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Design and Implementation of IMC-PID Controller for DC Drive with Z-N type Rules

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Abstract*— The tuning of controller is a big issue for a better system performance. This paper describes the modified method of measuring the delay time, time constant from the open loop response (S-curve) of the DC drive for step input. Later, using the same values of delay time and time constant, a modified tuning algorithm using Internal Model Control is proposed. Finally the time response of the DC drive with proposed control is compared with the Ziegler Nichols S-curve and modified S-curve algorithms in MATLAB/ Simulink environment. From the comparison, the proposed method shows a better performance than other methods in all aspects like rise time, peak overshoot and settling time.

Keywords*— S-curve, PID controller tuning, Internal Model Control, DC drive, Time domain specifications.

I. INTRODUCTION

Practically, compare to AC drives, the DC drive speed control is simple and less expensive but they required more maintenance than AC drives and they are not suitable for high speed applications because of commutator. With the used of Chopper, it possible to get a variable DC voltage from a fixed DC voltage and with the use of Controlled Rectifiers a variable dc output voltage is obtained from a fixed ac voltage. The Controlled Rectifiers and Choppers made a revolution in modern industrial control equipment and variable-speed drives due to their ability to supply a continuously variable dc voltage [1]. Most of the industrial drives and processes consume DC power with different voltage levels. For example, the Trolley and Subway cars mainly run with fixed DC source but they requires a conversion of fixed voltage DC source to a variable voltage DC source for their speed control [2].

The PID controller is the most popularly used control technique for many decades even though, there is a lot of development in control theory and technology. This is because of robust performance for a wide range of operating conditions. In addition, most of the researcher has given a wide range of control schemes for evaluating/tuning of the parameters of PID controllers in both time and frequency domain. The authors R. Vilanova and A. Visioli [3] have given an elaborated and detailed overview on control techniques of controller in chapter 1.

Recently, Ziegler–Nichols rules are generalized for tuning the Internal Model Control PID controllers. The Ziegler–Nichols method has its own advantages and disadvantages. This paper describes an alternative empirical tuning method of an unidentified process for tuning classical PID parameters. This tuning method based on open loop experiment which is similar to the classical Ziegler– Nichols experiment. This method works well for time delay processes also [4]. Note that the controller parameters, which are obtained with this proposed method, utilizes the data of open loop response (S-curve) of the plant model same as open loops response of Ziegler-Nichols method. In this paper we propose to use an empirical method for tuning fractional controller parameters to control an un identified process which is the set point over shoot method. In this paper the objective is the generalization of the idea of B.W. Bequette in [5] to the IMC- PID controllers. Some changes were made to this method in order to adapt it for tuning the new kind of IMC-PID controllers.

II. TUNING OF PID CONTROLLER

The purpose of this section is to show the PID controller structure. The structure and transfer function of PID controller is as shown below:

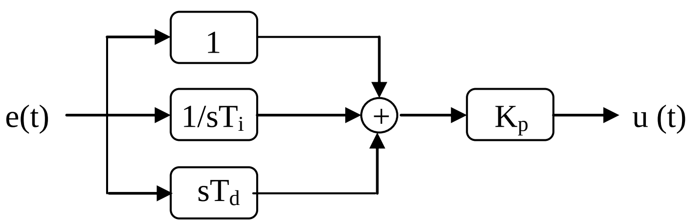

Fig. 1 Structure of PID controller

From the Fig.1, the control signal is $u(t) = K_P + \frac{K_i}{s} + sK_d$ (1)

Where K_P = Proportional constant, $K_i = K_p/T_i$ = Integral constant and K_d = Derivative constant = K_pT_d

A. Ziegler Nichols S Curve Method

The very commonly used rules for tuning of standard feedback controller in real time control systems are Ziegler Nichols rule. The coefficients of the PID controller using Ziegler Nichols -S curve method are as follows [6-8,9].

Step-1: Experimentally obtained the open loop response of plant/system with step input as shown in below Fig. 2.

