Closed Loop control of magnetic materials converter fed motor

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Abstract - Numerous industrial and practical applications of single-phase induction motors are extensively used owing to cost effective, reliable and deficient maintenance. It is necessary to maximize the efficiency of induction motor. The destitute quality of voltage and current obtained from conventional inverter fed induction motor, since there is the existence of harmonics which raises harmonic losses and reduces efficiency. A simplified speed control design of chopper fed Direct Current (DC) motor drive with single feedback control structure is proposed. First, Internal-Model-Control (IMC) is used to control speed without closed loop current control scheme. Then, an analytical method based on IMC principles is applied to design a single-loop IMC controller with a Proportional-Integral-Derivative (PID) form. The proposed in the paper a comparative transient and robustness analysis of closed loop speed control employing different linear controllers for the same dc motor using 4 quadrant chopper is investigated. The controller configurations can be broadly classified under *(i)* Integer order PID controller *(ii)* linear state space observer and *(iii)* fractional order PID controller. All of them exhibit superior performances, the first one is the conventional controller used in industries but the latter two are modern controllers that have rich potential for industry use and have large advantage over the conventional controllers. The closed loop control of chopper fed DC motor is shown with the 1st quadrant operation of chopper circuit.

Keywords—DC Motor; Integer Order Controllers; Fractional Order Controllers; Closed Loop Operation.

I. INTRODUCTION

DC motors have been available for roughly about 100 years. In fact these were the earliest motor to be designed and operated using direct current power. After invention of AC motors they became horse power of industry due to high speed (Ị) and differentiation (ù) in addition to the conventional controller parameters: Proportional gain (*Kp*),Integral gain (*Ki*) and Differential gain (*Kd*). The extra freedom provide improvement in the overall closed loop performance of any system such as overshoot, settling time, rise time, phase margin etc. Several schemes for the design of FOPID controller, employed in control system are pole distribution, frequency domain approach, state space design method etc. In recent years, few intelligent algorithms such as Genetic Algorithm (GA) [1], Particle Swarm Optimization (PSO) have been explored in literature [2].

II. SYSTEM ARTITECHTURE

A. Four quadrant chopper

A chopper shown in Fig 1. is a static device that converts fixed DC input voltage to a variable or chopped DC output voltage. It's also called as DC-DC converter [3,4]. They are used for DC motor control and also can run the motor in all 4quadrants of speed-torque plane.

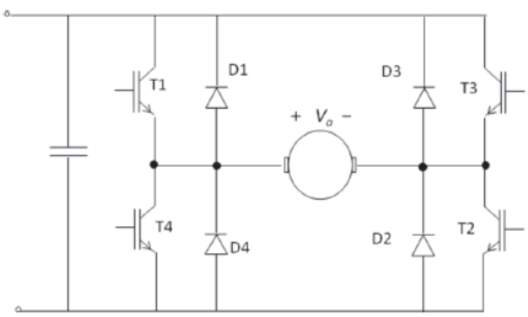

Fig. 1. Four Quadrant Chopper Circuit

The four quadrant chopper operates in all four quadrants as mentioned below:-

i. Quadrant 1

1st quadrant begins with condition of positive voltage and current to the motor building a positive power. Here the power from supply flows to motor. In this quadrant T1 and T2 is ON i.e. T1 is modulating and T2 is continuously ON.

ii. Quadrant 2

In the 2nd quadrant, the condition begins with positive voltage and negative current i.e. current comes out of the motor so, the power is negative. In this condition, the power flows in negative direction i.e. from load to source and this happens when an inductive load is present or in this case due to the back emf source present in dc motor .Here T1 and T3 is OFF, T4 *is* ON (modulating), T2 is ON continuously. Since the direction of inductor current can't be reversed instantaneously, T2 and D4 will be conducting the freewheeling the current.

iii. Quadrant 3

In the 3rd quadrant begins with negative voltage and current but the input power supplied to motor is positive. So, the power flows from supply to motor. In this quadrant T3 is ON (modulating), T4 is continuously ON and T1 and T2 is continuously OFF.

iv. Quadrant 4

In the 4th quadrant the condition is negative current and voltage becomes positive, power is becomes negative. Here T2 is ON (modulating), T4 is continuously ON. As the inductor doesn't allow sudden change in current, T4 and D2 will be conducting freewheeling the current when T2 is OFF.

