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CMOS Programmable PID Controller Circuit Based Analogue Switches

***Abstract**. This paper presents a new programmable proportional (P)-integral (I)-derivative (D) (PID) controller using current conveyor transconductance amplifiers (CCTAs). The proposed PID controller uses the second-generation current conveyor which is the first stage of CCTA to operate as current conveyor analogue switch. The proportional gain, integral time constant and derivative time constant can be controlled electronically using transconductance amplifiers of CCTA. Unlike previous analogue PID controllers, variant P, I, D, PI, PD and PID controllers of this circuit can be programmed by using bias currents without changing any input and output connections. The proposed structure is highly suitable for integrated circuit (IC) implementation by using only grounded passive comments. The proposed programmable PID controller circuits have been simulated using 0.18 µm CMOS process. The simulation results are used to confirm the workability of the proposed circuits. Additionally, the performance evaluation of the proposed programmable PID controller circuit is verified by unit step input for a close-loop system with the second-order low-pass filter in the plant.*

***Streszczenie.** W artykule przedstawiono nowy programowalny kontroler proporcjonalny (P) -całkowyy (I) -różniczkowy (D) (PID) wykorzystujący prądowe wzmacniacze transkonduktancyjne (CCTA). Proponowany regulator PID wykorzystuje konwojer prądowy drugiej generacji, który jest pierwszym stopniem CCTA, który działa jako przełącznik analogowy konwojera prądu. Wzmocnienie proporcjonalne, stała czasowa całkowania i stała czasowa różniczkowania mogą być sterowane elektronicznie za pomocą wzmacniaczy transkonduktancyjnych CCTA. W przeciwieństwie do poprzednich analogowych regulatorów PID, warianty regulatorów P, I, D, PI, PD i PID tego obwodu mogą być programowane przy użyciu prądów polaryzacji bez zmiany jakichkolwiek połączeń wejściowych i wyjściowych. Proponowana struktura jest wysoce odpowiednia do implementacji układu scalonego (IC) przy użyciu tylko uziemionych pasywnych komentarzy. Zaproponowane układy programowalnych sterowników PID zostały zasymulowane przy użyciu procesu 0,18 µm CMOS. (**Programowalne sterowniki PID w technologii CMOS**))*

Keywords: PID controller, programmable, analogue switch, current conveyor transconductance amplifier.
Słowa kluczowe: sterownik PID, wzmacniacz transkonduktancyjny, technologioa CMOS.

Introduction

Second generation current conveyor (CCII) [1] is a basic building block that can be used to realize analogue signal processing circuits. This active building block offers several advantages such as high signal bandwidth, simple circuitry, great linearity and lower power consumption. Thus, many CCII-based analogue circuits such as precision rectifiers, universal voltage-mode and current-mode filters, sinusoidal oscillators and relaxation oscillators have been proposed, for example [2]-[7]. CCII can be applied to realize analogue switches [8], [9] and it is the so-called current conveyor analogue switch (CCAS). There are several applications of CCAS available in technical literature [10]-[15]. In [10], [11], chopper modulator and programmable addition/subtraction voltage are respectively proposed while programmable amplifier and programmable full-wave rectifier are proposed in [12] and [13], respectively. The circuits such as sample-and-hold and digital-to-analogue converter are proposed by [14], [15].

Operational transconductance amplifiers (OTA) are important active building blocks for realizing analogue circuits that normally provide an electronic tuning capability via its transconductance gain. Moreover, OTA-based circuits normally require no resistor and, therefore, are suitable for IC implementation. Recently, a new current-mode active building block, the so-called current conveyor transconductance amplifier (CCTA), has been introduced [16]. This device is comprised of a CCII as input stage and followed by an OTA as an output stage. Therefore, the ad-vantages of both CCII and OTA are included into single CCTA. Several CCTA-based circuits are proposed [17]-[21]. Because the first stage of CCTA is CCII and this CCII can be worked as CCAS. Therefore, CCTA can be worked as programmable active building block. Programmable universal filter using CCTA as active device is proposed by [22].

