THE DESIGN OF A LOW COST PID CONTROLLER COMBINED WITH INVERSE DERIVATIVE CONTROL ACTION AND STUDY OF ITS APPLICATION IN A VOLTAGE CONTROL SYSTEM OF A DIRECT CURRENT GENERATOR
THE DESIGN OF A LOW COST PID CONTROLLER COMBINED WITH INVERSE DERIVATIVE CONTROL ACTION AND STUDY OF ITS APPLICATION IN A VOLTAGE CONTROL SYSTEM OF A DC GENERATOR [36, 37]

9.1 INTRODUCTION

In any process industry, the different process variables are maintained at the desired values by the operation of the different manual and automatic control loops in order to obtain the high quality product at lesser cost along with all the safety aspects of the plant operation and the $PID$ controller [77, 156, 170, 191, 221, 291] is one of the most important components of any automatic control loop. The offset produced in the proportional controller due to load change is eliminated by the integral controller, but this tends to increase the stabilization time, which may be minimized by the derivative control action. But in a very fast process, the $PI$ or $PID$ [267] control action may be excessively high enough, which may lead to the high frequency oscillations of the process variable about the set point. This high frequency oscillation may be minimized by reducing the effective gain of the controller. In the case of a proportional controller, the low frequency oscillation with offset may occur when a load change occurs in a process plant and this offset may be decreased by increasing the gain of the controller. The inverse derivative control action [156, 162], which is inversely related with the rate of change of deviation signal, may be used in combination with $P$, $PI$ or $PID$ control action to achieve both these effects at high and low frequencies. Many works on the design and tuning of $PID$ controllers are being reported. Isakson et al. [135] have

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37 Proceedings of the All India Seminar on “Advance Energy Systems”, organized by the Institution of Engineers (I) at Bhubaneswar, Orissa, India, pp. 47-53, 7-8 February 2004.
mentioned the non-functioning of derivative control action. W. L. Luyben [162] has developed tuning methods with inverse derivative control action. In the present work, a low cost IC based PID controller combined with inverse derivative control action has been designed. The transfer function of the whole network has been derived and is found to be identical with the standard form derived by the other workers [156, 162]. The function of this controller in an analogue process has been tested using a square wave signal and the experimental results are reported.

The output voltage of a generator [66, 76, 186] without any control mechanism is found to decrease with the increase of load current, which is due to various reasons such as armature resistance drop, armature reactance drop etc. This may be disadvantageous for the DC consumers in maintaining their equipment at the highest efficiencies. Hence, the voltage regulation or control of the terminal voltage of a DC generator at a desired constant value at all loads is very important in a DC supply system. This may be achieved by controlling the field flux or the speed of the prime mover. For a permanent magnet DC generator, the field flux is constant and hence the terminal voltage may be controlled by manipulating the speed of the prime mover. There may be various techniques of speed adjustment of the prime mover such as centrifugal proportional type fuel oil control, steam pressure control, hydel pressure control etc [77, 157, 170, 191]. In the present work, the application of the proposed PID controller with inverse derivative control action has been studied in a permanent magnet DC generator to obtain a regulated supply from an unregulated system. In this study, the motor generator technique has been used and the speed of the motor (prime mover) has been adjusted by the controller in order to obtain the stabilised output voltage at all loads. The operational characteristic of the control system has been studied and the experimental results are reported.
9.2 ANALYSIS

The inverse derivative control action is achieved along with PID control action by means of an operational amplifier based circuit as shown in Figure 9.1 by using only two operational amplifiers.

Figure 9.1: Circuit diagram of PID controller with inverse derivative control action

If \( e \) be the deviation signal at the input terminal \( A \) of the amplifier \( A_1 \) then the output signal \( V_B \) at the output terminal \( B \) of the amplifier \( A_1 \) is obtained from the following analysis.

