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# Design and Testing of a Low Cost PID Controller Combined with Inverse Derivative Control Action and Its Application in Voltage Control Systems of DC Generator

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**Abstract:** A single PID controller in a process control loop may suffer from high frequency oscillations without offset or low frequency oscillation with offset. An inverse derivative control action can eliminate both of these errors. In the present paper, a low cost operational amplifier based *PID* controller with inverse derivative control action has been described. Its transfer function has been derived and is found to be identical with the form already derived by other workers. It has been tested with a process plant analogue and implemented in the voltage control system of a DC generator. Its transfer function along with its characteristics in a process plant analogue and the load characteristics of DC generator with and without this controller have been determined experimentally and reported in this paper. *Copyright © 2008 IFSA.*

**Keywords:** *PID* control, Inverse derivative control, Control parameters, Voltage Control System, DC generator

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## 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 [5-10] is one of the most important components of any automatic control loop. The offset produced in the proportional controller due to the 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 $PID$ 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 [1, 7] 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. [2] has mentioned the non-functioning of derivative control action. W. L. Luyben [1] has developed tuning methods with inverse derivative control action. In the present paper the design of a low cost $IC$ based $PID$ controller combined with inverse derivative control action has been reported. 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 [1, 7]. 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 [12-15] without any control mechanism is found to decrease with the increase of load current which is due to various reasons such as armature resistance voltage drop, armature reactance drop etc. This may be disadvantageous for the DC consumers in maintaining their equipments 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. 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 stabilized output voltage at all loads. The operational characteristic of the control system has been studied and the experimental results are reported.

## 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 Fig. 1 by using only two operational amplifiers.

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 $e$

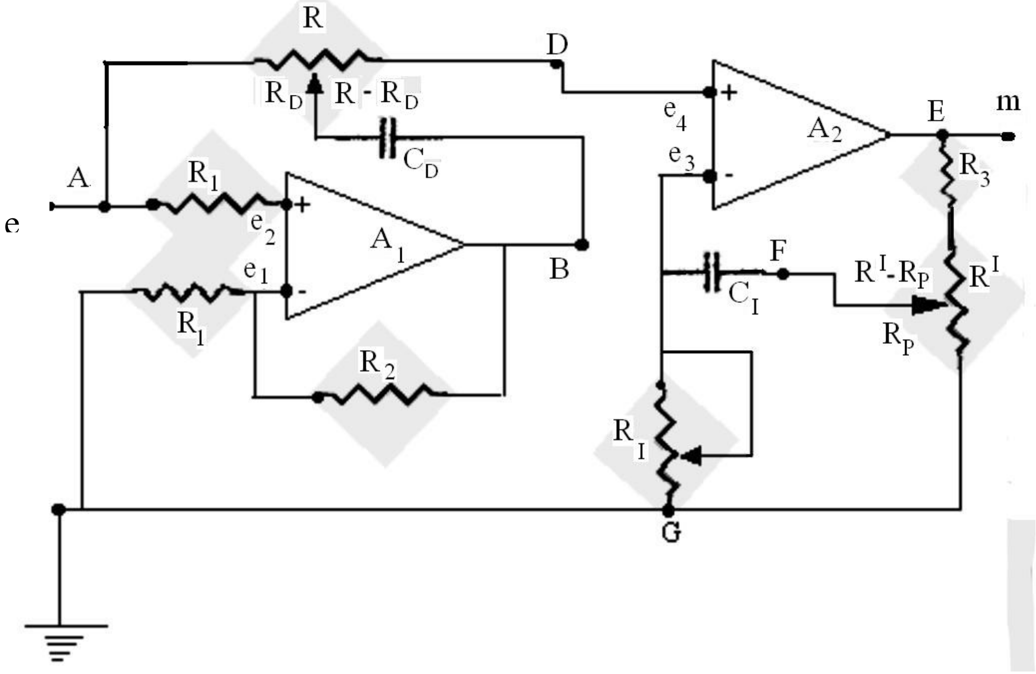


**Fig. 1.** Circuit diagram of $PID$ controller with inverse derivative control action.

i.e.,

$$e_1 \approx e_2 \text{ and } e \approx e_2 \tag{1}$$

Now,

$$e_1 = \frac{R_1}{(R_1 + R_2)} V_B \tag{2}$$

Hence,

$$e \approx e_1 = \frac{R_1}{(R_1 + R_2)} V_B$$

$$V_B = \frac{(R_1 + R_2)}{R_1} e$$

or

$$V_B = \alpha\, e\,, \tag{3}$$

where

$$\alpha = \frac{(R_1 + R_2)}{R_1} \tag{4}$$

Hence, the equivalent circuit of the network of amplifier $A_1$ between the terminals $A \,\&\, D$ may be as shown in Fig. 2 and the Laplace Transform of the circuit is given by

$$I(s) = \frac{[\alpha\, e(s) - e(s)]}{\left(R_D + \frac{1}{C_D\, s}\right)} \tag{5}$$