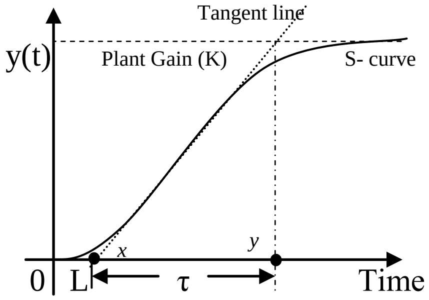

Fig. 2 Open loop response of plant/system with step input

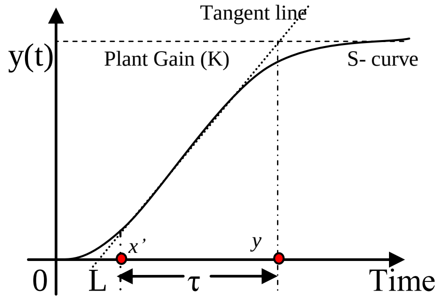

Fig. 3 Open loop response of plant/system with step input(modified)

Step-2: Measure the parameters Delay time (L) and Time constant (τ) from the S-curve. From the open loop response, the delay time **L** is measured from origin to *x* where the tangent line cuts the time axis and the time constant **τ** is measured between the points *x* and *y* on time axis as shown in Fig.2.

Step-3: Calculate the parameter values of PID controller using the rules

$K_P = 1.2\tau/L$, $K_i = 0.6\tau/L^2$ and $K_d = 0.6\tau$

B. Ziegler Nichols Modified S Curve Method

It the modified method of Ziegler Nichols - S curve method. In this method also the Delay time (L) and Time constant (τ) are measured from the modified S-curve, but the coefficients of the PID controller are obtained from the same rules. From the open loop response (see Fig.3), the delay time **L** is measured from origin to *x'* where the tangent line leave the S curve and cuts the time axis and the time constant **τ** is measured between the points *x*' and *y* on time axis.

Now calculate the parameter values of PID controller using the rules

$K_P = 1.2\tau/L$, $K_i = 0.6\tau/L^2$ and $K_d = 0.6\tau$

C. Internal Model Control (IMC)

In the IMC formulation, controller q(s) is based on the good part of the transfer function of process. The parameters of IMC PID controller are obtained using only one tuning parameter called IMC filter factor (λ). The value of λ is equivalent to closed loop time constant (i.e response speed of the closed loop system). The PID tuning parameters are then the function of closed loop time constant [5].

Let us consider a second order plant with plant gain K, time constants τ_1 and τ_2. The transfer function of the plant is

$$g_p(s) = \frac{K}{(1+s\tau_1)(1+s\tau_2)} \quad (2)$$

The followings steps are used to find the PID equivalent to IMC for the above second order plant.

Step-1: Prepare the transfer function of IMC controller q(s) which includes a filter f(s) to make q(s) improper. This is the important difference from the actual IMC procedure.

$$q(s) = g_p^{-1}(s).f(s) = \frac{(1+s\tau_1)(1+s\tau_2)}{K}\frac{1}{(1+\lambda s)} \quad (3)$$

Step-2: Using transformation technique, find the standard feedback controller i.e

$$g_c(s) = \frac{q(s)}{1-g_P(s)\,q(s)} = \frac{\frac{(1+s\tau_1)(1+s\tau_2)}{K}\frac{1}{(1+\lambda s)}}{1-\frac{K}{(1+s\tau_1)(1+s\tau_2)}\frac{(1+s\tau_1)(1+s\tau_2)}{K}\frac{1}{(1+\lambda s)}}$$

$$\therefore\ g_c(s) = \frac{s^2\tau_1.\tau_2 + (\tau_1+\tau_2)s + 1}{K\lambda s} \quad (4)$$

