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Differential Flatness and Sliding Mode Control of Boost Converter as Smooth Starter for a DC Motor

Reshma Jayakumar[1], Chama R. Chandran[2]

PG Student, Dept. of EEE, Sree Buddha College of Engineering, Pattoor, Kerala, India[1]

Assistant Professor, Dept. of EEE, Sree Buddha College of Engineering, Pattoor, Kerala, India[2]

ABSTRACT: The most common problem with DC motor includes its inefficiency to start immediately. There are many reasons for its incapability to start such as low voltage supply, wrong connections, excessive load, ground fault etc. To overcome the starting problems of DC motor, a hierarchical control system designed for DC motor powered by a DC – DC boost converter is presented here. The whole system is divided into two levels. The high level contains the DC motor which is controlled using differential flatness control and the low level contains the boost converter which is associated with a cascade control scheme. Differential flatness property is used to control the angular speed for tracking trajectory applications. This controller provides the voltage profile that has to be tracked by the boost converter and consequently a low hierarchy controller is designed to ensure the aforementioned. The main objective is to reduce the steady state error. The control of higher level allows the DC motor angular velocity to track a desired trajectory and also provides the desired voltage profile that must be tracked by the output voltage of the DC – DC boost power converter. In order to ensure the latter, a cascade control at low level is designed, considering a sliding mode control (SMC) for the inner current loop and a Proportional – Integral – Derivative (PID) control for outer voltage loop.MATLAB/Simulink is used to build up a smooth starter for a DC motor using the aforementioned controllers.

KEYWORDS: Boost converter, DC motor, Siding Mode Control, PID Controller, Differential Flatness Control.

I.INTRODUCTION

With the development of technology, there is a rapid increase in automation of industries which demand for improved operational characteristics of the motors being used. In order to improve these characteristics, effective controllers must be designed. DC motors are recognized for its high control applications such as rolling mills, traction, machine tools, high precision digital tools etc. DC motors can provide high starting torque and it is also possible to obtain wide range of speed control. It has problem at starting. Usually PWM drives are employed to control the DC motor. But due to the hard switching strategy of the PWM drives, sudden variations in the voltage and current of the motor are produced [1]. This creates undesirable dynamic behaviour. To overcome this major drawback of the PWM drives, DC/DC power converters can be employed. There are different types of DC/DC power converter based on applications. Boost converter is one such power converter which will be used here. These power converters are nonlinear and time variant systems due to the presence of nonlinear elements such as inductors and capacitors which build them [2]. Thus, in order to remove the nonlinearities, a robust controller is designed which is independent of parameter variations and external disturbances. Such a controller is named as Sliding Mode Controller (SMC). One of the main advantages of such a type of controller is that it keeps the load constant regardless of the change in line voltage and parameters.

The control of boost converter is difficult compared to the buck converter due to the presence of control input in both voltages and current equations. Thus, implementation of controlling the boost converter is very rare. For controlling the boost converter we are separately controlling the inductor current and capacitor voltage. Thus, SMC is used in the inner current loop and Proportional – Integral – Derivative (PID) controller is employed in the outer voltage loop. PID controller is a linear controller which collaborates the advantages of all the three controllers i.e. P controller stabilizes the gain but produces steady state error, I controller reduces or eliminates steady state error and D controller reduces the rate of change of error. Thus, combination of PID controller and SMC improves all the aspects of system

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performance. This cascade control is employed at the low hierarchy level in order to control the boost converter. This level also uses a feedforward control which eliminates all the demerits of feedback control. As a result, the speed and performance of the overall system improves, if feedforward control together with feedback action is employed.
Differential flatness is used at the high hierarchy level which ensures that the system is controllable or not. If the system is controllable, then the system is said to be stable. DC motor is placed in the high hierarchy level. The low hierarchy level ensures that the converter output voltage is equal to the one required to drive the DC motor whereas the high hierarchy level is designed to complete the velocity tracking task developed for the DC motor.

