Closed Loop Control of A DC Motor Using Cosine Control Technique

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Abstract
The research presents a closed loop control system to control the speed of a dc motor using cosine control method. The method generates a synchronized cosine voltage with an error dc level. The error level represents the difference between a voltage which represents actual speed and a voltage proportional to reference speed.

The proposed method proved to be effective in controlling the speed since it gives a linear relationship between the output voltage and the control voltage. Adequate torque-speed characteristics were obtained. The proposed system controls the speed by varying the control voltage and hence the average armature. A second loop which measures the current of the armature, compares it to the reference (rated) value and enable the AND for normal value of current or disables for over current conditions.

This method can be extended to drives operated from three phase converters.

1- Introduction
The purpose of a motor speed controller is to take a signal representing the demanded or reference speed and to drive the motor at that speed. Closed loop control implements the principle of comparing the actual speed in the form of an electrical signal proportional to it with reference or desired speed in the form of another electric signal. The result of this comparison is an error level which always proportional to the actual speed.

The use of universal learning network ULN was presented by (Hussein et al 2003). The speed of a separately excited dc motor drive fed from photo voltaic generators through intermediate power converters was simulated. The controller network is used to control the converter duty ratio so that the motor speed can follow an arbitrarily reference signal. The problem of synchronization for thyristors was discussed by (Weidenburg et al 1993), several methods of synchronizing for firing thyristors based power converters was presented and a proposed adaptive online waveform reconstruction method was presented.

In this proposed system, a voltage signal proportional to actual speed along with another voltage signal proportional to reference speed are two input signals to a difference amplifier circuit. The output from the difference amplifier is a dc level, which is referred to as the control voltage Ec. This voltage along with its negative complement is compared with a synchronously generated cosine voltage. Pulses are
obtained at the intersection points. The pulses are processed by adequate pulse processing circuits before fed to the gates of relevant SCR. An additional loop is also used to monitor over current cases and blocks the firing pulses when ever such a case occurs.

The proposed system gave adequate torque–speed characteristics. The proposed system can be used in various industrial and practical system. Also a wide control of speeds can be obtained from this control scheme.

2- Control of separately excited Dc motor drives

Exciting the field from a separate Dc source makes the speed control of the motor relatively easy. In most applications of speed control armature control is employed, where the applied armature voltage is varied either by controlled converters or dc choppers. Variation of the armature voltage is done by varying the delay (firing) angle of the controlled converter using closed loop techniques. Fig (1) shows the basic block diagram of a closed – loop feed back control system.

\[ \sum \quad \text{Speed controller} \quad \text{Converter} \quad \text{Dc motor} \]

Fig. 1: Basic block diagram of a closed loop speed control system

2.1. Motor transfer function

Fig (2) represents the model of a separately excited Dc motor. The voltage equation is

\[ e_a = e_g + R_a . i_a + L_a . d(i_a) / dt \]

Where

\[ e_g = k_a \times \Phi \times N \]

The torque balance equation is,

\[ T = T_L + B \times n + j \times d(n)/dt \]

\[ T = k_t \times a \times \Phi \times i_a \]

In the S- domain

\[ E_a (S) = E_g(S) + R_a \times I_a(s) + L_a \times S \times I_a(S) \]

\[ E_g (S) = k_a \times \Phi \times N(S) \]

\[ T(S) = T_L(S) + B \times N(S) + J \times S \times N(S) \]

Then from equation (5)

\[ I_a(S) = \frac{E_a(s) - E_g(s)}{R_a + S \times L_a} \]

\[ = \frac{[E_a(s) - E_g(s)]/R_a}{1 + \tau_a \times S} \]

Where \( \tau_a = L_a / R_a \) (electrical time constant of motor armature circuit)
\[ N(S) = \frac{T(S) - T_L(S)}{B + JS} = \frac{\left[T(S) - T_L(S)\right]}{1 + \frac{m}{S}} \]

Where \( \tau_m = \frac{J}{B} \) (mechanical time constant of the motor)

The block diagram is shown in Fig. (3)