B. DC MOTOR SYSTEM

The schematic diagram of DC motor used for the study is given in Fig 2. Separately excited DC motor is used in this paper for controlling the speed. For this example, it is assumed that voltage source (*V*) is the input applied to the motor's armature terminal, while the output is the rotational speed of the shaft $\frac{dy}{dx}$. It is assumed that the viscous friction model, that is, the friction torque of the motor is directly proportional to angular velocity of the shaft.

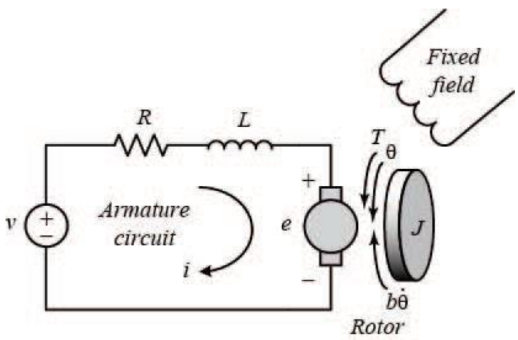

Fig. 2. Separately excited DC motor system

i. Dynamics of the system

In general, the torque produced by a DC motor is proportional to the armature current. In this example, it is assumed that the magnetic field of the motor is constant and, hence, the torque produced by the motor is proportional to the current in the armature by a constant factor K_t as shown in the equation (1). This can be referred as an armature-controlled DC motor.

$$\tau = K_t * i \qquad ......1$$

The back emf produced by the motor **'e'**, is proportional to shaft's angular velocity by a constant factor K_e

$$e = K_e * \dot{\theta} \qquad ......2$$

(2) According to SI units, the back emf constant and motor torque constant are equal, that is, $K_t = K_e$; therefore, only K is implemented to represent both the motor torque constant and the back emf constant.

From the Figure above, the following equations were derived based on Kirchhoff's voltaglaw and Newton's 2nd law.

$$J\ddot{\theta} + B\dot{\theta} = K_t i \qquad (3)$$

$$L\frac{di}{dt} + Ri = V - K_e\dot{\theta} \qquad (4)$$

ii. Transfer function

Applying the Laplace transform, the above modelling equations can be expressed in terms of the Laplace variable *s*.

$$s(Js + B) * \dot{\theta}(s) = K * I(s) \qquad (5)$$

$$s(Ls + R) * I(s) = V(s) - K * \theta(s) \qquad (6)$$

Open-loop transfer function was derived when $I(s)$ was eliminated between equations (5) and (6), where the output is rotational speed and the input was taken as armature voltage.

$$\frac{\dot{\theta}}{V} = \frac{K}{(Js+B)(Ls+R)+K^2} \frac{rad/sec}{volts} \qquad (7)$$

iii. State Space Model

In state-space representation, the above governing equations are expressed by picking the rotational shaft speed and armature current as the state variables. The input was armature voltage.

$$\frac{d}{dt}\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix} = \begin{bmatrix}-\frac{B}{J} & \frac{K}{J}\\ -\frac{K}{L} & -\frac{R}{L}\end{bmatrix} * \begin{bmatrix}\dot{\theta}\\ i\end{bmatrix} + \begin{bmatrix}0\\ \frac{1}{L}\end{bmatrix} * V \tag{8}$$

$$y = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix} \tag{9}$$

III. CONTROLLERS

A. Integer Order Controller

Controller is a device which monitors and alters the operating conditions of a given dynamical system. The control algorithms are usually divided into two main types: Open-loop and Closed-loop.

