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Digital Implementation of Sliding Mode Controller for Soft Starting of DC Motor in Robotic Arm Applications

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Abstract : This paper mainly focus on the soft starting of PMDC motor powered with *dc*/*d*c buck converter. To end of this paper a digitally implemented controller is designed for the converter fed motor. This controller tracks the desired angular velocity trajectory and also provides require voltage profile. Comparative analysis is done with the existing system and improved dynamic response is obtained. The cascaded controller with SMC for current loop and PI for voltage loop is designed and stability for the controller is analyzed. Simulation is Carried out and the results show that the effectiveness of the controller to obtain the desired trajectory is well tracked under different uncertainties.

1. INTRODUCTION

DC power generally was obtained by motor generator set or by converting AC power through converters or thyratorns [1]. Later the dc power is converted into variable dc through dc/dc converters. DC motor powered by dc/dc converters has various applications like traction control, automobile industries, forklift trucks, robotics and mine haulers. The buck converter is preferred and appropriate as it has low internal losses and high power conversion efficiency. As it has two storing elements (inductance and capacitance) the converter provides high efficiency and tracks the angular velocity that is required with small current ripples. [2] The combination of converter powered to dc motor to attain dynamic response is a challenging problem. For tracking the angular velocity profile or position the voltage required for a DC motor is driven by dc/dc converter. Small signal linearization, circuit averaging conventional design methods requires linearity for every operating point that is required to check the stability. Most of the converter study was focused on the design of a converter and the designer experience but the pre-sizing approach of the converter architecture yields to the best component selection which will be useful for optimal results in control [3]. During the past research number of non-linear feedback controllers like linearization, conventional methods, passivity-based flatness control, error correction through feedback controllers, PWM modulators are applied to power converters by Ramirez & Origoza in 2006. Back stepping technique is applied to buck converter was proposed by H.E. Fadil& F. Giri. Utkin, Guldner proposed sliding mode observers to improve transient response under open loop SMC. Guldemir, proposed the combination of PI controller for output voltage loop associated with boost converter and open loop SMC for the inner current loop. In 2012 Kamal Ejjaburavi, C Larouci proposed the pre-sizing of a buck converter to get optimal results under thermal and EMC constraints. Based on disturbance rejections and flatness control Sira and Oliver proposed the robust control for two combinations of converter driven motors in 2013. Open loop SMC is applied to different converters and is discussed in by Utkin, J. Guldner, & Shi. In 2015, The angular velocity is tracked for the dc /dc buck converter attached to dc motor system with two controllers one for dc motor and the other via cascaded scheme through (SMC and PI) for converter is carried by Ramon Silva Ortigozo Mayra Cruz. Although converter proposed in this paper is not an optimum one, this method results in a satisfactory dynamic output response but the robustness of the controller over a wide operating range cannot be ensured.

This paper focus on a smooth starting of a *dc* motor used for robotic applications where it is rigidly analyzed for a buck converter whose current loop uses SMC and voltage loop uses PI which also fills the gap showing the controller robust and reliable. This paper is organized as follows. Section 2 Control of dc motor via flatness based. Section 3: design of converter Section4 deals with the design of the controller. Section 5 discusses the results.