Proportional-integral-derivative (PID) is a controller system that provides proportional gain, integral time constant and derivative time constant parameters into a single system. PID controller is widely used in most automatic process controls in industry to regulate flow, temperature, pressure and level of the liquids [23]-[25]. There are several electronic PID controllers using different active devices available in the technical literature [26]-[42]. The structures in [26]-[29] use active devices such as operational amplifier (op-amp) [26]-[27], current differencing buffered amplifier (CDBA) [28] and current feedback amplifier (CFA) [29] as active elements. However, these structures use many floating passive components which are not ideal for IC implementation. Several PID controller circuits using grounded passive components have been proposed [30]-[35]. These circuits use different active devices such as OTAs [30], [31] and CCII [32]-[34] while the circuit in [35] uses log-domain circuit. However, these structures provide only PID controller, if either proportional (P), proportional-integral (PI) or proportional-derivative (PD) is required, changing circuit topology is needed. The controller circuits provided P, PI, PD and PID into one single topology have been proposed in [36]-[40]. In [36], [37], PI, PD or PID controller can be achieved by appropriately setting the passive components while in [38], [39] P, PI, PD or PID controller can be achieved by appropriately connecting the input terminals. CCTA-based PID controller circuits were already proposed by [40], [41]. Differential voltage current conveyor transconductance amplifier (DVCCTA)-based PID controller circuit was also proposed in [42]. The structures in [40], [42] are capable to obtain electronically adjustable controller parameters but only a PID controller is obtained while variant PID, PI, PD controllers can be obtained by [41] but these controller circuits can be obtained by changing circuit topology.

In this paper, a new programmable PID controller circuit is presented. The proposed circuit is employed CCTAs as active elements. The variant of P, I, D, PI, PD and PID controllers can be obtained by programming. The parameters such as proportional gain, integral time constant, derivative time constant and the overshoot can be controlled electronically though adjusting the bias current of OTA which is the second stage of CCTA without changing any input and output connections. The proposed structure is suitable for IC implementation by using only grounded passive components. The simulation results are used to confirm the workability of the proposed circuit. Moreover, the performance of the proposed PID controller circuit is verified by unit step input for a close-loop system with the second-order low-pass filter in the plant. The comparison between proposed circuit and some previous electronic controller is summarized in Table 1.

Table 1. Comparison of proposed electronic controller with those of some previouselectronic controllers

Circuits	Number of active elements	Number of resistor (R) & capacitor (C)	Obtaining controllers	Offer electronically tunable controller parameters	Technique for obtaining variant controllers
Proposed circuit	3-CCTA	2-C & 5-R	P, I, D, PI, PD, PID	Yes	Programming
Ref. [26]	4-opamp	2-C & 8-R	PID	No	-
Ref. [27] (Fig. 3) (Fig. 6) (Fig. 7)	1-opamp 1-OTA 1-CCII	3-C & 4-R 3-C & 3-R 3-C & 4-R	PID PID PID	No No No	- - -
Ref. [28]	4-CDBA	2-C & 8-R	PID	No	-
Ref. [29]	6-CFA	2-C & 12-R	PID	No	-
Ref. [30]	8-OTA	2-C	PID	Yes	-
Ref. [31]	6-TA	2-C	PID	Yes	-
Ref. [32]	8-CCCII	2-C & 2-R	PID	Yes	-
Ref. [33]	2-CCII	2-C & 3-R	Yes	No	-
Ref. [34]	1-CCII	2-C, 2-R	PID	No	-
Ref. [35]	22-BJT, 15-CS	2-C	PID	Yes	-
Ref. [36]	3-CCII	2-C & 4-R	PID	No	-
Ref. [37] (Fig. 2) (Fig. 3) (Fig. 4)	3-CCCDBA 3-CCCDBA 4-CCCDBA	1-C 1-C 2-C	PI PD PID	Yes Yes Yes	- - -
Ref. [38]	3-DDCC	2-C & 4-R	P, I, D, PI, PD, PID	No	Choosing input
Ref. [39]	2-FDCCII	2-C & 6-R	P, I, D, PI, PD, PID	No	Choosing input
Ref. [40]	2-CCCTA	2-C & 1-R	PID	Yes	-
Ref. [41] (Fig. 2) (Fig. 3) (Fig. 4)	1-CCTA 1-CCTA 1-CCTA	2-C & 2-R 2-C & 2-R 2-C & 2-R	PI PD PID	No No No	- - -
Ref. [42]	3-DVCCTA	2-C & 7-R	PID	Yes	-

Note: op-amp = operational amplifier, CDBA = current differential buffer amplifier, CFA = current feedback amplifier, TA = transconductance amplifier, CCCII = current-controlled current conveyor, BJT = bipolar junction transistor, CS = current source, CCCDBA = current controlled current differential buffer amplifier, DDCC = differential different current conveyor, FDCCII = fully differential current conveyor, CCCTA = current-controlled current conveyor transconductance amplifier, DVCCTA = differential voltage current conveyor transconductance amplifier.