II. OVERVIEW

A. DC Motor

When armature of a DC motor rotates under the influence of driving torque, the armature conductors move through the magnetic field due to the permanent magnet, thus an emf is induced in them as in a generator [3] [4]. Using Lenz's law, direction of the induced emf is in opposite direction to that of the applied voltage, V_t. This emf is also known as back emf or counter emf, E_b which is given by

$$E_b = \frac{P\phi ZN}{60A}$$

where, P = number of poles of the permanent magnet
- $\emptyset$ = flux per pole in Wb
- Z = total number of armature conductors
- N = speed of motor in rpm
- A = number of parallel paths

The back emf is smaller than the applied voltage, although the difference is small when the motor is running under normal conditions.

Armature voltage in the circuit, $V = V_t - E_b$

If R_a is the armature resistance, then $I_a = \frac{V_t - E_b}{R_a}$

Since V_t and R_a are constant, then value of e_b determines the current I_a drawn by the motor. If the speed of the motor is high, then $E_b = \frac{P\phi ZN}{60A}$ is large. Hence, motor draws less armature current and vice versa. Motor voltage equation is given by,

$$V_t = E_b + I_a R_a$$

$$\Rightarrow E_b = V_t - I_a R_a$$

$$\text{Thus, } \frac{P\phi ZN}{60A} = V_t - I_a R_a$$

$$\Rightarrow N = \frac{(V_t - I_a R_a)60A}{P\phi Z}$$

$$\Rightarrow N = \frac{K(V_t - I_a R_a)}{\phi}$$

$$\text{where, } K = \frac{60A}{PZ}$$

For a dc motor A, P and Z are constants. Therefore it is clearly evident from equation that speed is directly proportional to back – emf and inversely proportional to the flux per pole. As the flux per pole in a PMDC motor is constant we cannot control the speed by changing the flux. Therefore two methods are used for the speed controlling:

- Armature resistance control method
- Armature voltage control method

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B. Boost Converter

Boost converter is designed in such a manner such that the output voltage is always greater the input voltage. It is also known as step – up converter. It is a class of switched mode power supply (SMPS) with not less than two semiconductor switches (a diode and a transistor) and at least one energy storage device. Generally boost converter is powered using DC sources such as batteries, rectifiers, DC generators, solar panels, etc. Switches of the converter can be implemented using BJT, MOSFET, GTO and IGBT. Switching elements must be chosen in such a manner that it can handle the worst situation of current and voltage stresses. In order to reduce the output voltage ripple, a capacitor (act as filter) is connected across the output. When these converters are working in open loop, they exhibit undesirable dynamic response and poor voltage regulation [5]. To conserve the power (P = VI), the output current is lower than the source current. Based on the ON and OFF state of the power switch, the converter can be analyzed in two ways:

CASE 1: When switch is ON at time t = 0 ($0 \leq t \leq DT$)