Since the input impedance of the amplifier is high, the input signals \( e_1 \) and \( e_2 \) at the inverting and non-inverting terminals respectively of the amplifier \( A_1 \) may be assumed to be identical. Again, due to the high impedance, negligible current passes through the input resistance \( R_1 \) from the input deviation signal. Hence, the input signal \( e_2 \) at the non-inverting terminal of \( A_1 \) will be almost equal to the input signal \( e \).
i.e., \( e_1 \approx e_2 \) and \( e \approx e_2 \). \hspace{1cm} (9.1)

Now,
\[
e_i = \frac{R_1}{(R_1 + R_2)} V_\theta. \hspace{1cm} (9.2)
\]

Hence,
\[
e \approx e_1 = \frac{R_1}{(R_1 + R_2)} V_\theta.
\]

\[
V_\theta = \frac{(R_1 + R_2)}{R_1} e
\]
or
\[
V_\theta = \alpha e \hspace{1cm} (9.3)
\]

where
\[
\alpha = \frac{(R_1 + R_2)}{R_1}. \hspace{1cm} (9.4)
\]

Hence, the equivalent circuit of the network of amplifier \( A_i \) between the terminals \( A \& D \) may be as shown in Figure 9.2 and the Laplace Transform of the circuit is given by
\[
I(s) = \left[ \frac{\alpha e(s) - e(s)}{R_0 + \frac{1}{C_0 s}} \right]. \hspace{1cm} (9.5)
\]
Hence in the frequency plane, the voltage signal at \( D \) will be given by

\[
V_D(s) = e(s) + R_D I(s)
\]

or

\[
V_D(s) = e(s) + R_D \left[ \frac{\alpha e(s) - e(s)}{R_D + \frac{1}{C_D s}} \right]
\]

(9.6)

or

\[
V_D(s) = \left[ 1 + R_D (\alpha - 1) \right] \frac{e(s)}{R_D + \frac{1}{C_D s}}
\]

\[
V_D(s) = \left[ 1 + \frac{R_D C_D s (\alpha - 1)}{R_D C_D s + 1} \right] e(s)
\]

\[
V_D(s) = \left[ \frac{1 + R_D C_D s + \alpha R_D C_D s - R_D C_D s}{1 + R_D C_D s} \right] e(s)
\]
\[ V_D(s) = \frac{(1 + T_D \cdot s)}{(1 + \frac{T_D \cdot s}{\alpha})} e(s) \]  \hspace{1cm} (9.7)

where

\[ T_D = \alpha R_D C_D = \frac{(R_i + R_f)R_D C_D}{R_i} \]  \hspace{1cm} (9.8)

Now this voltage signal is again input to the non-inverting terminal of the second amplifier \( A_2 \) through the resistance \( R_D \) of the derivative potentiometer \( R \). Since the current drawn by \( A_2 \) is negligibly small, the voltage signals \( e_4(s) \) at the non-inverting terminal of the amplifier \( A_2 \) will be approximately equal to \( V_D(s) \)

i.e., \[ e_4(s) = V_D(s) \]  \hspace{1cm} (9.9)

Let the voltage signal at the output terminal \( E \) of the amplifier \( A_2 \) be ‘\( m \)’ and that at its inverting input terminal be \( e_3 \). Hence in the frequency plane, the voltage signal \( V_F(s) \) at the point \( F \) of the circuit diagram as shown in Figure 9.1 is given by

\[ V_F(s) = \frac{R_P}{(R_3 + R')} m(s) = K \cdot m(s) \]  \hspace{1cm} (9.10)

where

\[ K = \frac{R_P}{R_3 + R'} \]  \hspace{1cm} (9.11)

This voltage is being discharged through \( R_i \) and \( C_i \). Hence the voltage across the capacitor \( C_i \) will be given by
\[ V_F(s) - e_3(s) = \frac{1}{C_1 s} \frac{V_F(s)}{R_f + \frac{1}{C_1 s}} \]

\[ V_r(s) - e_3(s) = \frac{V_F(s)}{1 + R_C s} \]

\[ V_r(s) \left[ 1 - \frac{1}{1 + R_C s} \right] = e_3(s) \]

or

\[ V_r(s) = \left( 1 + \frac{1}{R_C s} \right) e_3(s). \]  (9.12)

From the equation nos. (9.10) and (9.12) we have

\[ K_m(s) = \left( 1 + \frac{1}{T_i s} \right) e_3(s) \]  (9.13)

where

\[ T_i = R_i C_i. \]  (9.14)

Now for the operational amplifier \( A_2 \) we have,

\[ e_3(s) = e_4(s). \]  (9.15)