Proposed circuit

Conventional CCII has three terminals; x, y and z-terminals, the voltage and current relations of these terminals of ideal CCII can be given by

$$\begin{pmatrix} I_y \\ V_x \\ I_z \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} I_x \\ V_y \\ V_z \end{pmatrix} \tag{1}$$

There are several CMOS implementation for CCIIs available in literature, for example [43]-[46]. The CMOS implementation of CCII used in this paper is shown in Fig. 1 [47]. From the operation of CCAS in [9], voltage from y-terminal to x-terminal and current from x-terminal to z-terminal can be transferred by CCII if appropriately bias current I_c is supplied. Thus, CCII can be operated as CCAS and turn-on and turn-off of switch can be controlled by a constant current source. The switch will be turned-on, if a constant current source is supplied. The voltage from y-terminal to x-terminal and the current from x-terminal to z-terminal can be transferred. Inversely, the switch will be turned-off, if the constant current source I_c is not supplied (I_c = 0 A). In this case, CCAS is cut-off, resulting in the voltage from y-terminal to x-terminal and the current from x-terminal to z-terminal cannot be transferred.

The CCTA is the active building block that included both CCII and OTA into single active device [16]; the first stage of CCTA is CCII and the second one is OTA. The CMOS implementation of CCTA can be shown in Fig. 2. Transistors M_1 to M_{13} are used to implement the CCII which is similar the circuit in Fig. 1 while transistors M_{14} to M_{21} are used to implement the OTA. Conventional CCTA has four terminals; x-, y-, z- and o-terminals, the voltage and current relations of four terminals of the ideal CCTA can be given by

$$\begin{pmatrix} I_y \\ V_x \\ I_z \\ I_o \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & g_m & 0 \end{pmatrix} \begin{pmatrix} I_x \\ V_y \\ V_z \\ V_o \end{pmatrix} \tag{2}$$

where g_m is the transconductance gain of CCTA. Generally, y-, z-, and o-terminals possess high impedance level while x-terminal possesses low impedance level. From Fig. 2, assuming that the transistors M_{14} and M_{15} are identical and the operating in saturation region all current mirrors are matched, transconductance gain of CCTA can be expressed by

$$g_m = \sqrt{\mu_n C_{ox}\left(\frac{W}{L}\right) I_b} \tag{3}$$

where I_b is the bias current, μ_n is the carrier mobility of nMOS, C_{ox} is the gate-oxide capacitance per unit area, W and L are the channel width and length, respectively. From (3), it is seemed that g_m-value of CCTA can be controlled electronically by I_b.

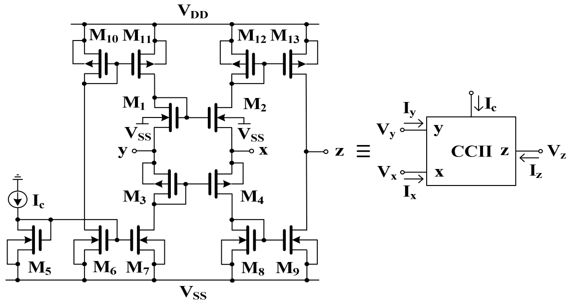


Fig.1. CMOS implementation of CCII

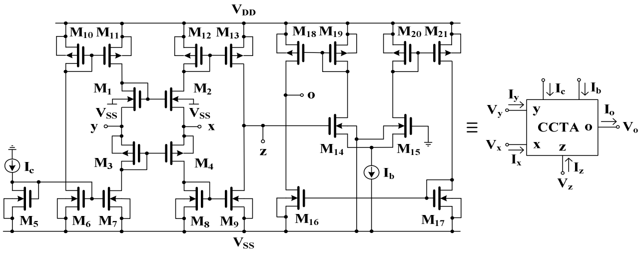
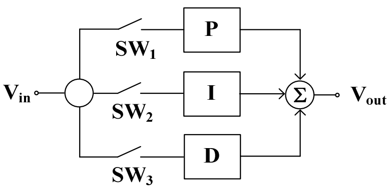
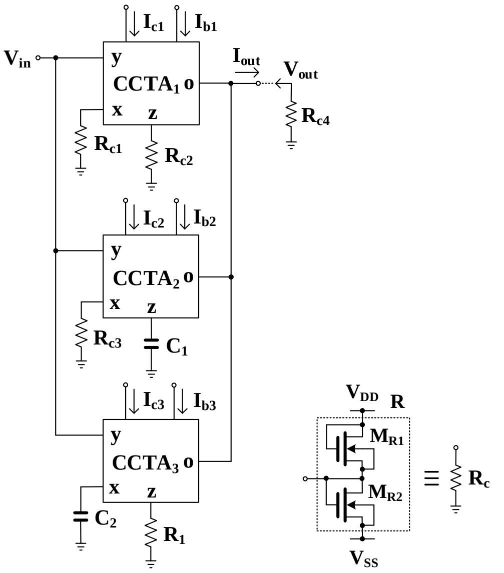