2. PROPOSED SYSTEM

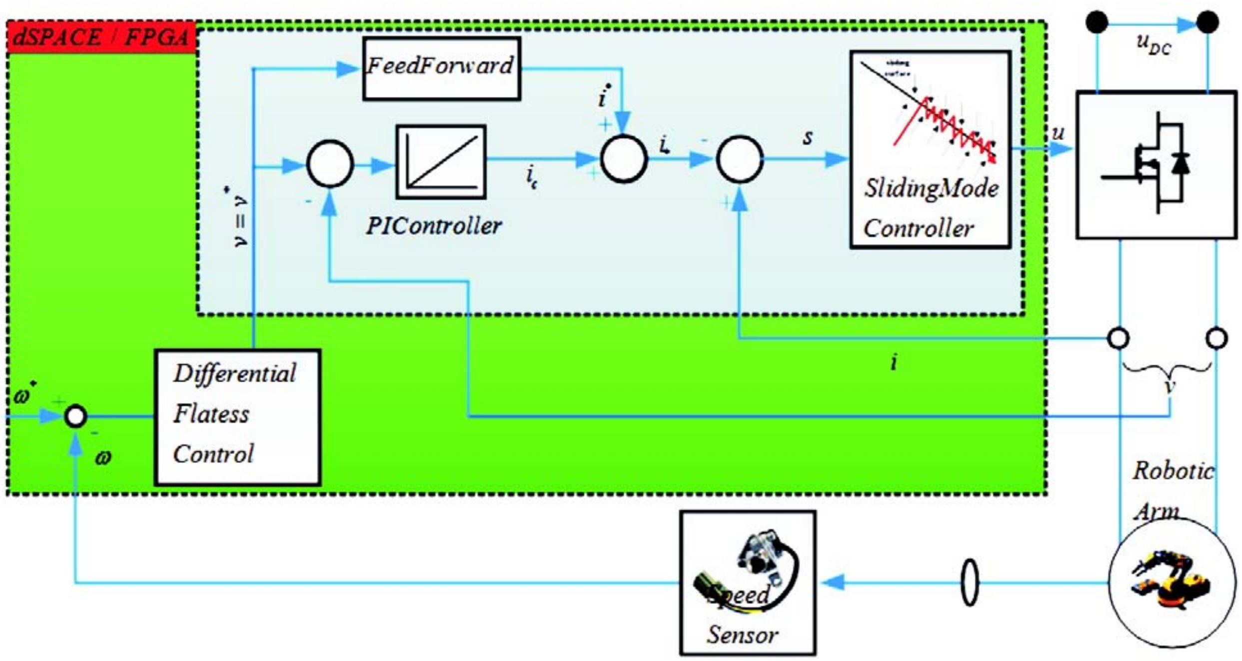

Figure 1: Smooth Starter for a DC Motor Based on a Hierarchical Controller Digital implementation for Robotic Application

2.1. Control of DC Motor based on differential flatness

The design of a controller, for flatness approch concept tracks the angular velocity trajectory of a PMDC motor where its armature inductance is considered, the motor shaft speed is given as ω,

$$V - i_a R_a - L_a \frac{di_a}{dt} = K_e \omega$$

$$L_a \frac{di_a}{dt} = V - i_a R_a - K_e \omega \quad (1)$$

$$J \frac{d\omega}{dt} = -b\omega + k_m i_a \quad (2)$$

Where V is the armature voltage, i_a is the armature current K_e counter electromotive force constant, k_m torque constant of the given motor. L_a inductance of the armature, J moment of inertia of the rotor, R_a armature resistance and b is the viscous friction coefficient. The control strategy for the motor is synthesized by the above equations (1) and (2) and is expressed in matrix form below.

$$\dot{X} = AX + BU$$

$$y = CS \quad (2)$$

where

$$X = [i_a \omega]^T$$

and

$$A = \begin{pmatrix} -\frac{R_a}{L_a} & -\frac{k_e}{L_a} \\ \frac{k_m}{J} & -\frac{b}{J} \end{pmatrix}$$

$$B = \begin{pmatrix} \frac{1}{L_a} \\ 0 \end{pmatrix}$$

$$C = (01)$$

The controllability matrix Q_c is given as

$$Q_c = (B \;\; AB)$$

$$= \begin{pmatrix} \frac{1}{L_a} & -\frac{R_a}{L_a^2} \\ 0 & -\frac{k_m}{JL_a} \end{pmatrix} \quad (4)$$

Since,

$$|Q_c| = \frac{k_m}{JL_a^2} \neq 0 \quad (5)$$

The above analysis states that the proposed system is controllable and therefore it is differentially flat. Multiplying the last row with Q_c^{-1} by state vector X, the output of the system is obtained

$$[Q_c^{-1}]X = \frac{JL_a}{k_m}\omega \quad (6)$$

For flat output the variable taken is angular velocity without considering the loss of generality,

$$F = \omega \quad (7)$$

Thus, by simple calculation of motor equation (1) and (2) derives that the differential parameterization of the system variables and its derivatives is defined in terms of F which is given by

$$i_a = \frac{1}{k_m}(J\dot{F} + bF) \quad (8)$$

$$\omega = F \quad (9)$$

$$v = \frac{JL_a}{k_m}\ddot{F} + \frac{1}{k_m}\left(bL_a + JR_a\right)\dot{F} + \left(\frac{bR_a}{k_m} + k_e\right)F \quad (10)$$