Step-3: Multiplying the equation (4) on both numerator and denominator by $(\tau_1+\tau_2)$ and rearranging the equation, we get

$$g_c(s) = \frac{\tau_1 + \tau_2}{K\lambda} \cdot \frac{s^2\tau_1.\tau_2 + (\tau_1 + \tau_2)s + 1}{(\tau_1 + \tau_2)s} \quad (5)$$

But the standard form of the PID controller of 2nd order system is

$$g_c(s) = K_p \frac{s^2\tau_i.\tau_d + s\tau_i + 1}{s\tau_i} \quad (6)$$

Equating the equations (5) and (6), we get

Proportional Gain $K_p = \frac{\tau_1 + \tau_2}{K\lambda}$, Integral time constant $\tau_i = \tau_1 + \tau_2$ and Differential time constant $\tau_d = \frac{\tau_1.\tau_2}{\tau_1 + \tau_2}$

Now the parameters of IMC PID controller are represented in terms of a standard feedback controller as

$$\text{Control signal } u(t) = \frac{\tau_1 + \tau_2}{K\lambda} + \frac{1}{K\lambda}\frac{1}{s} + \frac{\tau_1.\tau_2}{K\lambda}s \quad (7)$$

Even though the procedure of IMC is simple and easy to implement, the most commonly used controller is still the PID controller.

III. PRACTICAL EXAMPLE

The purpose of this section is to design the PID controller based on the rules which are discussed in previous section. The validity, effectiveness and superiority of the proposed controller, in this paper, are checked by considering the DC Drive as practical example. The field of the drive is excited by a separate dc supply. The load is represented in terms of angular velocity and is given as $T_l = B_l\,\omega_m$. The block diagram of armature voltage controlled DC drive with load is as shown in Fig.4 [10-11,12].

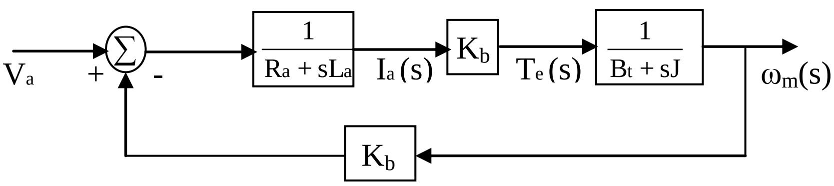

Fig. 4 Block diagram of DC drive with load

The modeling of DC drive is complicated because of crossing of back emf loop by inner current loop. To split the inner current loop from the back emf loop, it is required to break the transfer function between speed and voltage into two cascade transfer functions, first between speed and armature current and then between armature current and input voltage i.e

$$\frac{\omega_m(s)}{V_a(s)} = \frac{\omega_m(s)}{I_a(s)} * \frac{I_a(s)}{V_a(s)} = \frac{K_1(1 + s\tau_m)}{(1 + s\tau_1)(1 + s\tau_2)} * \frac{K_b / B_t}{(1 + s\tau_m)}$$

$$\therefore \frac{\omega_m(s)}{V_a(s)} = \frac{K}{(1 + s\tau_1)(1 + s\tau_2)} \quad (8)$$

Where $B_t = B_1 + B_l$, $K_1 = B_t/(K_b^2 + R_aB_t)$, $K = K_1K_b/B_t$, Mechanical time constant $T_m = J/B_t$ and J = Inertia constant. The parameters of DC Drive are taken from *Lanco* industries, Indi and are shown in Table 1.

TABLE I
PARAMETERS OF DC DRIVE

Parameters	Values
Power Rating	5 H.P
Rated Voltage (Vdc)	220 V
Rated Speed	1235 r.p.m
Armature Resistance (Ra)	4.0 Ω
Armature Inductance (La)	0.072 H
Inertia (Drive + Load) J	0.0607
Friction coefficient (Bt)	0.0869
Back EMF constant (Kb)	1.26

The transfer function of the DC drive, from eq.(8), is

$$\frac{\omega_m(s)}{V_a(s)} = \frac{0.651}{(1+0.1077s)(1+0.0208s)} = \frac{279.02}{s^2+56.77s+446.43} \tag{9}$$

The open loop response of eq. (9) with step input is as shown in Fig.5.