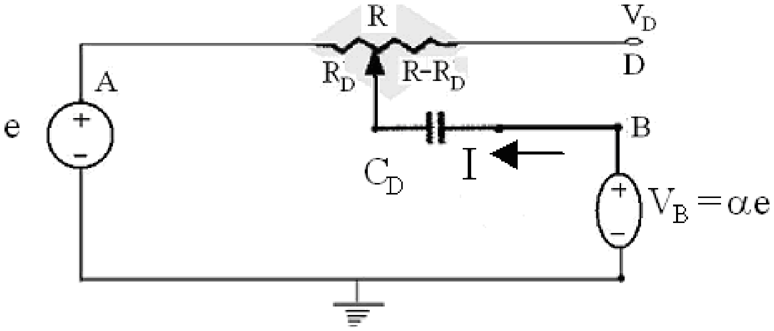


**Fig. 2.** Equivalent circuit of Fig. 1.

Hence in the frequency plane, the voltage signal at $D$ will be given by

$$V_D(s) = e(s) + R_D\; I(s)$$

or

$$V_D(s) = e(s) + R_D\; \frac{[\alpha\, e(s) - e(s)]}{\left(R_D + \frac{1}{C_D\, s}\right)} \tag{6}$$

or

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

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

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

$$V_D(s) = \frac{(1 + T_D\, s)}{\left(1 + \frac{T_D\, s}{\alpha}\right)}\, e(s), \tag{7}$$

where

$$T_D = \alpha\ R_D C_D = \frac{(R_1 + R_2)R_D C_D}{R_1} \tag{8}$$

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.,

$$e_4(s) = V_D(s) \tag{9}$$

Let the voltage signal at the output terminal $E$ of the amplifier $A_2$ should be 'm' and that at its inverting input terminal should 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 Fig. 1 is given by

$$V_F(s) = \frac{R_P}{(R_3 + R')} m(s) = K\ m(s), \tag{10}$$

Where

$$K = \frac{R_P}{(R_3 + R')}. \tag{11}$$

This voltage is being discharged through $R_1$ and $C_1$. Hence the voltage across the capacitor $C_1$ will be given by

$$V_F(s) - e_3(s) = \frac{\frac{1}{C_I\ s}}{\left(R_I + \frac{1}{C_I\ s}\right)} V_F(s)$$

or

$$V_F(s) - e_3(s) = \frac{V_F(s)}{(1 + R_I C_I\ s)}$$

or

$$V_F(s)\left[1 - \frac{1}{1 + R_I C_I\ s}\right] = e_3(s)$$

or

$$V_F(s) = \left(1 + \frac{1}{R_I C_I\ s}\right) e_3(s) \tag{12}$$

From the equation nos. (10) and (12) we have

$$K\ m(s) = \left(1 + \frac{1}{T_I\ s}\right) e_3(s), \tag{13}$$

where

$$T_I = R_I C_I \tag{14}$$

Now for the operational amplifier $A_2$ we have,

$$e_3(s) = e_4(s) \tag{15}$$

From the equation nos. (7), (9), (13) and (15) we have,

$$K\ m(s) = \left(1 + \frac{1}{T_I\ s}\right) V_D(s)$$

or

$$K\ m(s) = \left(1 + \frac{1}{T_I\ s}\right) \frac{(1 + T_D\ s)}{\left(1 + \frac{T_D\ s}{\alpha}\right)} e(s)$$

Thus the transfer function of the controller circuit as shown in Fig. 1 is given by

$$\frac{m(s)}{e(s)} = K_C \left(1 + \frac{1}{T_I\ s}\right) \frac{(1 + T_D\ s)}{\left(1 + \frac{T_D\ s}{\alpha}\right)}, \tag{16}$$