Equation (10), gives the system control of the dc motor which is required

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

3. BUCK CONVERTER

DC/DC Buck power converter parameters are constituted as a capacitor C,input voltage V_{in}, switch of transistor S, a diode D, an inductor L and a load resistance R_L. Let the current through be i_L and voltage across the resistor is V_R. The value V_R will be either greater or less than V_i , and V_R is in opposite polarity with V_i. When the converter switch S is turned on the voltage V_i is applied through the inductor L, capacitor C and load resistor R_L. When switch is turned off the inductor L acts as source and supplies energy to the capacitor C and to load R_L. When the control signal $u = 1$ the converter switch is on when $u = 0$ it is in off position. The differential equations can be given as

$$i_L = \frac{1-u}{L}V_R + \frac{u}{L}V_i \quad (12)$$

$$v = \frac{(1-u)}{C}i - \frac{1}{CR_L}V_R \quad (13)$$

(12) and (13) represent the state space format in discontinuous mode, where the controller and state variables have a bilinear relation.

4. ANALYSIS FOR CLOSED LOOP SYSTEM

4.1. Cascaded control

The hierarchal controller involves PI as voltage controller for outer loop and sliding mode control for inner loop which is designed to track the reference voltage with tolerable error in spite of disturbances and uncertainties. Let i^* reference current for feedback. V_d is the reference input voltage, V_i input voltage, V_R output voltage and u control signal. e is defined as the error between V_d and $V_{R,}$ and $_{\text{positive}}$ feedback current i is given for SMC.

A: PI control given to Outer voltage loop: For constant value of control input, while control variable $u = U_c$ where U_c is constant, let the equations (12) and(13) be equal to zero. Equations for inductor current i_{eq} and voltage which is equal to V_d is given by

$$\frac{1-U_c}{L}V_d + \frac{U_c}{L}V_i = 0 \quad (14)$$

$$-\frac{(1-U_c)}{C}i_{eq} - \frac{1}{CR}V_d = 0 \quad (15)$$

Eliminating U_c in (3) and (4) i_{eq} and V_d is given as

$$i_{eq} = \frac{V_d}{R}\left(\frac{V_d}{V_i} - 1\right) \quad (16)$$

The reference input current under open loop sliding mode with error $e = V_d - V_R$ provides a relation between inductor current and voltage when the converter is in steady state mode. The current for inner loop for PI controller is given as

$$i^* = K_p e + K_i \int_0^t e dt \tag{17}$$

4.2. Sliding Mode Control for current loop

The switching assorted for buck converter with sliding mode control is given as

$$s = i - i^* \tag{18}$$

$$u = \frac{1}{2}[1 - \text{sgn}(s)] \tag{18}$$

$$\text{sgn}(s) = \begin{cases} +1, s < 0 \\ 0, s > 0, \end{cases} \tag{19}$$

The switching controller s and its derivative are zero when sliding mode occurs. The existence of sliding mode indicates when the system can reach and stay on $s = 0$, this can be proved by lyapnov function.

Consider the time derivative of the positive definite and radially unbound scalar function

$$V_i = \frac{1}{2}s^2 > 0$$

if $$s \neq 0 \tag{20}$$

Differentiating equation (20) we get

$$s' = i' - i^{*'}$$

$$= \frac{1-u}{L}V_R + \frac{u}{L}V_i - i^{*'} \tag{21}$$

From equation (21) analysis are made and the sufficient condition for $V' < 0$ is

$$|s|(|(V_i + V_R - 2Li^{*'}| - (V_i - V_R)) < 0 \tag{22}$$

The inequality leads to

$$|(V_i + V_R - 2Li^{*'}| < V_i - V_R \tag{23}$$

When sliding mode is attained V_d is tracked, i^* must be almost equal to i_d since L << 0, and i^* close to zero. Then $Li^* \approx 0$, due to $V_i > 0$ and $V_R < 0$, the inequality is shown in eq(23). The inequality attracts the sliding assorted. As there is no control gain associated.

In steady state the inequality is fulfilled by inverting buck converter polarities where input voltage V_i and output voltage V_R are opposite to each other regardless of their magnitudes, such a voltage controller the motion eventually reaching phase and reaches sliding mode.

4.3. Closed loop analysis

It is applied to the system after the occurrence of sliding mode. To hold the sliding mode at $s = 0$ and $\dot{s} = 0$. The discontinuous control u in $\dot{s} = 0$ can be replaced by u_{eq} which is close to u where it contains both low and high frequency signals.