The PID controller has been widely used in industrial applications owing to its simplicity, robustness, reliability and easy tuning parameters. PID commonly interpreted as Proportional, integral and Derivative controller possesses the following properties show in TABLE I.

TABLE I. PID PROPERTIES

Controller	***Response time***	***Overshoot***	***Error***
Proportional (P)	Small	Large	Small
Integral (I)	Decrease	Increase	Zero
Derivative (D)	Increase	Decrease	Small Change

• ***P*** denotes for present values of the error. It means that if the error is large, the control output will also be large. • ***I*** provides past values of the error. For example, if the present output is not very strong, error will accumulate over time, and the controller will respond by applying a stronger action.

• ***D*** provides the possible future values of error, based on its present rate of change.

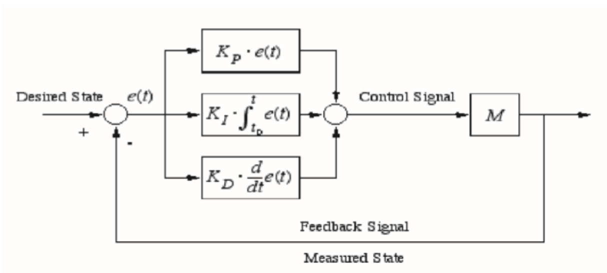

Fig. 3. General scheme of PID controller

PID given in Fig 3 controller minimizes the error value by adjusting the control variable, such as Position and Speed etc. The transfer function of the PID controller can be represented in (10)

$$G_c(s) = K_P + \frac{K_I}{s} + K_D s \tag{10}$$

B. Fractional Order Controller

Fractional order calculus has been a topic of immense interest since last few decades. The application of fractional calculus in electro-chemistry, biological systems, material science, visco elastic and chaotic systems has been explored in, [4- 5]. Reference [6] discusses about the design of a FOPID controller whose parameters are the solution of a constrained min-max optimization problem. The objective function is the minimization of the maximum sensitivity subjected to the various constraints among which the most important one is the damping condition. Reference [7] provides the stability criteria for uns TABLE time delay processes by fractional order controllers whereas Reference [8] focuses on tuning algorithms to design fractional order internal model controllers for time delay processes. The modelling of systems employing the concept of fractional differentiation has become extremely popular in recent times because of the availability of advanced computational packages that has simplified the simulation and implementation of these systems with adequate precision [9]. General scheme of FOPID is provided in Fig 4.

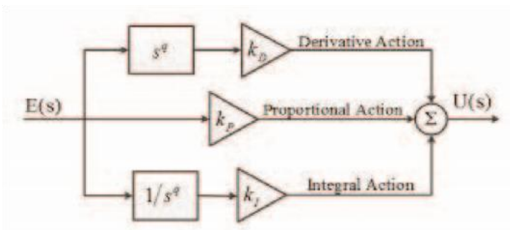

Fig. 4. General scheme of FOPID controller

C. State Space Observer

In control theory, a state observer provided in Fig 5 is a system that provides an estimate of the internal state of any given system, from measurements of the input and output of the system. Gaining a proper knowledge about the state of the system is mandatory for solution of control theory problems, for example, stabilizing a system using state feedback [10, 11]. In maximum cases, the physical state of the system cannot be determined by direct observation.

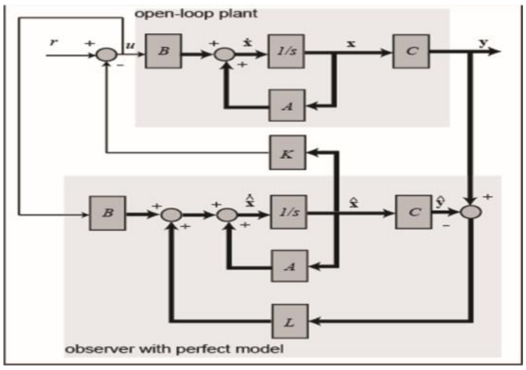

Fig 5 Linear state observer system for closed loop operation

IV. SIMULATION RESULTS

Open loop and closed loop speed responses with and without load disturbances with PID controller, state observer, and fractional order PID Controller is shown in Fig. 7-11. The reference speed was taken to be 1500rpm.