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

$$K_C = \frac{1}{K} = \frac{(R_3 + R')}{R_P}, \qquad T_I = R_I C_I, \qquad T_D = \alpha\ R_D C_D$$

and

$$\alpha = \frac{(R_1 + R_2)}{R_1} \tag{17}$$

## 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 Fig. 3.

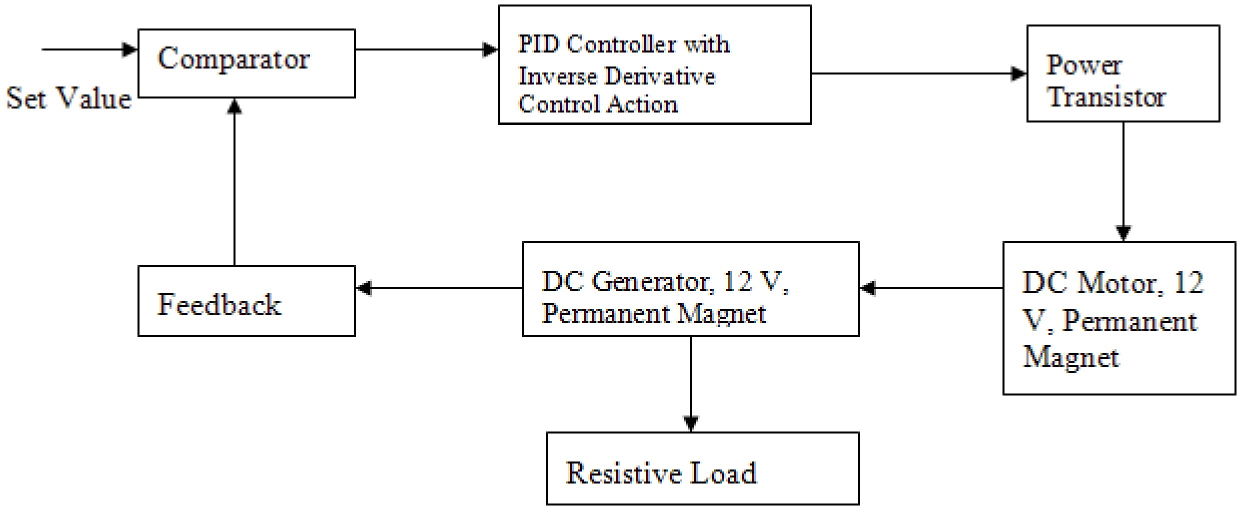


**Fig. 3.** The block of the proposed motor-generator type DC voltage control system.

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 is used as the armature voltage of a low voltage permanent magnet type DC motor through a buffer transistor. Hence the speed of the motor is adjusted until the deviation is reduced to zero and the generator output voltage is maintained at the desired value.

## 4. Experiment

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 Fig. 4.

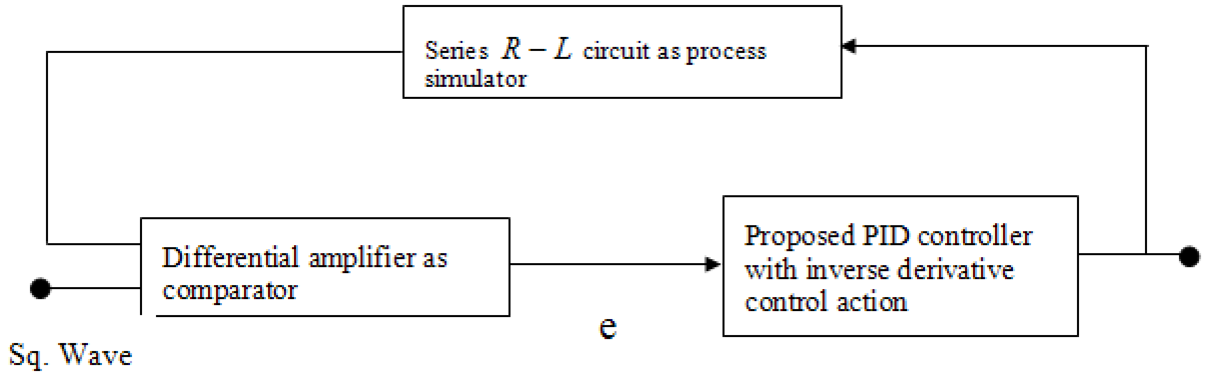


**Fig. 4.** Process analogue circuit of $PID$ controller with inverse derivative control action.

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 observed and printed by storage $CRO$. The waveforms are shown in Fig. 5.