From Fig. (3) an expression can be obtained for the change in speed \( N(S) \) due to the disturbances in applied voltage \( E_a(S) \) and load torque \( T_L(S) \),

\[ N(S) = \frac{G_1(S)}{1 + G_1(S) \times H_1(S)} \times E_a(s) + \frac{G_2(S)}{1 + G_2(S) \times H_2(S)} \times T_L(S) \]

Where

\[ G_1(S) = \frac{1}{Ra} \times (k_a \phi) \times \frac{(1/B)}{1 + S \times \tau_m} \]

\[ H_1(S) = k_a \times \phi \]

\[ G_2(S) = \frac{(1/B)}{1 + S \times \tau_m} \]

\[ H_2(S) = \frac{(k_a \phi)^2 / Ra}{1 + S \times \tau_m} \]

If the load torque term is neglected for now, from equations (10), 10 a and 10 b

\[ \frac{N(S)}{E_a(S)} = \frac{k_a \phi}{(k_a \phi)^2 + Ra \times B (1 + S \times \tau_m)} \]

If \( \tau_a << \tau_m \), then \( \tau_a \) can be neglected and the expression simplifies to

\[ \frac{N(S)}{E_a(S)} = \frac{k_a \phi}{(k_a \phi)^2 + Ra \times B + S \times Ra \times B \times \tau_m} \]

Where

\[ \tau_{ml} = \frac{Ra \times B}{(k_a \phi)^2 + Ra \times B} \times \tau_m \]

\[ k_m = \frac{k_a \phi}{(k_a \phi)^2 + Ra \times B} \]

\[ \tau_{ml} < \tau_m \]

Fig. 2: Separately excited dc motor model
2.2 Closed loop speed control

A closed-loop system compared to an open loop system has generally greater accuracy, improved dynamic response and reduced effects of disturbances such as loading. When the drive requirements include rapid acceleration and deceleration, closed-loop control is necessary.

To employ closed loop control a tachogenerator is attached to the shaft of the motor, the voltage output from the tachogenerator represents a signal proportional to actual speed. This signal is compared to another voltage signal representing reference (or desired) speed. The error signal (algebraic difference of the two signals) is the error signal which is used to vary the delay angle of the controlled converter and eventually the average armature voltage of the motor.

The average armature voltage in this research is to be controlled by a single phase semi-controlled converter. The proposed cosine control method gives a linear relationship between the control voltage $E_c$ and the average armature voltage $E_a$.

3- Cosine control of phase (delay) angle $\alpha$

In this scheme of control, a control Dc voltage $E_c$ generates the firing pulses for $\text{SCR}_1$ and $\text{SCR}_2$ of the semi controlled power converter. The proposed system which is designed in this research generates the pulses at the crossing points of the control voltage and a synchronously generated cosine voltage which is to be derived from the input voltage to the power converter (Sen, 1981). One of the most important consideration in the design of any firing circuit used in rectifier circuits is the way of synchronizing the power converter circuit with the relevant control (or firing) circuit, such that the phase (delay) angle is measured with respect to the same voltage zero as that of the power converter circuit. A general block diagram of the proposed control scheme is shown in fig. (4)

The problem that now arises is how to modify the proposed method such that two firing pulses are obtained in order to fire $\text{SCR}_1$ and $\text{SCR}_2$ of the semi controlled power converter, here two pulses are needed one during the positive cycle and the other during the negative cycle of the Ac input to the converter. This problem was solved by introducing the control voltage $E_c$ and its negative complement (-$E_c$) referred to as $E_d$. These two voltages are compared with the cosine voltage derived from the input voltage to the converter. The timing circuit diagrams are shown in fig.(5).

![Fig. 3: Functional block diagram](image-url)
Fig. 4: Block diagram of the proposed cosine control method

Fig. 5: Timing diagrams of cosine control
3.1 Mathematical analysis of the proposed cosine control method

For the cosine method, the attempt is made to derive the phase angle in terms of the control signal $E_C$.