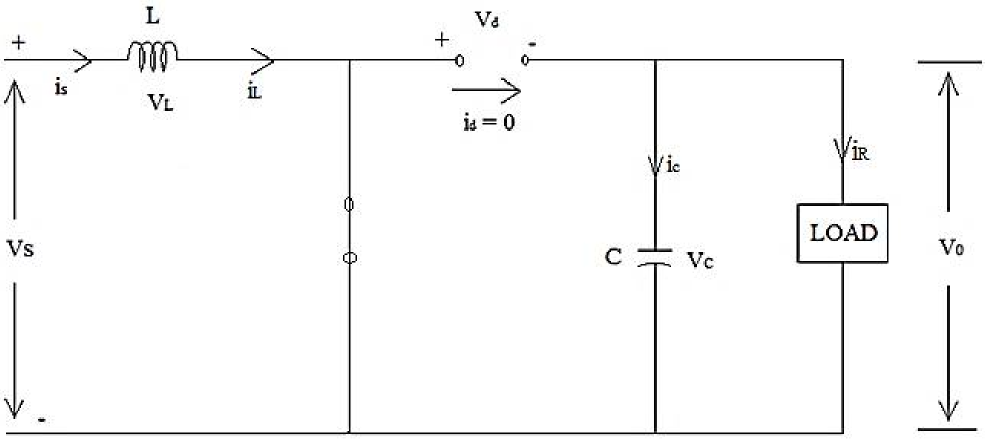

Fig. 1 Circuit diagram of boost converter when switch is ON

In this mode, inductor L is connected to the supply E and inductor stores energy. The output side is isolated from the input as the diode is reverse biased by capacitor voltage. Thus it will act as open circuit. Inductor current rises linearly. Output side gets energy from the stored charge of the capacitor.

CASE 2: When switch is OFF at time t = t_1 ($DT \leq t \leq T$)

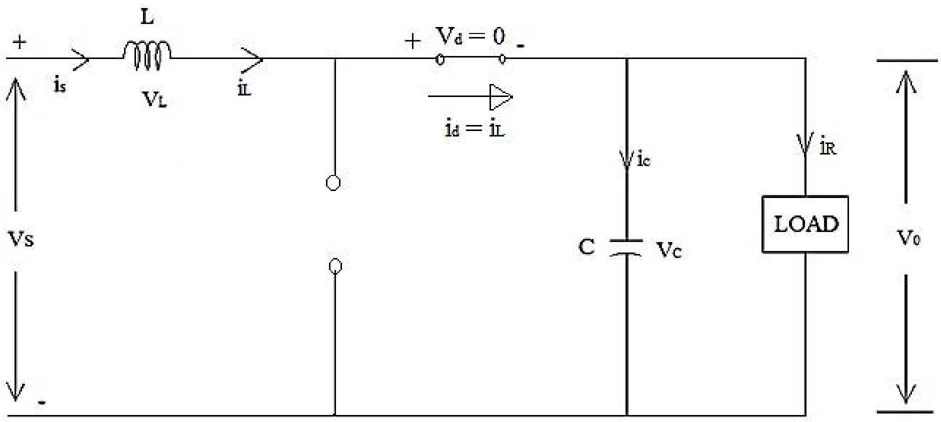

Fig. 2 Circuit diagram of boost converter when switch is OFF

In this mode, output side receives energy from the inductor as well as from the input. Current flows through L, D_F, C and load. Until the next cycle, there is a linear drop in inductor current. If the capacitor voltage is greater than the supply voltage, then inductor will adjust itself so that $V_d + V_L = V_0$. This is needed for the inductor current to become low. In this mode, the inductor has to reverse its polarity so as to attain output voltage to be greater than the input voltage.

C. PID Controller

The collaboration of proportional, integral and derivative control action is known as PID controller which enhances all the aspects of the system performance. In industrial control systems, a proportional – integral – derivative (PID) controller is a common feedback loop element. The proportional controller stabilizes the gain but produces a steady error [6]. The integral controller reduces or eliminates the steady state error. The derivative controller reduces the rate of change of error. Hence, the introduction of PID controller stabilizes the gain, reduces the steady state error and peak overshoot of the system. The controller uses the measured value from a plant or any other equipment and compares it with a reference set point value [7]. The error signal (or difference) is used to modify some input to the plant in order to bring the plant's measured value to its desired set point. PID can alter the plant output based on history and rate of change of error signal which gives more accurate and stable control when compared to the simpler controllers.

Fig. 3 shows a classic PID feedback control scheme. Let us consider a motor in the place of plant. PID controller is placed in the forward path, so that its output becomes the voltage applied to the motor's armature [8]. Velocity is the feedback signal. Velocity signal c(t) is compared with the reference signal r(t) to get the error signal e(t). This error signal is fed to the PID controller.