Fig.2. CMOS implementation of CCTA



(a) Block diagram of the proposed programmable PID controller by analogue switches



(b) Schematic (c) MOS resistor

Fig.3. Proposed CMOS programmable PID control circuit based analogue switches

The proposed CMOS programmable PID control circuit based analogue switches is shown in Fig. 3. It can be realized to use the principle of switches for P, I, D, PI, PD, ID and PID by SW_1, SW_2, SW_3 and together all, respectively, as shown in Fig. 3(a). The circuit is composed of thee CCTAs, two grounded capacitors and five grounded resistors as shown in Fig. 3(b). It is based on the development from [48]. The input voltage V_{in} of the circuit is connected at the high impedance terminal of the CCTAs (y-terminal); hence the circuit has the feature of high-input impedance. The circuit in Fig. 3(b) will work as voltage-mode if R_{c4} is connected and it will work as transconductance-mode if R_{c4} is removed. Resistors R_{c1} to R_{c4} can be implemented using two-matched MOS transistor as shown in Fig. 3(c). Assume that M_{R1} and M_{R2} are matched and operated in saturation regions, R_c-value can be determined [49] as

$$R_c = \frac{1}{2\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{DD}\text{-}V_{TH})} \tag{4}$$

where V_{DD} (V_{DD}=-V_{SS}) and V_{TH} are the supply voltage and threshold voltage, respectively.

Obtaining variant P, I, D, PI, PD and PID controllers can be obtained by appropriately programming the bias currents I_{c1}, I_{c2} and I_{c3}. Using the operation of CCAS [8] - [9], if I_{c1}, I_{c2} and I_{c3} are not supplied (0 A), all CCIIs will be turned-off (switch "open"). Conversely, the switches will be turned-on (switch "close") if I_{c1}, I_{c2} and I_{c3} are supplied by constant current source. Letting SW_1, SW_2 and SW_3 are respectively controlled by I_{c1}, I_{c2} and I_{c3}, V_{in} is the input and V_{out} is the output, the transfer functions of the proposed circuit in Fig. 3(b) can be expressed as

$$H(s) = \frac{g_{m1}R_{c2}R_{c4}}{R_{c1}}\left(SW_1\right)+\frac{g_{m2}R_{c4}}{sC_1R_{c3}}\left(SW_2\right)+sC_2g_{m3}R_1R_{c4}\left(SW_3\right) \tag{5}$$

In addition, if V_{in} is the input and I_{out} is the output, the transfer functions of transconductance-mode of electronic controller can be expressed by

$$H(s) = \frac{g_{m1}R_{c2}}{R_{c1}}\left(SW_1\right)+\frac{g_{m2}}{sC_1R_{c3}}\left(SW_2\right)+sC_2R_1g_{m3}\left(SW_3\right) \tag{6}$$

The proposed programmable PID electronic controller can be programmed via SW_1, SW_2 and SW_3 using I_{c1}, I_{c2} and I_{c3}. Variant controllers can be obtained as Table 2.

Table 2. Using programmable PID electronic controller circuit

SW_1	SW_2	SW_3	Type of controller
1	0	0	P
0	1	0	I
0	0	1	D
1	1	0	PI
1	0	1	PD
0	1	1	ID
1	1	1	PID

By compared the conventional of PID controller using $H(s)=K_P+\left(1/sT_I\right)+sT_D$ with (5), the PID controller parameters; K_P, T_I and T_D can be expressed, respectively as

$$K_P = \frac{g_{m1}R_{c2}R_{c4}}{R_{c1}} \tag{7}$$

$$T_I = \frac{g_{m2}R_{c4}}{sC_1R_{c3}} \tag{8}$$

$$T_D = sC_2g_{m3}R_1R_{c4} \tag{9}$$

From (7) - (9), the proportion gain (K_P) and the integral time constant (T_I) can be controlled electronically by adjusting the values of g_{m1} and g_{m2}, respectively, while the derivative time constant (T_D) can be controlled by adjusting the value of g_{m3} and R_1. If R_1 is used, electronically tuneable of T_D can be obtained by replacing R_1 with electronic-controlled circuit.