From the equation nos. (9.7), (9.9), (9.13) and (9.15) we have,

\[ K_m(s) = \left( 1 + \frac{1}{T_i s} \right) V_D(s) \]
\[ K \frac{m(s)}{e(s)} = \left(1 + \frac{1}{T_i s}\right) \left(\frac{1+T_D s}{1+\frac{T_D s}{\alpha}}\right) e(s). \]

Thus the transfer function of the controller circuit as shown in Figure 9.1 is given by

\[ \frac{m(s)}{e(s)} = K_c \left(1 + \frac{1}{T_i s}\right) \left(\frac{1+T_D s}{1+\frac{T_D s}{\alpha}}\right) \]

where

\[ K_c = \frac{1}{K}. \]

The above transfer function is identical with the transfer function of a PID controller with derivative control action derived by other investigators where the proportional constant \( K_c \), integral action time \( T_i \), derivative action time \( T_D \) and dynamic gain \( \alpha \) are given by

\[ K_c = \frac{1}{K} = \frac{(R_1 + R^*)}{R_p} \]

\[ T_i = R_i C_i \]

\[ T_D = \alpha R_D C_D \]

and \[ \alpha = \frac{(R_1 + R_2)}{R_i}. \]
9.3 DESIGN

The controller has been designed using low noise operational amplifier $OP - 07$. The deviation signal is generated by subtracting the measured signal from the set point signal. Hence, the operational amplifier based differential amplifier using $OP - 07$ has been designed to produce the deviation signal. Thus the controller along with this differential amplifier constitutes the complete controller unit and is fabricated on a breadboard to test its performance.

The proposed motor generator type DC voltage control system has been designed according to the block diagram, as shown in Figure 9.3.

![Figure 9.3: The block of the proposed motor generator type DC voltage control system](image)

In this system, the generator and the motor are selected to be small DC type, so that the proposed operational amplifier based controller with inverse derivative control action may be directly used avoiding high cost on a large capacity buffer unit. The output voltage of the generator is compared with the set point or desired value by the controller and the controller output is accordingly varied when there is a deviation. This controller output voltage changes the armature voltage of a
The experiments have been performed in two parts. In the first part, the performance of the proposed controller has been tested by using a process analogue. Since the main function of an actual process is to produce a time lag between input and output, a series $R-L$ circuit has been used as the process analogue as shown in Figure 9.4.

![Diagram](image)

**Figure 9.4:** Process analogue circuit of PID controller with inverse derivative control action

The control action due to a square wave input signal has been passed through this series $R-L$ circuit. The signal obtained from the $R-L$ circuit is compared with the input square wave signal by the differential amplifier to produce the deviation signal. This deviation signal is sent to the controller input. The controller output for the different values of controller parameters $[K_c,T_i,T_d,\alpha]$ are as shown in TABLE 9.1 are observed and observed values are printed by storage CRO. The waveforms are shown in Figure 9.5(a) through Figure 9.5(e).
TABLE 9.1: The parameters of PID controller with inverse derivative control action with the control parameters $L = 163 \, mH$, $R_L = 63 + 997 = 1060 \, \Omega$, $C_I = 0.263 \, \mu F$, $C_D = 1.7 \, \mu F$, $R_3 = 100 \, \Omega$, $R_i = 1000 \, \Omega$, $R_p = R'_p$.

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<th>$R_1$</th>
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<th>$T_I = R_I C_I$</th>
<th>$\alpha = \frac{(R_i + R_3)}{R_1}$</th>
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Figure 9.5(a)
Figure 9.5(b)
Figure 9.5(c)
Figure 9.5(d)
Figure 9.5: The characteristic of the proposed PID controller with inverse derivative control action
In the second part of the experiment, the performance of the voltage control system of a DC generator using the proposed PID controller with inverse derivative control action has been tested. The experiments are performed to determine the V–I characteristics of the DC generator without and with controller. The experimental results for the DC generator without controller are shown in the TABLE 9.2 and those with controller are shown in the TABLE 9.3. The V–I characteristic graphs for generator without controller and those for the generator with controller are shown in Figure 9.6(a) through Figure 9.6(d) and Figure 9.7(a) through Figure 9.7(d) respectively. The variation of output voltage at different set points at given load is shown in Figure 9.8.