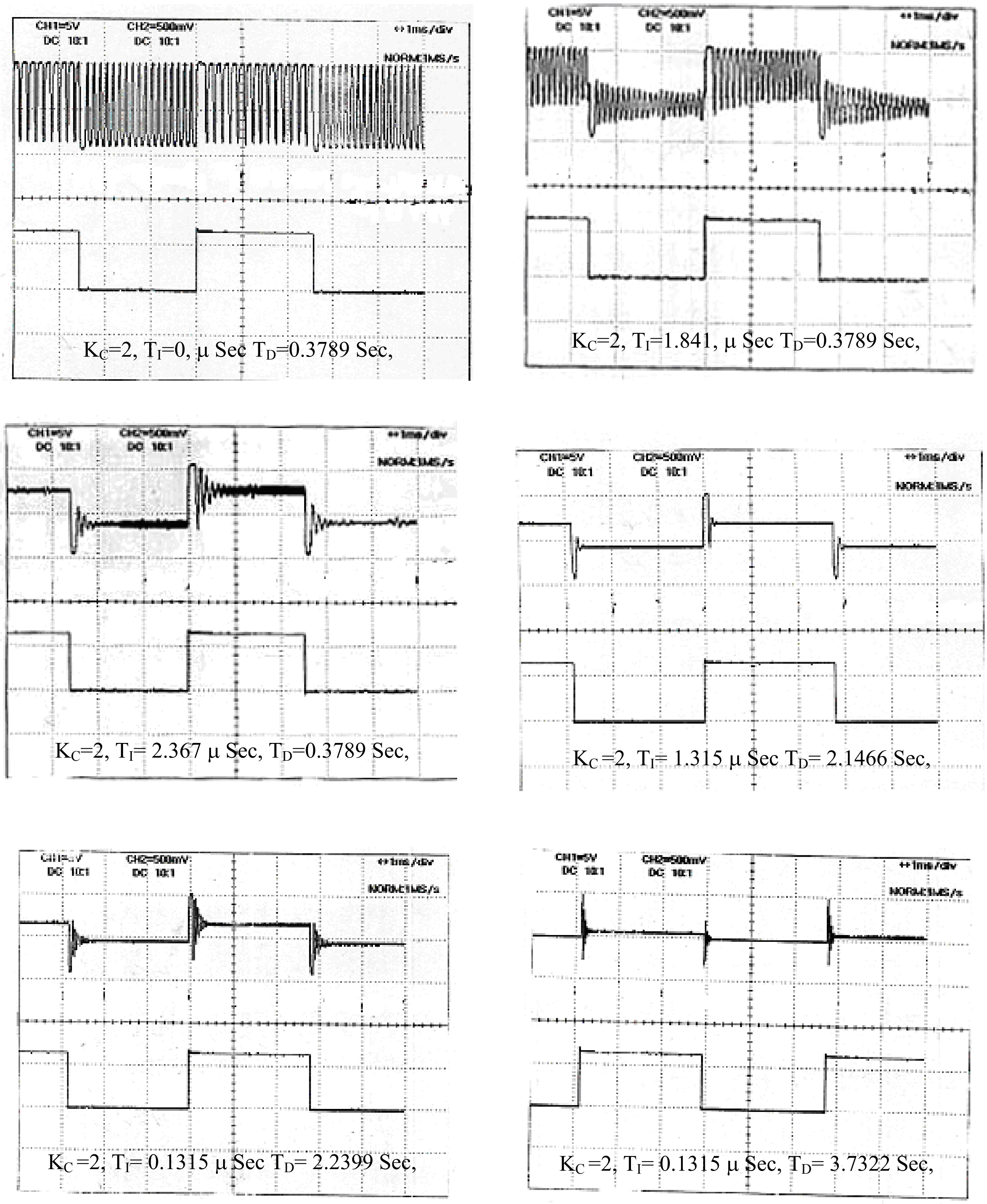
In the second part of the experiment, the performance of the voltage control system of a DC generator using the proposed $PID$ controller with inverse derivative control action has been tested. The experiments are performed to determine the V–I characteristics of the DC generator without and with controller. The V-I characteristic graphs for generator without controller and with controller [$K_C$ = 1.05 ($R_P$ = 9.52 kΩ), $T_I$ = 73.64 μsec ($R_I$ = 0.28 kΩ), $T_D$ = 1.67 m sec ($R_D$ = 0.29 kΩ), α= 3.38 ($R_2$ = 2.38 kΩ)] are shown in Fig. 6 and Fig. 7 respectively. The variation of output voltage at different set points at given load is shown in Fig. 8.