Since

$$V(t) = E_{\text{max}} \cos(\omega t)$$  \hspace{1cm} 12

At the crossing point between the control voltage $E_C$ and cosine voltage,

$$V(t) = E_C \text{ and } \omega t = \alpha$$

Then

$$E_C = E_{\text{max}} \cos \alpha$$  \hspace{1cm} 13

$$\alpha = \cos^{-1}(E_C/E_{\text{max}})$$  \hspace{1cm} 14

The output voltage of the converter is given by,

$$E_o = E_{\text{max}} \cos \alpha$$  \hspace{1cm} 15

$$= E_{\text{max}} \cos [\cos^{-1}(E_C/E_{\text{max})}]$$  \hspace{1cm} 16

Then

$$E_o = K_1 E_C$$  \hspace{1cm} 17

Where

$$K_1 = E_{\text{max}}/E_{\text{max}}$$

It is clear that the cosine control scheme provides a linear transfer characteristics between the output voltage $E_o$ and the control voltage $E_C$.

4- Torque and speed as a function of delay angle and control voltage

For a semi- converter with free wheeling action the armature circuit equations are (Sen 1981)

$$e_a = v = R_a i_a + L_a \frac{di_a}{dt} + e_g \hspace{1cm} | \hspace{0.2cm} \alpha < \omega_1 < \pi$$  \hspace{1cm} 18
\[ e_a = 0 = R_a i_a + L_a \frac{dia}{dt} + e_g \quad \pi < \omega_t < \pi + \alpha \]

If \( v(t) = \sqrt{2} \ V \sin \omega t \)

With a semi-converter the average motor terminal voltage is

\[ E_a = \frac{1}{\pi} \int \sqrt{2} V \sin \omega t \ d(\omega t) = \frac{\sqrt{2}V}{\pi} (1 + \cos \alpha) \]

The variation of motor terminal voltage \( E_a \) as a function of the firing angle \( \alpha \) is shown in Fig. 7. The inverter operation of the full converter occurs in the range \( 90^0 < \alpha < 180^0 \) for continuous motor armature current.

Hence the equation for speed in terms of \( \alpha \) and the torque \( T \) is written as

\[ N = \left( \frac{\sqrt{2}V / \pi}{K_a \phi} \right) (1 + \cos \alpha) - \frac{R_a}{(K_a \phi)^2} T \]

Where \( K_a \) is constant of Dc machine.

The torque – speed equation on the bases of equation 22 is shown in Fig. 8 for various values of \( \alpha \).

The object now is to rewrite the equations for average terminal voltage at motor terminals and torque speed characteristics in term of the control voltage \( E_c \). From equation 14 the average motor voltage is,

\[ E_a = \frac{\sqrt{2}V}{\pi} \left( 1 + \frac{E_c}{E_{\max}} \right) \]

The torque – speed characteristic as a function of the controlled voltage is,

\[ N = \left( \frac{\sqrt{2}V / \pi}{K_a \phi} \right) \left( 1 + \frac{E_c}{E_{\max}} \right) - \frac{R_a}{(K_a \phi)^2} T \]
4-Implementation of the proposed system

The proposed system is implemented by a four stage procedure

4.1 Stage one:

In this stage the control voltage \( E_c \) & its negative, \( E_d \) is generated. The average output voltage from the tacho- generator, \( E_t \) is proposed. Then \( E_t \) along with a reference dc voltage which represents the reference (desired) speed, \( E_{ref} \) is made as two inputs of a difference amplifier. The output of the difference amplifier is

\[
E_{AP} = K' (E_{ref} - E_t)
\]

Where \( E_{AP} \) is the output dc level from the difference amplifier

\( K' \): constant of amplifier

Hence \( E_{AP} \) is the equal to \( E_c \) the control voltage which is compared to the synchronized cosine voltage. The control voltage is inverted by a unity gain amplifier to give its inverse signal \( E_d \).