![Figure 9.6(a)](image)

![Figure 9.6(b)](image)
Figure 9.6: $V-I$ characteristic of DC generator without controller

Figure 9.6(c)

Figure 9.6(d)

Figure 9.7(a)

$V-I$ characteristic of DC generator without controller
Figure 9.7(b)

Figure 9.7(c)

Figure 9.7(d)

*Figure 9.7: V-I characteristic of DC generator with controller*
From the equation (9.17) it is found that the controller parameters $K_c$, $T_i$, and $T_d$ may be adjusted by the linear potentiometers $R_p$, $R_i$, $R_d$ respectively and accordingly, these parameter scales may be selected to be linear by which it will be easier to adjust the parameters during the tuning of the controller in a control loop in a process plant. The term $1 + \frac{T_p \cdot s}{\alpha}$ in the denominator of the transfer function of the controller as shown in equation number (9.16) shows that this part of the transfer function of the controller is inversely related with the rate of change of deviation signal and hence it gives the inverse derivative control action. This term decreases the overall gain of the controller at high frequency and increases the overall gain of the controller at low frequency. Thus, a fast process, where the process variable has a tendency to oscillate at a high frequency system, may be easily stabilised due to this decrease of overall gain by the inverse derivative control action. Similarly, in a slow process where the low gain of a controller has a tendency to oscillate at a low frequency along with an offset, this inverse derivative control action may be used to reduce the offset, since it increases the overall gain of the controller at low frequency.

**Figure 9.8:** Variation of DC generator output voltage with set point

9.5 DISCUSSIONS

From the equation (9.17) it is found that the controller parameters $K_c$, $T_i$, and $T_d$ may be adjusted by the linear potentiometers $R_p$, $R_i$, $R_d$ respectively and accordingly, these parameter scales may be selected to be linear by which it will be easier to adjust the parameters during the tuning of the controller in a control loop in a process plant. The term $1 + \frac{T_p \cdot s}{\alpha}$ in the denominator of the transfer function of the controller as shown in equation number (9.16) shows that this part of the transfer function of the controller is inversely related with the rate of change of deviation signal and hence it gives the inverse derivative control action. This term decreases the overall gain of the controller at high frequency and increases the overall gain of the controller at low frequency. Thus, a fast process, where the process variable has a tendency to oscillate at a high frequency system, may be easily stabilised due to this decrease of overall gain by the inverse derivative control action. Similarly, in a slow process where the low gain of a controller has a tendency to oscillate at a low frequency along with an offset, this inverse derivative control action may be used to reduce the offset, since it increases the overall gain of the controller at low frequency.
From the equation no. (9.17) it is found that the adjustments of the controller parameters $K_c, T_i$ and $T_d$ by the potentiometer $R_p, R_f$ and $R_d$ for a given value of dynamic gain $[\alpha]$ are independent from each other. Hence it will be much easier to select any one or any combination of the control actions as demanded by a particular process control loop. The cost of the controller will be very small since it involves only two operational amplifiers for all the modes of control action.

The experimental characteristic graphs of the controller as shown in Figures 9.4(a) through Figures 9.4(e) reveal the satisfactory operation of the controller in process plant. A very good response of the controller to the various parameters have been observed.

From the experimental results shown in Figure 9.7(a) through Figure 9.7(d), it is observed that the output voltage of the DC generator is maintained almost at a constant value under all dynamic conditions of the load. The variation of the generator output voltage with set point as shown in Figure 9.8, is found to be quite linear. More accurate results may be obtained by following the proper tuning criteria of the controller.
TABLE 9.2: Experimental results for the V-I characteristics of DC generator without controller

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TABLE 9.3: Experimental results for the V-I characteristics of DC generator with PID controller along with inverse derivative control action with control parameters $K_c = 1.05$ [$R_p = 9.52 \text{k}\Omega$] $T_i = 73.64 \mu \text{sec}$ [$R_i = 0.28 \text{k}\Omega$], $T_d = 1.67 \text{msec}$ [$R_d = 0.29 \text{k}\Omega$], $\alpha = 3.38$ [$R_2 = 2.38 \text{k}\Omega$]

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