## 5. Discussions

From the equation no. (17) it is found that the adjustments of the controller parameters $K_{C,}T_I$ and $T_D$ by the potentiometer $R_{P,}R_I$ 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 Fig. 5 reveal the satisfactory operation of the controller in process plant. A very good response of the controller to the various parameters has been observed.

From the experimental results shown in Fig. 7, 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 Fig. 8, is found to be quite linear. More accurate results may be obtained by following the proper tuning criteria of the controller [3, 4, 11].



$K_C$=2, $T_I$=0, µ Sec $T_D$=0.3789 Sec,

$K_C$=2, $T_I$=1.841, µ Sec $T_D$=0.3789 Sec,

$K_C$=2, $T_I$= 2.367 µ Sec, $T_D$=0.3789 Sec,

$K_C$ =2, $T_I$= 1.315 µ Sec $T_D$= 2.1466 Sec,

$K_C$ =2, $T_I$= 0.1315 µ Sec $T_D$= 2.2399 Sec,

$K_C$ =2, $T_I$= 0.1315 µ Sec, $T_D$= 3.7322 Sec,

**Fig. 5.** The characteristic of the proposed *PID* controller with inverse derivative control action.

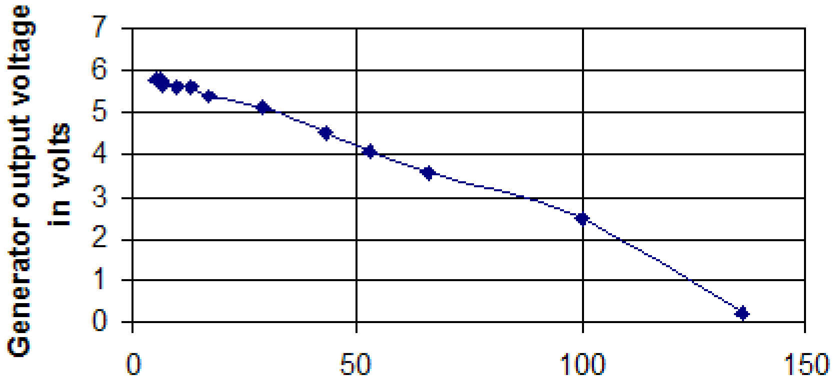


**Fig. 6.** V – I characteristic of DC generator without controller.

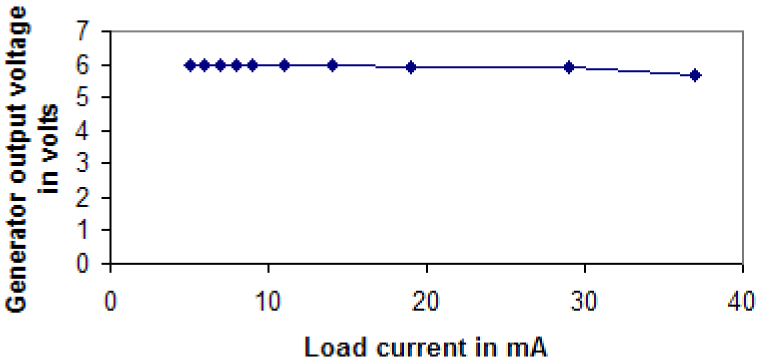


**Fig. 7.** V – I characteristic of DC generator with controller.

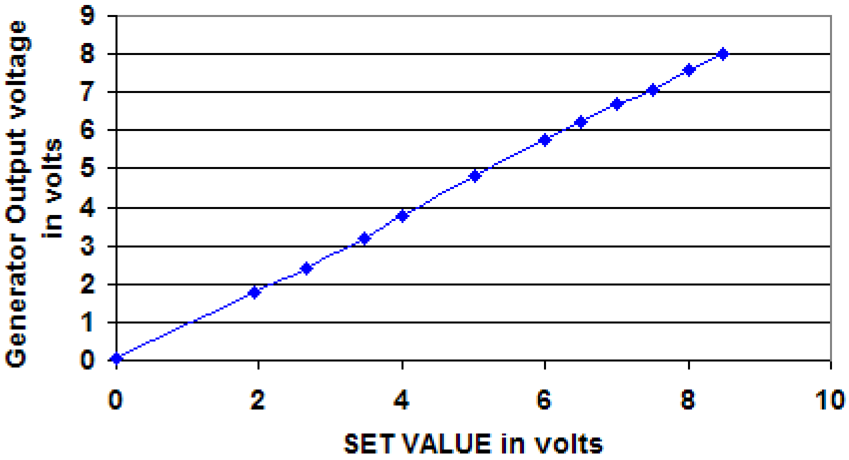


**Fig. 8.** Variation of DC generator output voltage with set point.

The term $1+\frac{T_D\, s}{\alpha}$ in the denominator of the transfer function of the controller as shown in equation number (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 stabilized 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.