4.2 Stage two

In this stage the input voltage (from power circuit) is stepped down and then integrated to generate a synchronized cosine voltage. This voltage is compared to the control voltage \( E_c \) and negative complement \( E_d \). This voltage is clamped using two back to back Zener diodes. Comparing \( E_c \) & \( E_d \) with the cosine voltage will produce signals \( e_c \) and \( e_f \) respectively. These signals are fed to monostable \( M_1 \) & \( M_2 \) to produce signals \( e_g \) & \( e_h \) respectively. These signals trigger a set- rest flip flop (F-F) to generate signals \( e_j \) & \( e_i \).

4.3 Stage three

This stage consists of modulating signals \( e_j \) & \( e_i \) with a high frequency (usually 15 – 20 KHZ). This stage was implemented by anding each signal with a high frequency from 555 timer. It is clear that a modulated firing pulse for thyristor will reduce gate dissipation and ensure firing, therefore reducing the risk of misfiring the

Fig. 8: Torque speed characteristics for various values of delay angles
values of resistances and capacitances are calculated using well known formulas of 555 timer circuits.

4.4 Stage four

The two signals (e_j & e_k) from the proposed system may be sufficient to fire the thyristors of the power converter circuit or in some practical cases it may need amplification. The use of an amplifier depends on the gate ratings of thyristors used in the starter. Hence an optional amplification circuit may be used.

4.5 Stage five

From a practical point of view a speed control loop requires current monitoring. This is to ensure that no over current case will occur while varying the control voltage and in turn armature voltage. The method of pulse blocking (PC sen 1987) may be used. The blocking of pulses can be carried out in numerous ways. The most practical method of pulse blocking is AND the firing pulses from the controller with a timing pulse. The timing pulse assume Vcc when no over current occurs and zero when an over current occurs. A DCCT is connected in the armature of the motor which measures the actual current (I_act). This signal is compared to a reference current signal which could be equal to the rated current of the motor (I_ref). When I_act < I_ref the clear output goes high so as the Q which is the output of the flip flop and the firing pulses are passed to the converter. When I_act > I_ref indicating an over current condition the clear goes low and Q is also low. Hence the output of the AND is low and the pulses are blocked from the converter, causing the system to turn off. The AND gate remains disabled until its reset by pressing the preset button. This protection circuit is shown in fig 9 and relevant timing diagrams in fig 10.

4.6 Stage six

The last stage of the proposed system deals with the Dc sources for different components. These include Vcc and –Vcc for all operational amplifiers. This is done by connecting a center tap transformer to the Ac mains, full wave rectifier, rectifier and regulator. This will generate the Dc voltage which can be distributed to all necessary components. This practical circuit in fig 11.

The complete designed circuit and relevant timing diagrams are shown in fig 9 and fig 10 respectively.

Fig. 9: Practical circuit for over current protection
Fig. 10: Timings diagram for over current protection circuit

Fig. 11: Hard ware implementation of proposed control system
Fig. 12: Hardware implementation of proposed control system
6. Experimental Results

The proposed system of control was applied on a 10 hp, 230 V, 1200 rpm separately excited dc motor. The full load current of this motor is 38 A. The average motor voltage and torque/speed characteristics as a function of the control voltage $E_C$
is shown in fig 11 and fig 12 respectively. It's clear that the proposed system is suitable for variable speed drives simply by varying the control voltage $E_c$.

![Graph showing average motor voltage versus control voltage](image1)

**Fig 14** Average motor voltage varies control voltage

![Graph showing torque/speed characteristics](image2)

**Fig. 15**: torque/speed characteristics for various values of control voltage $E_c$.
7. Conclusions

From the results of this work the following conclusions could be drawn:-

1. A closed loop speed control system is proposed which easily achieves synchronization between power converter circuit and firing circuit.

2. The designed system is quiet suitable for various drives which require various types of speed torque characteristics. To obtain variable speed torque characteristics simply by varying the control voltage $E_C$.

3. The proposed method can be extended to control DC drives operated from single phase fully controlled converters.

4. The proposed control circuit can be modified to control DC motors drives operated from three phase converters (semi or fully controlled).

5. The proposed scheme of control gives adequate range of control for speed.

References


Sen, P.C (1988), Power Electronics, Tate Mc grew –hill publishing company pp 590.