Non-ideal analysis

Taking the non-ideal CCTA into the account, (2) can be rewritten as

$$\begin{pmatrix} I_y \\ V_x \\ I_z \\ I_o \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \beta & 0 & 0 \\ \alpha & 0 & 0 & 0 \\ 0 & 0 & g_{mn} & 0 \end{pmatrix} \begin{pmatrix} I_x \\ V_y \\ V_z \\ V_o \end{pmatrix} \tag{10}$$

where $\beta(s) = \beta = 1-\varepsilon_v$ and $\varepsilon_v(|\varepsilon_v| \ll 1)$ denote the voltage tracking error from y-terminal to x-terminal, $\alpha(s) = \alpha = 1-\varepsilon_i$ and $\varepsilon_i(|\varepsilon_i| \ll 1)$ denote the current tracking error from x-terminal to z-terminal, $g_{mn} \approx g_m(1-\tau s)$ denote the non-ideality of transconductance gain of CCTA, where $\tau = 1/\omega_g$ and ω_g denote the first-order high frequency pole. Re-analysis the proposed electronic controller in Fig. 3 by using (10), the controller parameters K_P, T_I and T_D can be respectively rewritten by (11). Then, from (8), the tracking errors slightly change the controller parameters K_P, T_I and T_D.

$$\begin{aligned} H(s) &= \alpha_1\beta_1 \frac{g_{mn1}R_{c2}R_{c4}}{R_{c1}}(SW_1) \\ &+ \alpha_2\beta_2 \frac{g_{mn2}R_{c4}}{sC_1R_{c3}}(SW_2) \\ &+ sC_2R_1 g_{mn3}R_{c4}\alpha_3\beta_3(SW_3) \end{aligned} \tag{11}$$

Simulation results

The proposed programmable PID electronic controller in Fig. 3(a) was verified through PSPICE simulators using 0.18 µm TSMC CMOS parameters [50]. The CCTA in Fig. 2 was simulated using aspect ratios as listed in Table 3 and its summarized performances were shown in Table 4.

Table 3. Transistors aspect ratios of Fig. 2

MOS transistors	W/L(µm/µm)
M_1-M_2, M_9-M_{13}	3/0.3
M_3-M_4, M_5-M_8	8/0.3
M_{14}-M_{15}	10/0.8
M_{16}-M_{19}	25/0.8
M_{20}-M_{21}	8/0.8
M_{R1}, M_{R2}	0.63/0.3

Table 4. Summarized performances of CCTA of Fig. 2

Parameters	Value
Technology	0.18 µm
Supply voltage	±0.9 V
Voltage gain (V_x/V_y)	0.986
Current gain (I_z/I_x)	1.1
g_m (I_b = 2 – 300 µA)	28 - 909 µS
-3dB bandwidth (I_b = 300 µA)	369 MHz
-3dB bandwidth: V_x/V_y I_z/I_x	5.8 GHz 880 MHz
R_y//C_y	7 GΩ//1 fF
R_x//L_x	2 kΩ//0.38 µH
R_z//C_z	150 kΩ//33.9 fF
R_o//C_o	13 kΩ//3.64 fF

The power supplies were given as $V_{DD} = -V_{SS} = 0.9$ V. The CCTA used I_{c1}, I_{c2} and I_{c3} of 20 µA for logic "1" and I_{c1}, I_{c2} and I_{c3} of 0 A for logic "0". As an example, the resistor R_1 = 65 kΩ, the capacitors $C_1 = C_2$ = 86 pF, the bias currents I_{b1} = 55 µA (g_{m1} = 400 µS), I_{b2} = 24 µA (g_{m2} = 228 µS) and I_{b3} = 30 µA (g_{m3} = 267 µS) were given. This setting was designed by $K_P = 1$, $T_I = 0.37\times10^{-6}$ s and $T_D = 5.59\times10^{-6}$ s. Fig. 4 shows simulated frequency responses of PI controller when the digital signals were $SW_1 = 1$, $SW_2 = 1$ and $SW_3 = 0$. Fig. 5 shows simulated frequency responses of PD controller when the digital signals were $SW_1 = 1$, $SW_2 = 0$ and $SW_3 = 1$. Fig. 6 shows simulated frequency and phase responses of the proposed PID controller when the digital signals were $SW_1 = 1$, $SW_2 = 1$ and $SW_3 = 1$. From Fig. 6, the integral frequency (f_I) and the derivative frequency (f_D) were found as about 21 kHz and 408 kHz, respectively. The power consumption of this case was 1.16 mW. Therefore, it was evident from Figs. 4 to 6 that PI, PD and PID controllers can be obtained into a single topology. In addition, if P controller was required, the digital signals of $SW_1 = 1$, $SW_2 = 0$ and $SW_3 = 0$ were needed. From simulation result, the parameter K_P of P controller was 0 dB.