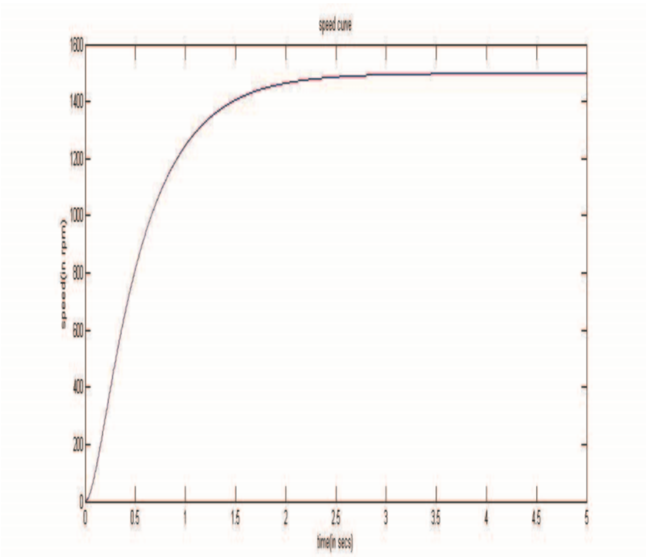

Fig 6. The open loop speed vs. Time curve when no controller is applied

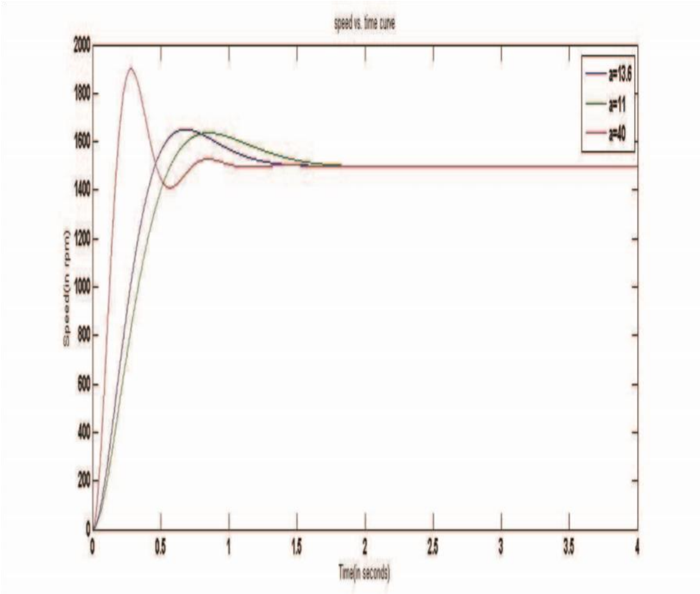

Fig. 7. Speed versus time various values of Ị for closed loop system without any load disturbances

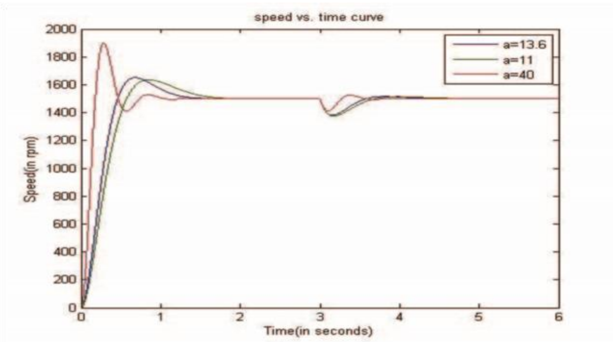

Fig. 8. Speed versus time various values of Ị for closed loop system with load disturbances