After SMC occurs at $$s = i - i^* = 0 \tag{24}$$

$$s' = i - i^{*'}$$

$$= \frac{1-u_{eq}}{L}V_R + \frac{u_{eq}}{L}V_i - i^{*'} \qquad (25)$$

Solving $$i = i^* \qquad (26)$$

Solving (23) for u_{eq} gives $$u_{eq} = \frac{V_R - Li^{*'}}{V_R - V_i} \qquad (27)$$

In sliding mode u_{eq} takes the values 0 to1 and the inequality in equation (24) is solved as

$$-(V_i - V_R) < (V_i + V_R - 2Li^{*\prime})$$

$$< V_i - V_R \qquad (28)$$

5. SIMULATION RESULTS

Taking into account the parametric uncertainties, this section deals with the simulation results associated with the dc/dc Buck power converter–dc motor system in closed-loop.

In the synthesized controller, the nominal values used for the Buck converter parameters are shown in Table 1.

Table 1
Design Specifications of converter

Quantity	*Existing*	*Proposed*
R	61.7 Ω,	61.7
L	118.6 mH	11.86mH
C	114.4 μF	11.44uF
E	56 V	56

The nominal values of GNM5440E *dc* Engel motor (24V, 95W), connected to a G3.1 gearbox with a reduction ratio of 14.5 : 1, was used for simulation purpose is as follows

$$k_e = 120.1 \times 10^{-3}\,\text{N}-\text{m/A},$$
$$L_a = 2.22 \times 10^{-3}\,\text{H}$$
$$k_m = 120.1 \times 10^{-3}\,\text{V} - s/\text{rad},$$
$$J = 118.2 \times 10^{-3}\,\text{kgm}^2$$
$$R_a = 0.965\,\Omega,$$
$$b = 129.6 \times 10^{-3}\,\text{N} - \text{ms}.$$

Control gains associated to motor and converter is

$$a = 15,$$
$$\zeta = 2,$$
$$\omega_n = 120.$$
$$k_p = 0.001,$$
$$k_i = 50.$$

The desired angular velocity trajectory ω^* was proposed is given by

$$\omega^* = 2 + 5.495\left[\left(1 - e^{-2t^3}\right)\left(1 + \sin 2.5t\right)\right]$$

where t is the time.

Using the transfer function of the buck converter, the stability of the converter is studied by plotting the bode plot and the performance and robustness of the controller is shown in table 2

Table 2
Performance and robustness of Buck Converter

Rise time (T_r)	*0.00157sec*
Settling time (T_s)	0.0152sec
Percentage peak overshoot (% M_p)	17.2
Peak value	1.17
Gain Margin (GM)	64dB
Phase Margin (PM)	60
Phase crossover frequency (W_{pc})	1052rad/sec
Gain crossover frequency(W_{gc})	417 rad/sec
Closed loop system	Stable