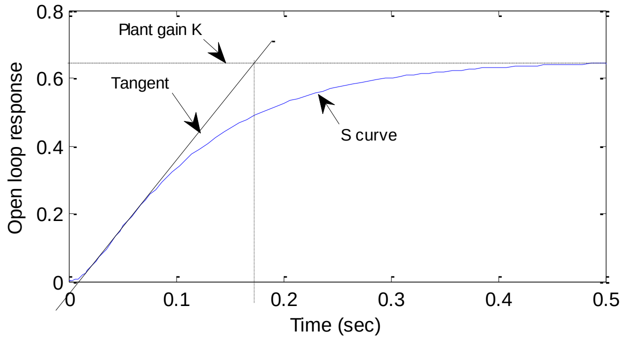

Fig.5 The open loop response of DC drive with step input

From the open loop response, the L and τ values with Ziegler Nichols – S curve method are L = 0.0104sec and τ = 0.1625sec respectively. Therefore the controller parameters are

$K_p = 18.75$, $K_i = 901.44$ and $K_d = 0.0975$

Similarly, L, τ values with Ziegler Nichols – modified S curve method are L = 0.01458sec and τ = 0.15833sec respectively. The controller parameters are

$K_p = 13.03$, $K_i = 446.88$ and $K_d = 0.095$

Comparing the equations (2) and (9), we get

Plant gain K = 0.651, Time constants $\tau_1 = 0.1077$Sec & $\tau_2 = 0.0208$Sec

Substituting above values in eq. (7), we get

$$\text{Control signal, } u(t) = \frac{0.1974}{\lambda} + \frac{1.536}{\lambda}\frac{1}{s} + \frac{0.00344}{\lambda}s \tag{10}$$

For good performance of the controller, λ value is chosen as 0.01 (see the Fig.8 in simulation result and discussion section). Now the parameters of PID controller using IMC rules are

Proportional Gain $K_p = 19.74$, Integral Gain $K_i = 153.61$ and Differential Gain $K_d = 0.344$

IV. Simulation Result and Discussion

The Fig.6 shows the closed loop response of drive without controller. Since there is no controller, it produces a steady state error (e_{ss}) as 0.6pu. To nullify this steady state error, the controllers which are designed in section 2 are used.