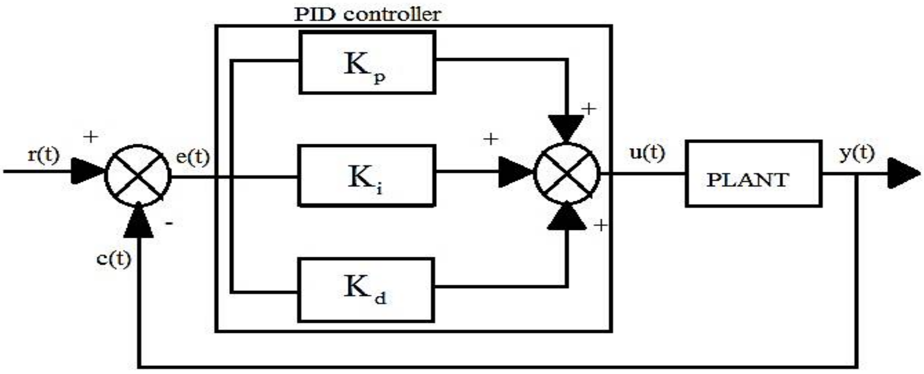

Fig. 3 PID feedback control

The PID controller is a device which generates an output signal, u(t) consisting of three terms:

- Proportional to input signal, e(t)
- Proportional to integral of input signal, e(t)
- Proportional to derivative of input signal, e(t)

i.e., in a PID controller

$$u(t)\alpha\left[e(t)+\int e(t)dt+\frac{d}{dt}e(t)\right]$$

$$\Rightarrow u(t)=K_p e(t)+K_i\int e(t)dt+K_d\frac{d}{dt}e(t)$$

Taking Laplace transform of equation (5.1), we get

$$\Rightarrow U(s)=E(s)\left[K_p+\frac{K_i}{s}+K_d s\right]$$

Transfer function of PID controller, $G_C(s)=\frac{U(s)}{E(s)}=K_p+\frac{K_i}{s}+K_d s$

Method of achieving desired control response by adjusting the control parameters to the optimum values is known as tuning. Stability is the basic requirement of tuning. However different systems have different behaviour, different applications have different requirements and requirements may conflict with one another. In spite of the fact that there are only three parameters to control and description of principle is simple, the tuning of PID is very hard. This is

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because it must meet complex criteria within the restrictions of PID control. Values of K_p, K_i and K_d are adjusted until desired system response is achieved.

D. Sliding Mode Control

Sliding Mode Control (SMC) is a variable structure control system (VSS) where structure or topology of control is intentionally varied to stabilize the control and make its response robust. It is one of the non – linear feedback control method. The theory of SMC was first proposed and elaborated in early 1950's in Soviet Union by Emelyanov and several co – researchers [9]. Desired control performance and system stability can be achieved by using SMC techniques.

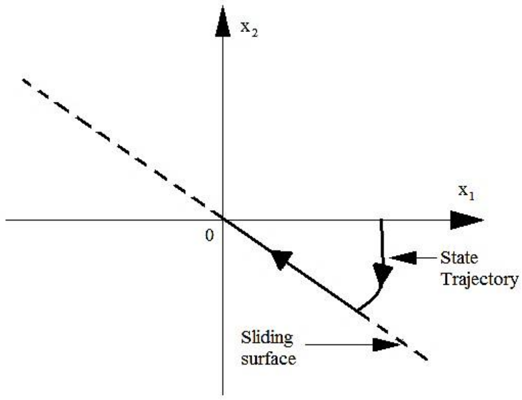

Fig. 4 Phase portrait of a sliding motion

The surface which defines rules for proper switching is called the switching surface or sliding surface. Robust regulator design, tracing system, state observers, fault detection schemes and stabilization can be obtained through proper design of switching surface. SMC is designed in such a way to force the system trajectory to move through the predefined sliding surface and approach the equilibrium point all along its surface with finite time. Switching function equation controls the closed loop dynamics of the systems, provided the system trajectory remains along its surface. Fig. 4 gives a brief description of the phase portrait of sliding motion. Following are the different phases or conditions which must be followed to obtain a stable system.