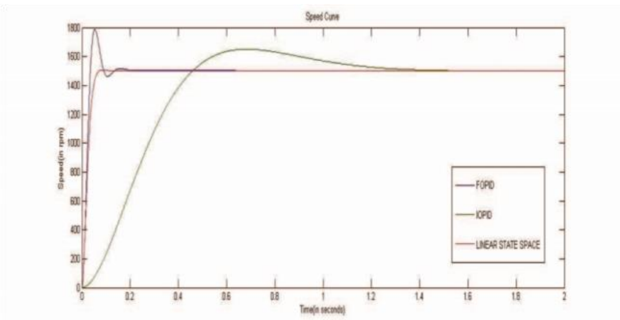

Fig. 9. Speed vs. time plot for various controllers when step input is provided

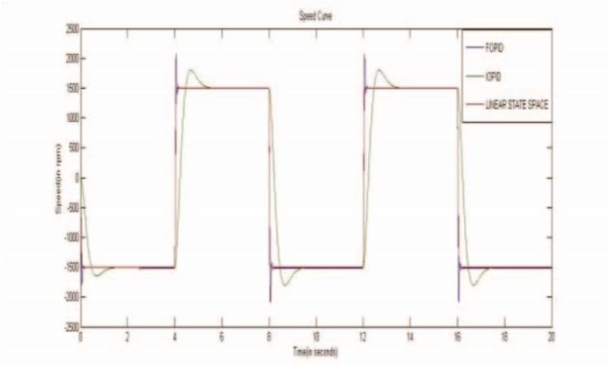

Fig. 10. Speed versus time plot with various controllers when square wave input is provided

V. RESULTS AND DISCUSSION

The results of simulations shown in Fig 8 and 9 indicate that by changing the values of 'a', the speed response of the dc motor changes. Fig 10 shows the comparative analysis of speed response of conventional PID controller, fractional order PID controller and state space observer cascaded with DC motor when step input was provided. Fig 11 also provides the speed response of various controllers when square wave input was provided. TABLE III represents transient specifications of various controllers employed for the speed control of DC motor. It can be observed that linear state space observer provides superior performance compared to all other controller configurations. TABLE IV provides the comparison of performance indices for various controller configurations.

TABLE III. COMPARISON BETWEEN VARIOUS VALUES OF POLES PLACED

controllers	**Comparison**						
	overshoot	***Settling time***	***Kp***	***Ki***	***Kd***	***Į***	***ù***
PID(11)	9%	1.9s	16.1	46.2	1.5	1	1
PID(13.6)	10%	1.6s	29.3	57.1	2.8	1	1
PID(40)	25%	1.3s	74.1	168.08	16	1	1
FOPID	25%	0.2s	20	20	20	0.92	0.11
State Observer	2%	0.18s	-	-	-	-	-

TABLE IV. PERFORMANCE INDICES OF CONTROLLERS

Controllers	***ISE***	***ITSE***	***IAE***	***ITAE***
PID (11)	4.37e+05	6.15e+04	491	156
PID (13.6)	3.675e+05	4.333e+04	410.7	107.6
PID (40)	1.915e+05	1.495e+04	241.7	45.42
FOPID	4406	2.644e+04	66.38	398.3
State Observer	1603	4527	95.85	285.4

VI. CONCLUSION

In this paper various controllers were employed for closed loop operation of the separately excited DC motor with and without load. PID controller values were computed by dominant pole calculation and varying the value of the 3rd pole i.e. 'a' but the FOPID parameters were obtained after minimizing the objective function using MATLAB. Nonlinear interior point optimization technique in Matlab was used to compute the values of FOPID parameters. Various other optimization techniques can also be used to find the values of FOPID parameters. From the above section it can be clearly observed that the state space observer for the plant provides us superior results than the other controllers employed. FOPID also provides us far better results than conventional PID controllers and can be a great replacement for conventional PID. The extension of this work can be an experimental setup for the closed loop speed control of dc motor. Sufficient hardware can be designed for the advanced controllers and the chopper circuit and its triggering circuit.

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