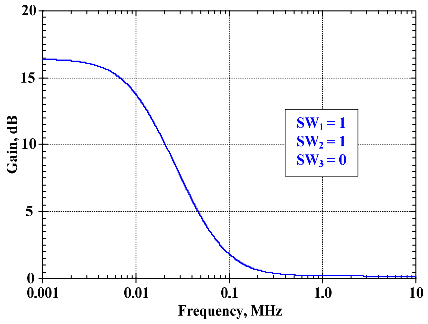


Fig.4. Simulated frequency response of PI controller

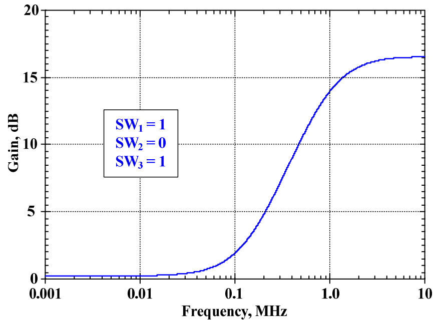


Fig.5. Simulated frequency response of PD controller

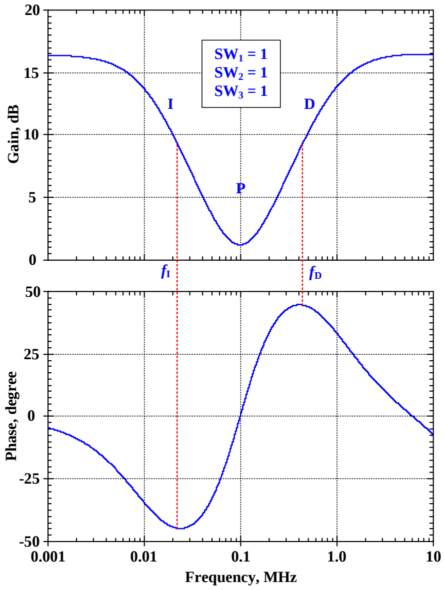
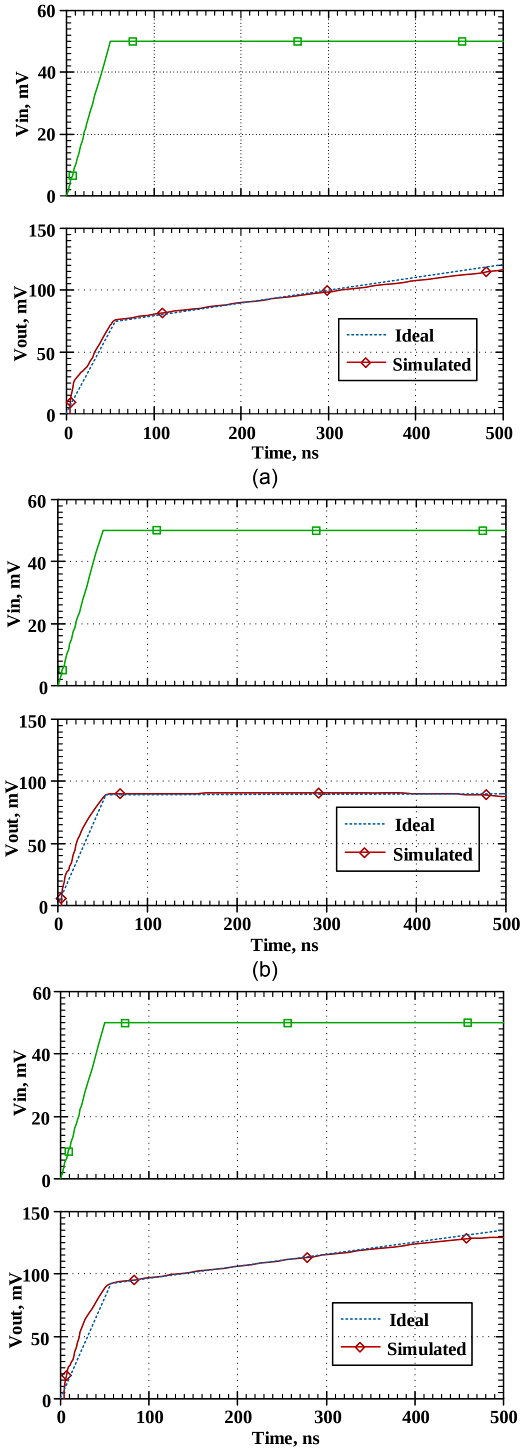