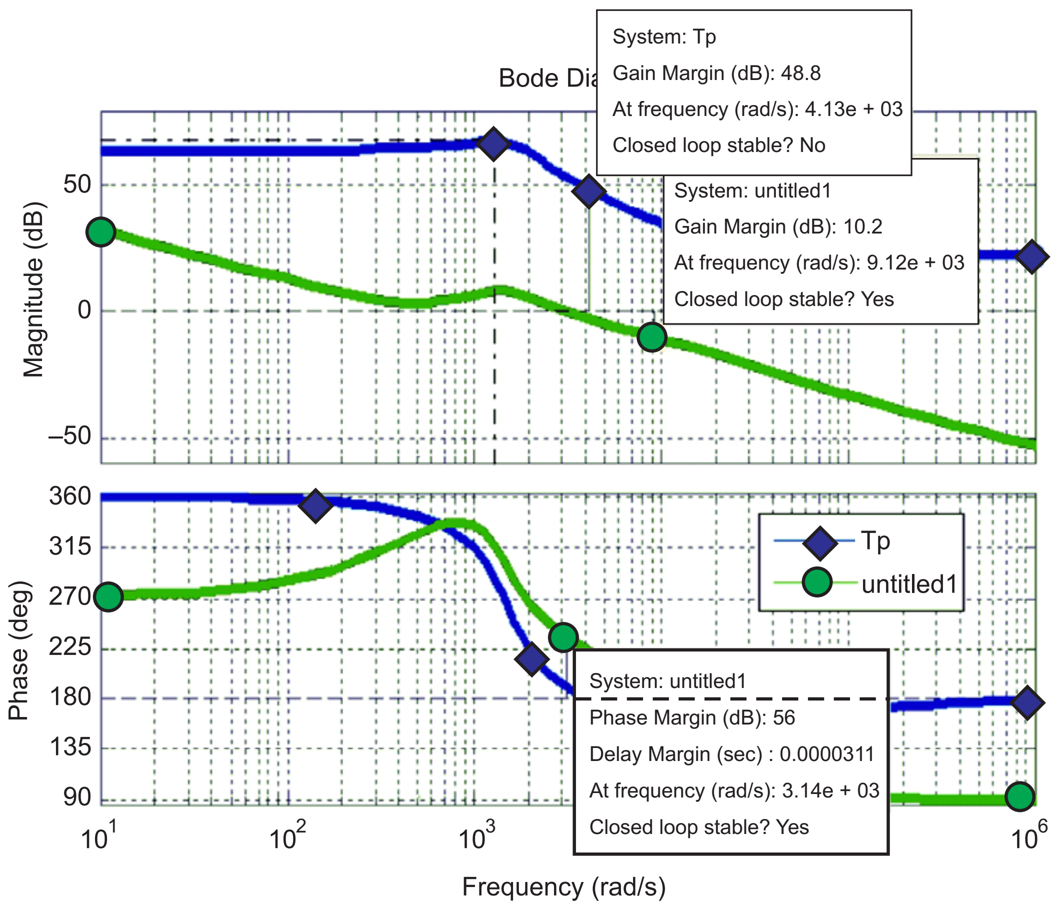

Figure 2: Bode Plot for the transfer function in s-domain of DC-DC converter

Fig 3 illustrates the firing pulses of the converter based on the duty cycle achieved. Fig 4 gives the digital implementation of the cascaded controller through FPGA fed to the combination of converter and dc motor