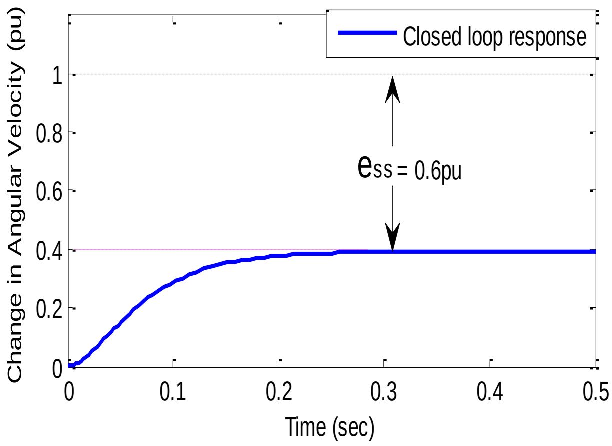

Fig.6 The closed loop response of DC drive

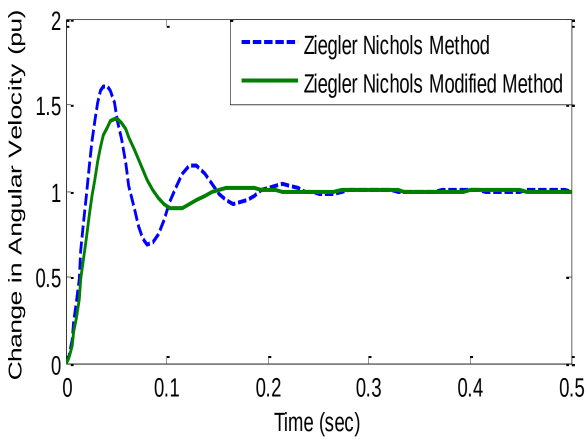

Fig. 7 Change in Angular velocity

The Fig.7 shows the change in angular velocity (pu) using Ziegler Nichols method. From the figure, it is clear that with the modified Ziegler Nichol method the settling time and oscillations are reduced. The Fig.8 and Fig.9 show the control signal and change in angular velocity respectively for various values of λ (tuning parameter of IMC filter). From Fig. 9, it is clear that the PID controller for λ = 0.01 gives a superior performance than other values of λ.

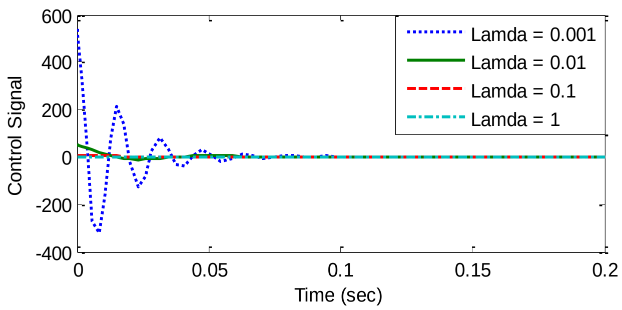

Fig. 8 Control signal for different values of λ

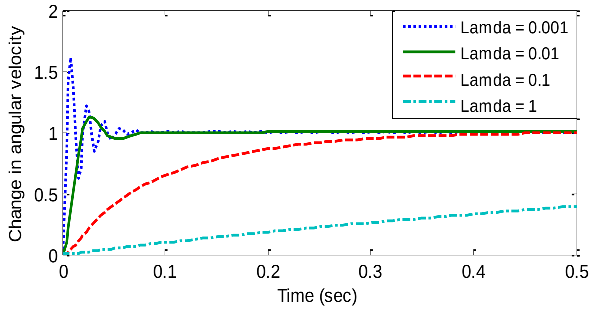

Fig. 9 Change in angular velocity for various values λ

The Fig.10 and Fig.11 show the error signal and control signal with different PID controllers respectively. Compare to other PID controllers, the error signal and control signal which are produced by the proposed controller is lower and smoother. The other PID controllers produce more error and control signal consists of oscillations.

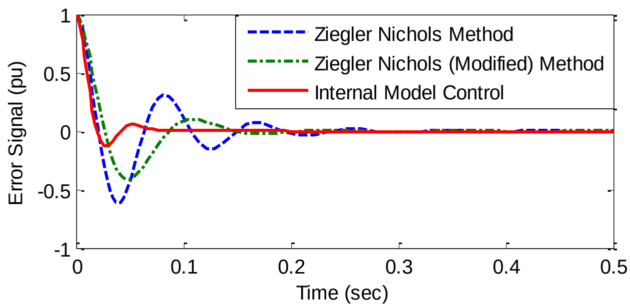

Fig. 10 Error signal with different PID Controllers

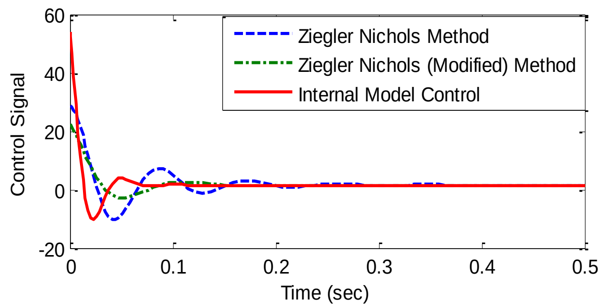

Fig. 11 Control signal with different PID Controllers

The Fig.12 shows the variations in angular velocity (pu) with Ziegler Nichols, Ziegler Nichols Modified and Internal Model Control methods. From the comparison, the IMC-PID controller provides improved performance in the aspects of peak over shoot, response speed (i.e rise time), settling time and steady state error. Similarly, the Fig. 13 shows the variations in electromagnetic torque w.r.t time.