Fig.6. Simulated frequency response of PID controller

Next, the unit step voltage input is 50 mV with 50 ns for the rise time, the resistor R_1 = 65 kΩ, the capacitors C1 = C2 = 86 pF, the bias currents I_{b1} = 55 µA (g_{m1} = 400 µS), I_{b2} = 40 µA (g_{m2} = 323 µS) and I_{b3} = 4 µA (g_{m3} = 52 µS) were given for obtaining the performance evaluation of the proposed controller their time domain responses. The transistors aspect ratios for M_{R1} and M_{R2} of R_{c1}, R_{c2} and R_{c3} are used by Table 3. The parameters $K_P = 1$, $T_I = 0.26\times10^{-6}$ s and $T_D = 0.73\times10^{-6}$ s are set, for the proposed PI controller by using programmable electronic controller circuit from Table 2, the logical can be selected by $SW_1 = 1$, $SW_2 = 1$ and $SW_3 = 0$ which mean I_{c1} and I_{c2} are 20 µA but I_{c3} is 0 A.

The simulated time domain responses of the ideal and simulated PI controller is shown in Fig. 7(a). Then, by using programmable electronic controller circuit from Table 2 for PD controller, I_{c1} and I_{c3} are 20 μA but I_{c2} is 0 A that the logical can be selected by $SW_1 = 1$, $SW_2 = 0$ and $SW_3 = 1$. The simulated time domain responses of the ideal and simulated PD controller with unit step input is shown in Fig. 7(b). However, the simulated time domain responses of the ideal and simulated PID controller is shown in Fig. 7(c) by using programmable electronic controller circuit from Table 2, I_{c1}, I_{c2} and I_{c3} are 20 μA that the logical can be selected by $SW_1 = 1$, $SW_2 = 1$ and $SW_3 = 1$, respectively.



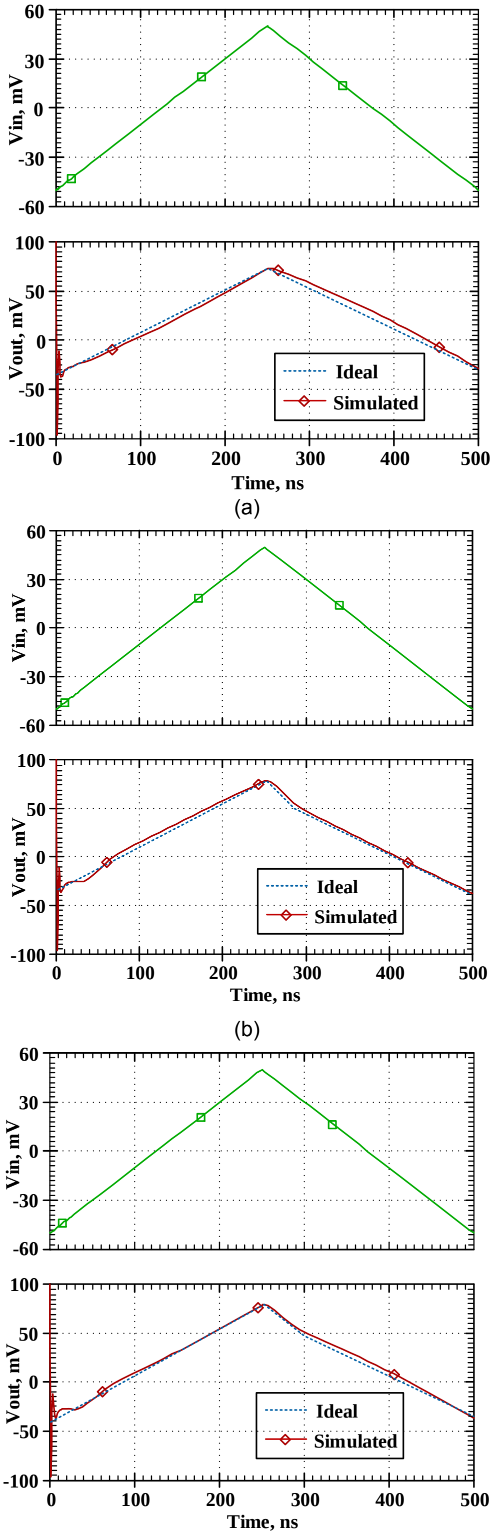
(a)

(b)

(c)

Fig.7. Simulated time domain response of proposed controller with step input, a) PI controller, b) PD controller and c) PID controller

Moreover, 50 mV peak triangular input voltage is applied and the component values are chosen with the same previously values but another changes are $C_2 = 5$ pF and $I_{b3} = 2$ μA ($g_{m2} = 28$ μS). The time domain responses of the ideal and simulated PI, PD and PID controller with triangular input voltage are shown in Fig. 8 (a) – 8(c). In addition, Fig. 7 - 8 are shown that the proposed PID controller can be programmed by electronic controller circuit without changing any input and output connections.