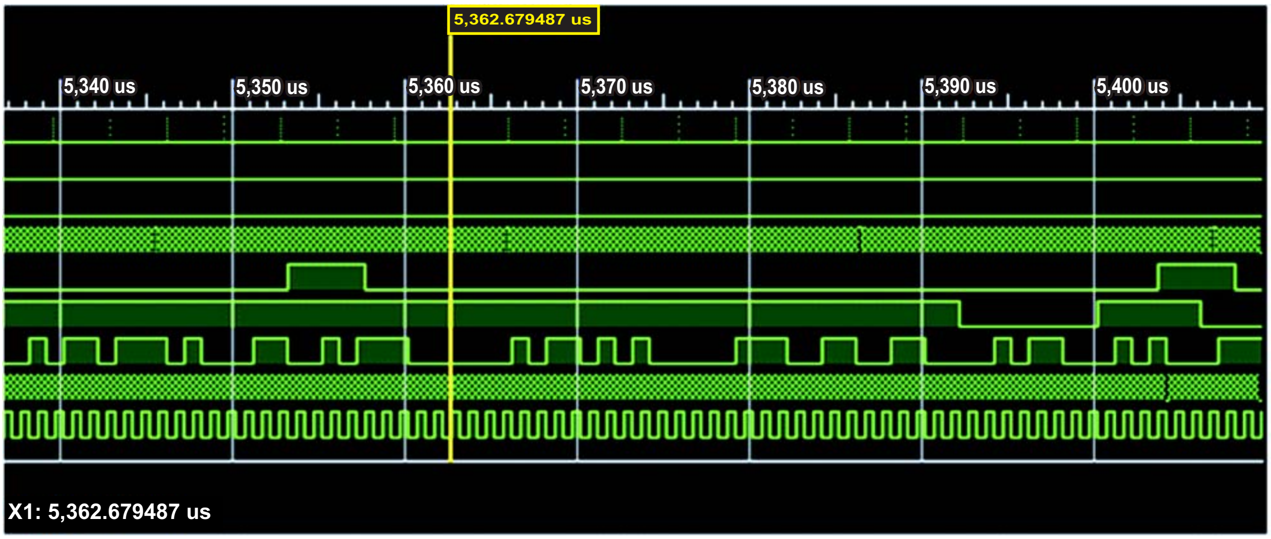

Figure 3: Firing Pulses given to the converter

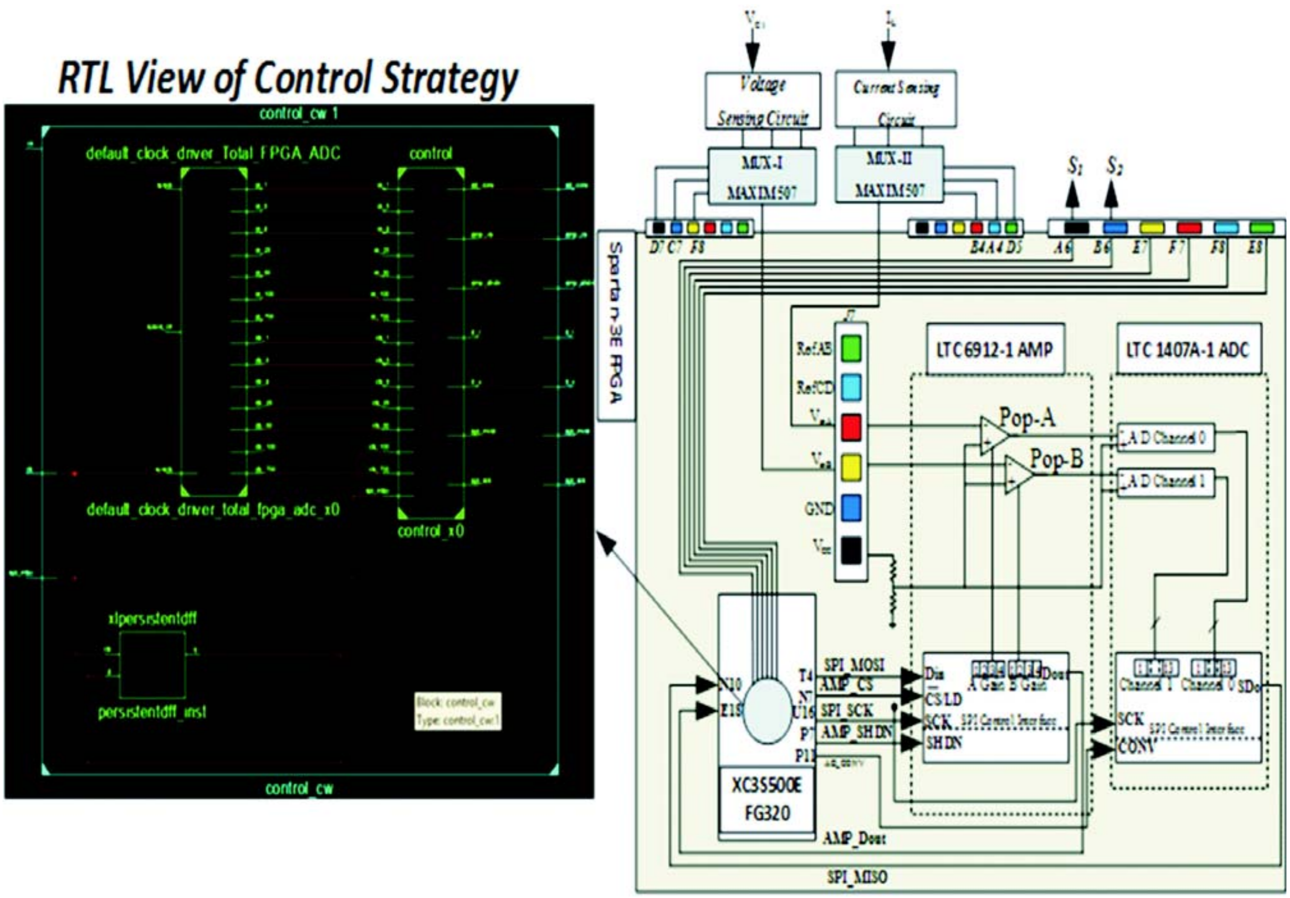

Figure 4: Digital implementation of the controller through FPGA fed to the converter

Fig 5 illustrates the behavior of output voltage and inductor current of a converter and armature current of the motor it shows the comparative results from the existing controller to the proposed controller, where the proposed controller is reliable. Despite of uncertainties and perturbations occurred the trajectory performance is satisfactory.