Conditions for Sliding Surface

- Hitting condition – In this phase irrespective of the starting point, the system trajectory is forced to reach the sliding line within a finite time. This phase is known as reaching, hitting or non – sliding phase [10]. The system is prone to parameter variations and disturbance rejection in this phase.
- Existence condition – Once the system trajectory is in the vicinity of the switching line, and then in this phase it is directed towards the line. This condition ensures that the system trajectory never leave the sliding surface. Here the system is independent of parameter variations and external disturbances.
- Stability condition – This condition ensures that the system should operate in a stable point and operates based on the designed sliding equation.

Thus, sliding mode controller can be designed in two steps:

- Sliding surface design – Here, sliding or switching surface is designed to meet the design specifications.
- Selection of control law – It is designed with an aim of attracting the system trajectory towards the sliding surface. This law assures that reaching condition has been met.

E. Differential Flatness Control

Flatness in control theory is a system property that extends the notion of controllability from linear systems to nonlinear dynamical systems. A system that has the flatness property is called a flat system. Flat systems have a (fictitious) flat output, which can be used to accurately express all states and inputs in terms of the flat output and a finite number of its derivatives. The flatness property is useful for both the analysis and controller synthesis for nonlinear dynamical systems. It is especially excellent for solving trajectory planning problems [11].

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III.PROPOSED METHOD

In the existing method, the DC motor is controlled using a DC/DC Buck converter. Buck converter is controlled using the cascade control. Cascade control has been implemented using SMC at the inner current loop and proportional – integral (PI) control at the outer voltage loop.

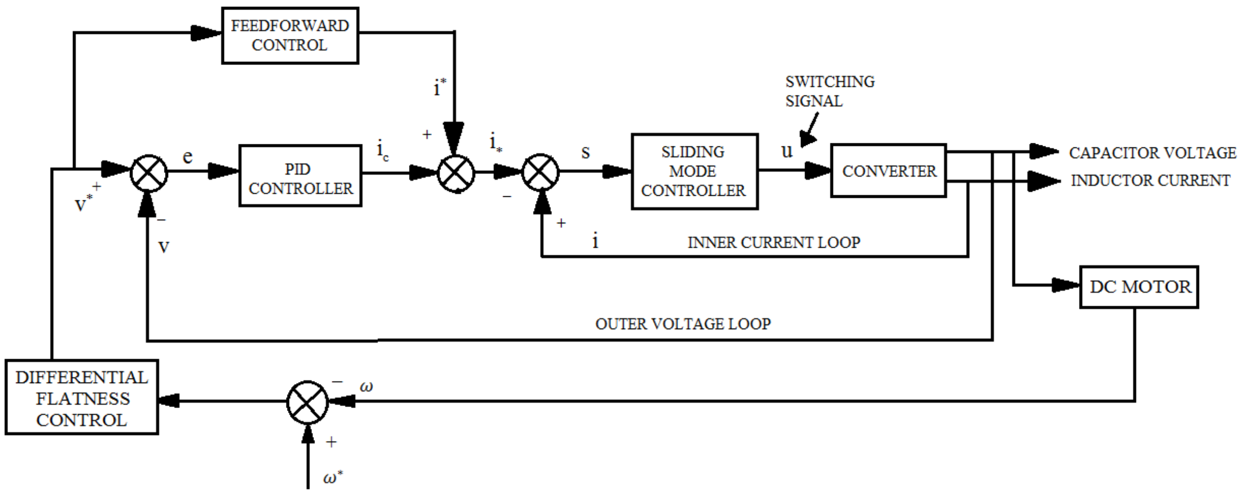

Fig. 5 Block diagram of Hierarchical controller

The proposed method is based on hierarchical controller which is outlined for the determination of implementing the angular velocity trajectory tracking task for the combination of DC/DC boost converter and DC motor system as shown in fig. 5. Such a controller can be designed in the following manner.