(a)

(b)

(c)

Fig.8. Simulated time domain response of proposed controller with triangular input, a) PI controller, b) PD controller and c) PID controller

Furthermore, the close-loop system as shown in Fig. 9 is used to verify the proposed PID controller circuit by the second order in the plant. The performance of the second order in the plant is analysed by low-pass filter that has been presented in [22].

Fig.9. Proposed PID for application with the second order close-loop system in the plant

The PID controller with using the programmable from Table. 2 is used to assess the performance of the proposed PID for the application with the second order close-loop system in the plant that is shown in the Fig. 9. Then, Fig. 10 shows the effect on the step response 100 mV peak input to the close-loop system of the proposed PID controller that the logical can be selected by SW_1 = 1, SW_2 = 1 and SW_3 = 1, the parameters K_P = 1, $T_I = 0.23\times10^{-6}$ s, $T_D = 0.096\times10^{-6}$ s and overshoot of roughly 15 %. Additionally, Fig. 11 shows the bias current of OTA adjusting for PID controller without changing any input and output connections that can be controlled the overshoot of the proposed PID circuit by I_{b3}. The parameters values of K_P, T_I, T_D and overshoot percentage when I_{b3} is adjusted that are shown in Table. 5.

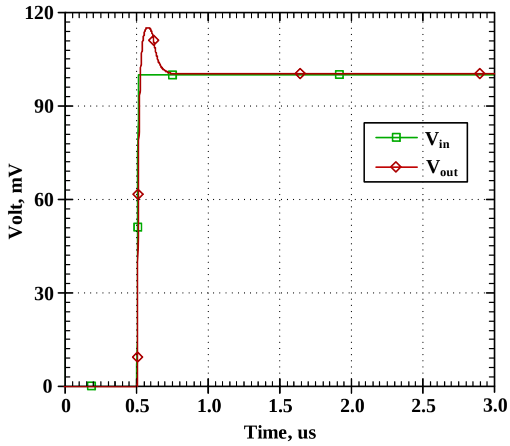


Fig.10. Simulated step response of the second order close-loop system in the plant with PID controller

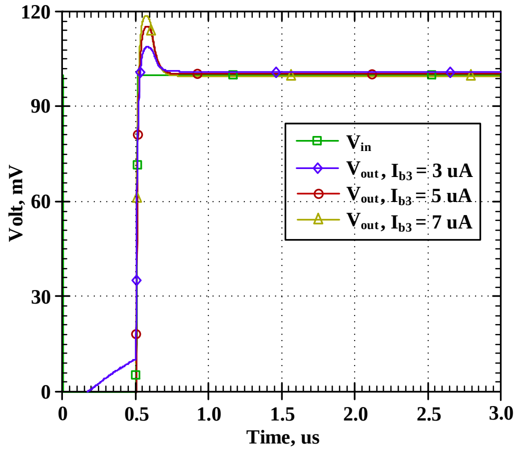


Fig.11. Simulated step response of the second order close-loop system in the plant with PID controller

Table 5. The values of K_P, T_I, T_D and overshoot percentage of Fig. 11

I_{b3} (μA)	K_P	T_I ($\times10^{-6}$ s)	T_D ($\times10^{-6}$ s)	Overshoot (%)
3	1	0.23	0.061	0.11
5	1	0.23	0.096	0.15
7	1	0.23	0.128	0.18

Conclusions

In this paper, a new programmable electronic controller employing three CCTAs, two grounded capacitors and five resistors is presented based analogue switches. The use of grounded passive components makes the proposed structure attractive for IC implementation. The controllers such as P, I, D, PI, PD, ID and PID controllers can be obtained by programming the bias currents of CCTAs. The controller parameters such as proportional gain, integral time constant and derivative time constant can be controlled electronically by adjusting the bias currents. Moreover, the proposed PID controller circuit is verified by unit step input for a close-loop system with the second-order low-pass filter in the plant. The overshoot in the system can be adjusted by bias current of OTA without changing any input and output connections. PSPICE simulation results are included to show workability of the proposed circuit.

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