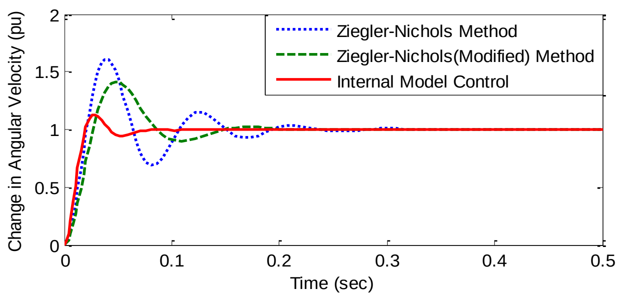

Fig. 12 Variations in angular velocity with different PID controllers

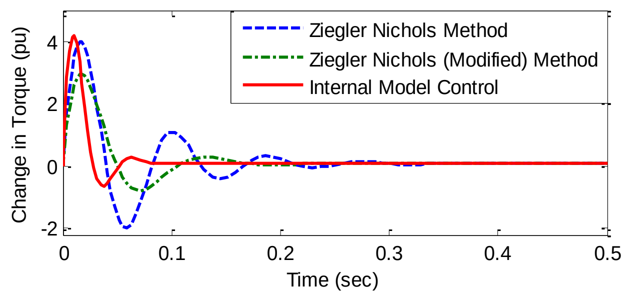

Fig. 13 Variations in angular velocity with different PID controllers

The Table II provides the summary of performance of the proposed PID controller for various values of λ (Lamda). Here with the increase of λ, the peak overshoot is decrease but both the rise and settling times are increased drastically. Also the steady state value is deviated slowly from its set point with increase of λ value and produces a steady state error.

TABLE III
PERFORMANCE OF IMC- PID CONTROLLER FOR VARIOUS VALUES OF LAMDA

Tuning parameter of IMC filter	**Overshoot**	**Settling time (sec)**	**Steady State Error**
λ = 0.001	60%	0.08	0
λ = 0.01	**12.60%**	**0.08**	**0**
λ = 0.1	0.3%	1.20	0
λ = 1	0.60%	5.10	Small change

The Table III provides the summary of the performance of various PID controllers along with the proposed PID controller. From the table, it is clear that the performance of the DC drive is improved with the Internal Model Control tuning in all aspects i.e quick response, lower peak over shoot and settling time with zero steady state error.

TABLE IIIII
PERFORMANCE OF VARIOUS PID CONTROLLERS

Tuning Methods	**Performance of PID Controllers**			
	Rise time (sec)	**Overshoot**	**Settling time (sec)**	**Steady State Error**
Z- N Method	0.017	61.10%	0.318	0
Z -N Method (Modified)	0.014	41.60%	0.202	0
IMC	**0.011**	**12.60%**	**0.08**	**0**

V. CONCLUSIONS

In this research paper, for tuning the controller of DC drive, two analytical methods which are explained in section 2 were reviewed. The new rules for PID controller of DC drive were developed based on IMC filter tuning parameter λ. These new rules were tuned with the use of two parameters i.e delay time (L) and time constant (T) of plant step response. To use this tuning method the plant response should be 'S' shaped, otherwise it is not applicable. The IMC-PID controller with these new rules has advantage of simple tuning and easy to implement.

The IMC-PID controller tuned with these new rules gives a superior performance for $\lambda = 0.01$ than other values of λ i.e with the increase of λ the peak overshoot is decrease but both the rise and settling times are increased drastically. Also the steady state value is deviated slowly from its set point with increase of λ value and produces a steady state error. The error and control signal which are produced by the proposed controller is lower and smoother for $\lambda = 0.01$. For the increase of λ value, the error is more and control signal consists of oscillations. Finally, with IMC-PID, the performance of the DC drive was improved in all aspects i.e quick response, lower peak over shoot and settling time.

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