Low Hierarchy Level: It consists of the control of boost converter. This level ensures that the converter output voltage is equal to the one required to drive the DC motor. In order to control the boost converter a cascade control is used here. Cascade control is designed, considering a sliding mode control (SMC) for the inner current loop and a proportional – integral – derivative (PID) control for outer voltage loop.

It has been noticed that the voltage profile V is required by the motor to track the desired angular velocity trajectory ω^*. This must be recalled that v is produced by a boost converter. Thus a control strategy for boost converter must be developed in order to replicate the desired voltage profile V. Thus this level presents a cascade control for the boost converter with the help of SMC and PID controller as shown in fig. 6.

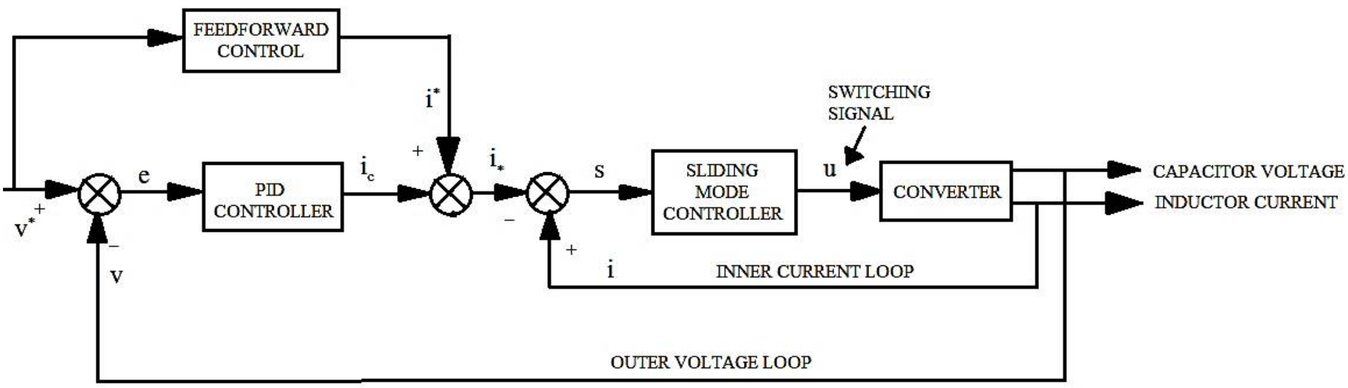

Fig. 6 Block diagram of Cascade control

Low hierarchy level is built up using the following equations which implement the controllers shown in fig. 6. SMC for boost converter was implemented using

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$$u = \frac{1}{2}[1 + \text{sign}(s)]$$
$$\text{where, } s = i - i_*$$
$$\text{sign}(s) = \begin{cases} +1, & s \geq 0 \\ -1, & s < 0 \end{cases}$$
$$i_* = i^* + i_c$$
$$i^* = C\frac{dv^*}{dt} + \frac{v^*}{R}$$
$$i_c = K_p e + K_i \int e(\tau)\,d\tau + K_d \frac{de(\tau)}{d\tau}$$
$$e = v^* - v$$

High Hierarchy Level: Itcontains a control constructed on differential flatness. Such a type of controller is designed to fulfill the angular velocity trajectory tracking task which has been developed for the DC motor.