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# Guide for Contributors

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## Aims and Scope

*Sensors & Transducers Journal (ISSN 1726-5479)* provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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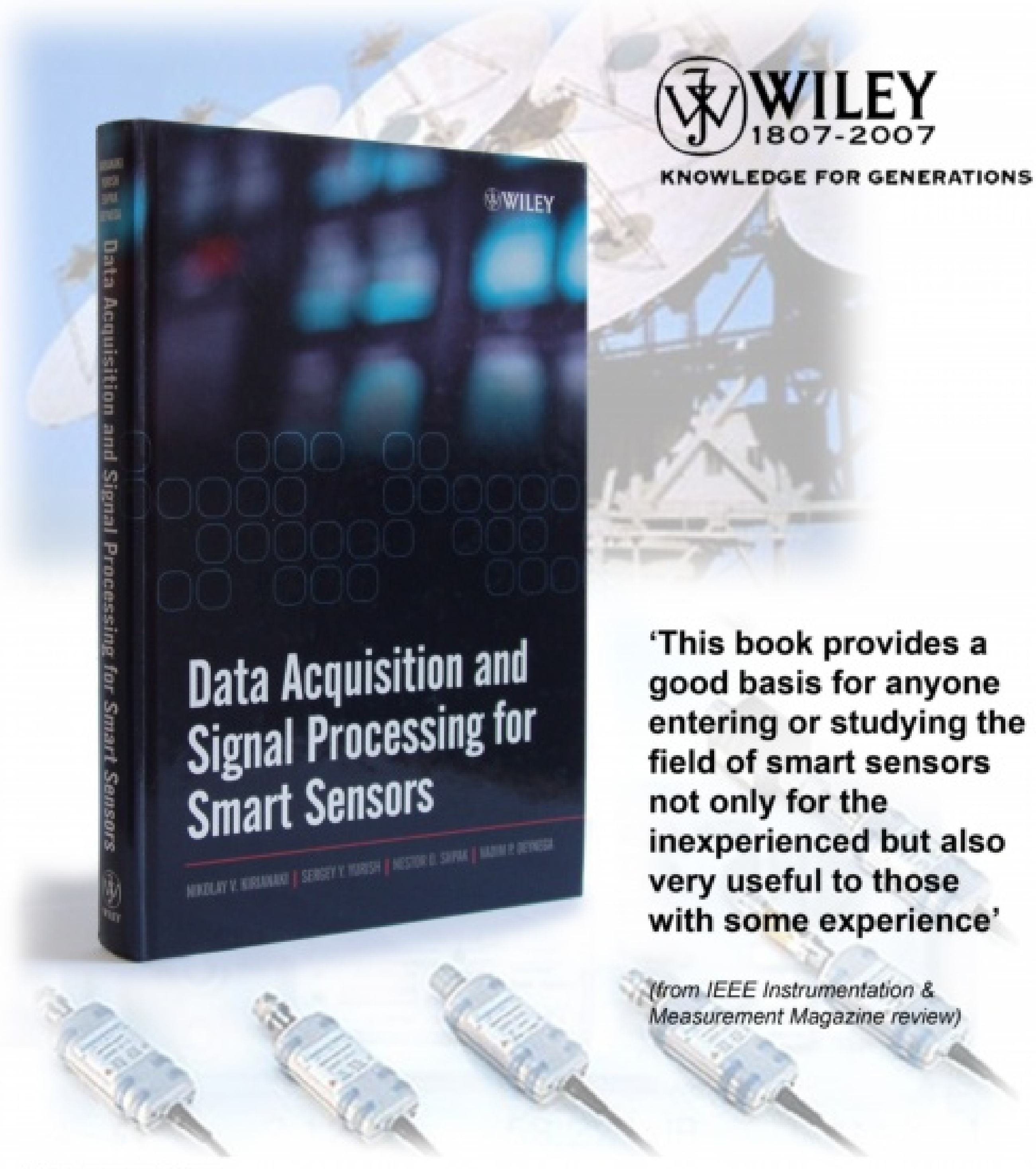

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