Fig 6 shows the performance results of the proposed hierarchal control associated to dc motor powered by converter. The angular velocity trajectory and required voltage profile is tracked

The results above produced shows the variations in inductor current, output voltage of converter, armature current, Load torque of dc motor, resistive load of the converter and speed tracking.

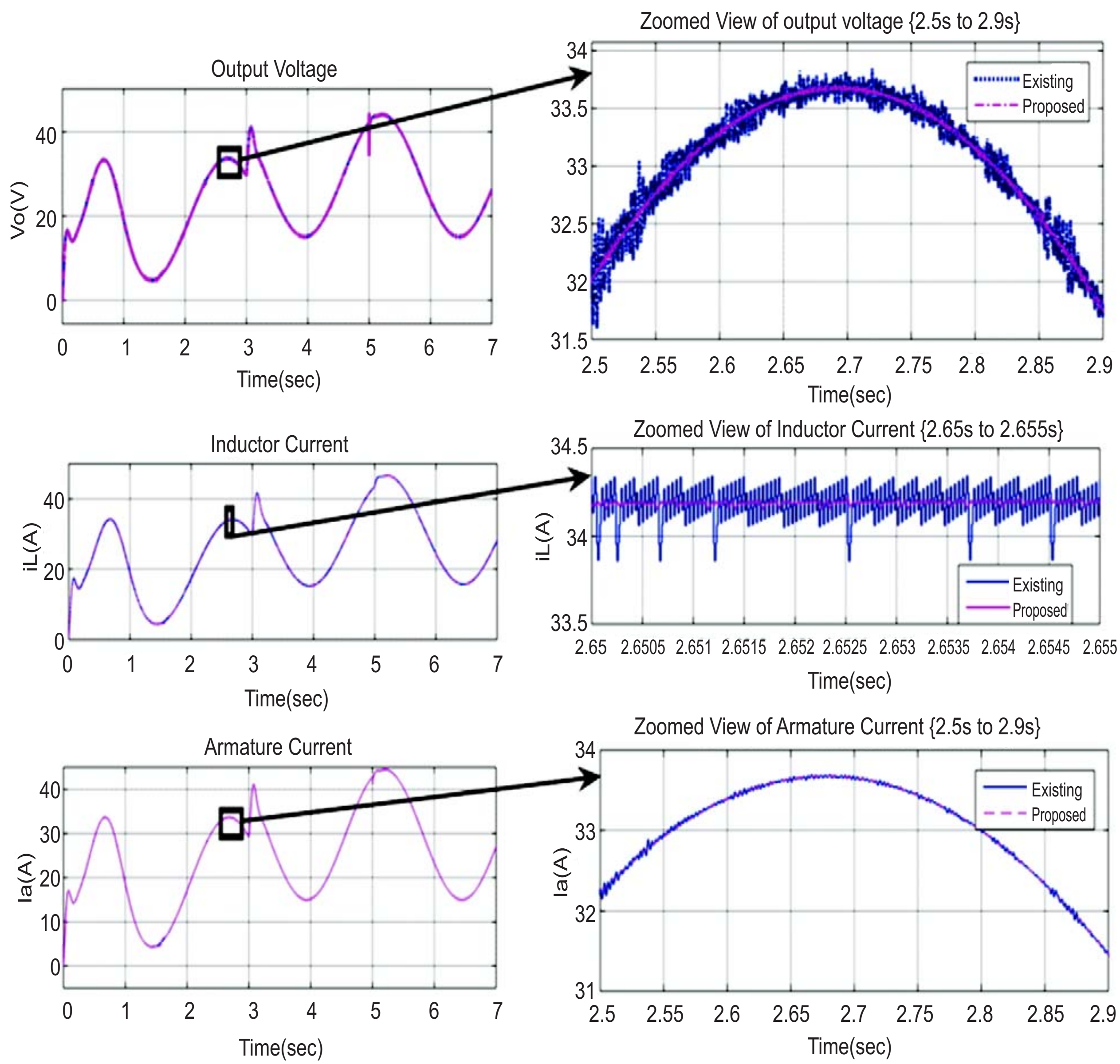

Figure 5: Simulation results compared with proposed controller

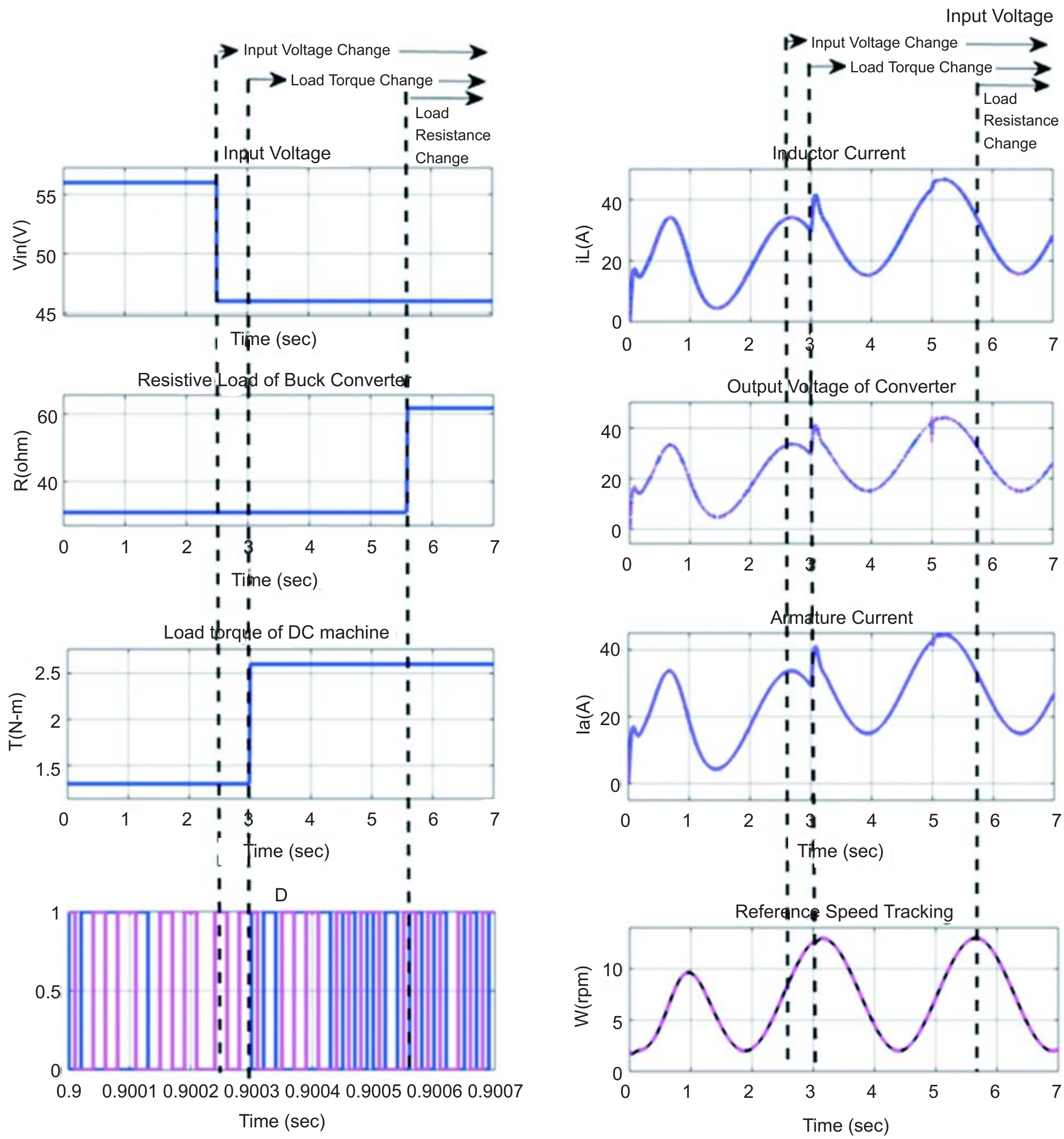

Figure 6: Simulation results for the proposed controller associated to dc motor powered by buck converter

6. CONCLUSIONS

Motivated by the robotic applications, a control for a 'soft starter' is developed for angular velocity rejection and voltage profile for buck converter driven dc motor. The overall combination shows an unstable internal dynamics, to avoid these a passivity based controller is devised. The controller provides a cascaded form where the inner current loop is designed with SMC and outer voltage loop designed for PI controller. The stability of the converter is analysed and digital implementation of the controller with FPGA is discussed to support the results.

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