IV. SIMULATION RESULTS

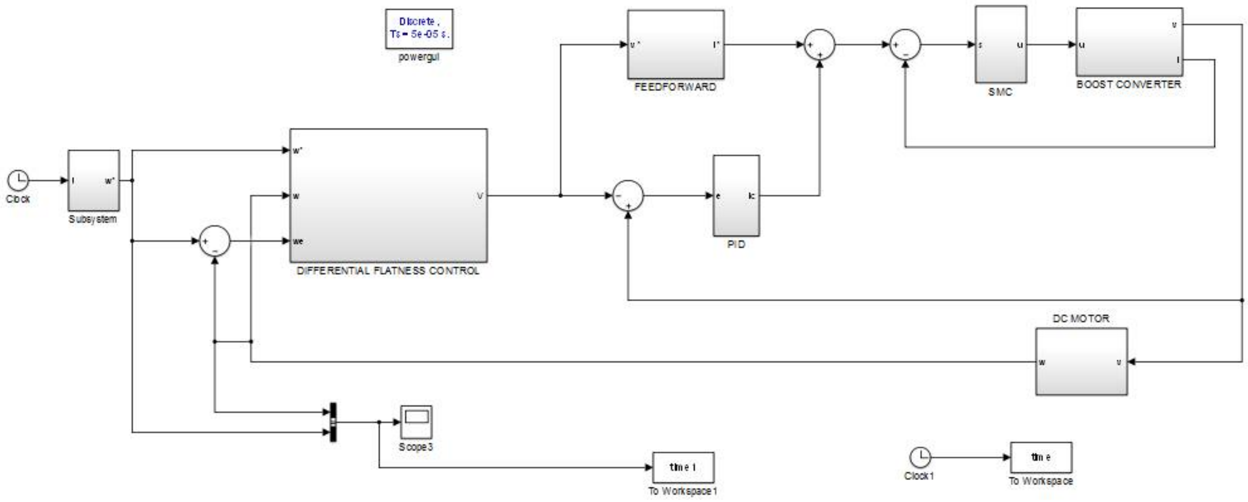

Fig. 7 Simulated block diagram of hierarchical control system

Fig. 7 shows the Simulink block diagram of hierarchical control system which was developed in MATLAB software by referring to fig. 5.

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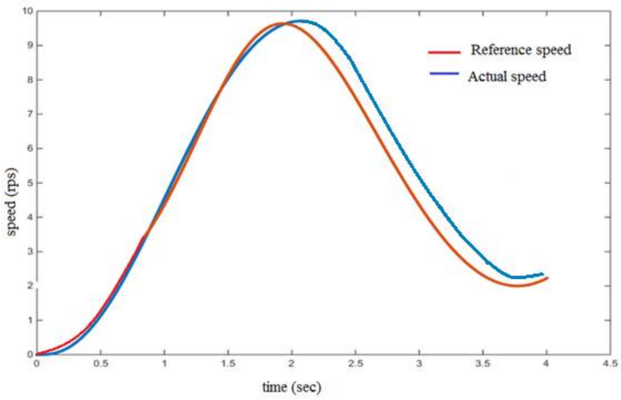

Fig. 8 Simulation result for hierarchical control system

Fig. 8 shows the output waveform where the actual speed coincides with the reference speed whose trajectory is designed using SMC. Thus, reducing the steady state error and making a stable system. Hence, motivation of developing a smooth starter has been obtained.

V. CONCLUSION

Outputs of the angular velocity trajectory tracking for the DC – DC boost power converter fed DC motor system was obtained. Specifically, the hierarchical controller is made of two controllers. The first is concerned with the control of the DC motor and the second with the control of boost converter, that is:

- The first control is based on differential flatness, which control the voltage profile V such that ω tracks to the desired angular velocity ω^*.
- The second control utilize a cascade control scheme applied to the boost converter to generate the voltage profile V required by the DC motor. This control accomplishes that the converter output voltage profile V tracks to the voltage profile v, that is, $v \to V$.

As specified by experimental results, the main motivation has been successfully attained, on account of the angular velocity of the motor tracks a desired angular velocity trajectory. The results obtained show the robustness of the hierarchical controller even during uncertainties. The experiments were taken to demonstrate that the proposed controller presents a good performance under abrupt variations associated with the system parameters, which would make possible the introduction of this controller in practical applications.

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