current of Motor exist.

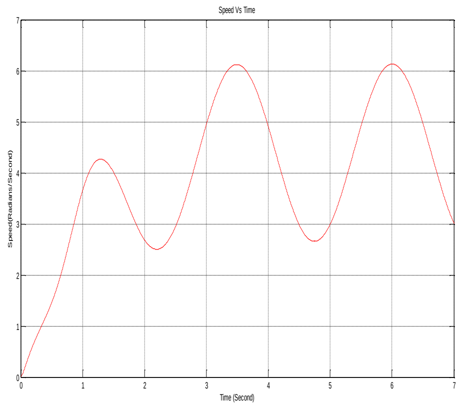

Fig 5.10 Simulation Results of Speed Vs Time

The Fig 5.10 shows the Simulation Results of Speed Vs Time and describes the relationship between Voltage applied across PMDC Motor and Time.The Solver used for this simulation is "ode45".Due to influence of the Sliding Mode Control Block, Feed Forward Block and PI Controller are controlling inner loop, mean while differential flatness control deduce Voltage Profile for Trajectory Tracking of PMDC Motor which is provided as input to Inner loop. Hence Trajectory of Speed of Motor tries to follow Reference Speed which yields Voltage Profile, which in turn yields reference current, which determines pulse generation of SMC Control but due to Controller and Loops, Actual Motor Speed Trajectory Wave form follows Reference Waveform with small change in time and magnitude.

Table 5.1 Parameters in PMDC Motor

Parameters	Specifications	Value
E	DC Voltage Source	56 V
R	Resistance	61.7 Ω
L	Inductance	118.6 mH
C	Capacitance	114.4 μF

Table 5.2 Parameters in DC/DC Buck Converter

Parameters	Specifications	Value
V	Voltage Rating	24 V
P	Power Rating	95 W
Ra	Armature Resistance	0.965 Ω
La	Armature Inductance	2.22 mH
J	Moment of Inertia	$118.2gm^2$
B	Damping Viscous Coefficient	0.129 N-ms
Km	Torque constant	0.1201 N-m/A
Ke	Back emf constant	0.1201 V-s/rad

The Table 5.1 shows the Parameters of DC/DC Buck Converter and the Table 5.2 describes the parameters of PMDC Motor used in this project work.

V. CONCLUSION AND FUTURE SCOPE

This Project work is motivated by the hierarchical control approach applied in the mobile robotics area which proposed a solution for the angular velocity trajectory tracking problem for DC motor system. The step by step control of the DC motor and with Buck converter is given below

1) The first control is based on differential flatness, which tracks to the desired angular velocity ω*.
2) The second control uses a cascade control scheme applied to the Buck converter to generate the voltage profile ϑ required by the DC motor.This control accomplishes that the converter output voltage tracks to the voltage profile ϑ, that is, $\upsilon \rightarrow \vartheta$.
3) Using a hierarchical controller, it was possible to carry out the integration of the two controllers.

According to the simulation results, the main objective of this project work was successfully achieved, since the angular velocity of the motor tracks a desired angular velocity trajectory.. Along with that, hardware is to be implemented for the simulation model of overall system.

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