ECONOMICAL AND ACCURATE DIGITALLY PROGRAMMABLE DUAL-POLARITY GAIN AMPLIFIER**

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A digitally programmable, dual-polarity gain amplifier is proposed. It uses total resistance less than those presented earlier. The effect of on-resistance of switches can be fully compensated.

1. INTRODUCTION

Some amplifiers that can be programmed for dual-polarity with a single switch, and use minimum number of resistors were presented in [1]. However, in IC fabrication it is preferable to have less total resistance rather than the number of resistors. In this paper, a new amplifier that has not only the facility of programming the polarity of the gain with a single switch, but also possesses total resistance considerably less, is proposed.

2. PROGRAMMABLE AMPLIFIER CONFIGURATION

The proposed amplifier configuration is shown in Fig. 1. Gain of the amplifier is:

\[
\frac{V_0}{V_i} = \begin{cases} 
  K_- = -p & \text{when } S \text{ closed} \\
  K_+ = \frac{1 + p + b/c}{1 + d} - p & \text{when } S \text{ open}
\end{cases}
\]

where

\[
p = a + b + \frac{ab}{c},
\]

\[
a = \frac{R_2}{R_1}, \quad b = \frac{R_3}{R_1}, \quad c = \frac{R_4}{R_1}, \quad d = \frac{R_5}{R_6}.
\]

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It is obvious from eqns (1) and (2) that polarity of the gain can be controlled by the switch $S$. Conditions for $K_-= -K_+ = K$ imposed by eqns. (1) and (2) are

$$K = a + b + \frac{ab}{c}$$

(4)

and

$$d = \left(1 + \frac{b}{c} - K\right)/(2K)$$

(5)

For $d$ to be non-negative, eqn. (5) demands

$$\left(1 + \frac{b}{c}\right) \geq K$$

(6)

Since, for finite gain, $1 \leq K < \infty$, eqns (4) and (5) imply

$$c \neq 0, a \neq \infty, b \neq \infty; b \neq 0, c \neq \infty, d \neq \infty.$$  

(7)

Out of many possibilities that satisfy eqns. (4), (5), we consider the following, which reduces one resistor

**Case A:** $a = 0$  \hspace{1em} $R_2 = 0$, or $R_1 = \infty$

**Case B:** $d = 0$  \hspace{1em} $R_5 = 0$, or $R_6 = \infty$.

$R_1 = \infty$ is not admissible, as it will reduce, see eqn. (3), $b = c = 0$, the undesirable conditions in eqn. (7). Also, $R_5$ cannot be zero, because when $S$ is closed (for
negative gains), input will be shorted. However, $R_s$ can be replaced by a switch $\bar{S}$, which opens when $S$ is closed and vice versa.

Case A: $R_2 = 0$

In this case the circuit of Fig. 1 reduces to a circuit that has been studied in detail in Ref. [1]. Out of the four cases, case (iv) in [1] restricts the gain $\leq 1$. Being a case of an attenuator (and not an amplifier), it will not be considered.

For the remaining cases, the amplifier circuits are shown in Fig. 2 (a), (b) and (c), where we have modified the resistances so as to yield an input resistance $\geq R$. In Fig. (c), the resistance $R_4$ is replaced by a switch $\bar{S}_1$, which opens when $S_1$ closes and vice versa. The total resistances for a specific gain $K$ for the three circuits are, respectively,

$$R_{ta} = 6(1 + K)R \quad K \geq 0$$  \hspace{1cm} (8a)

$$R_{tb} = 2\left(4 + \frac{2K^2}{2K - 1}\right)R \quad K \geq \frac{1}{2}$$  \hspace{1cm} (8b)

$$R_{tc} = \left(1 + \frac{K^2}{K - 1}\right)R \quad K \geq 1.$$  \hspace{1cm} (8c)

It can be verified that

$$R_{tb}, R_{tc} < R_{ta}, \quad \text{for all } K$$  \hspace{1cm} (9a)

$$R_{tc} \leq R_{tb}, \quad K = 1, K \geq 1.112$$  \hspace{1cm} (9b)

Case B: $R_6 = \infty$, $R_5$ replaced by a switch $\bar{S}$.

For this case, the design relations are

$$R_1 = R \quad (\text{For } R_{in} \geq R)$$  \hspace{1cm} (10a)

$$R_2 = aR$$  \hspace{1cm} (10b)

$$R_3 = K(1 - a)R$$  \hspace{1cm} (10c)

$$R_4 = \frac{K(1 - a)}{K - 1}R$$  \hspace{1cm} (10d)

The total resistance for a specific gain $K$ is

$$R_t = \left(1 + a + \frac{K^2(1 - a)}{K - 1}\right)R$$  \hspace{1cm} (11)

From eqns. (8) and (11), we see that $R_t \leq R_{t1}, R_{t2}, R_{t3}$ for all values of $a \leq 1$. 
FIGURE 2 Amplifier configurations reported in reference [1]
Thus, the present circuit has the least value for $R_t$ for any specific gain $K$. However, $a$ cannot be 1, because $a = 1$ reduces $R_3 = R_4 = 0$ and consequently, the output will be shorted. $R_t$ decreases with increase in $a$. Therefore, for minimum $R_t$, $a$ should be chosen as close as possible to unity. We choose $a = 0.9$ to yield low $R_t$ and also reasonably small spread in resistance values given by eqn. (10).

The complete set of design relations are

$$R_1 = R, R_2 = 0.9R, R_3 = \frac{KR}{10}, R_4 = \frac{K}{10(K-1)}R, R_6 = 0$$

$$R_t = \left(1.9 + \frac{K^2}{10(K-1)}\right)R$$

3. IMPLEMENTATION

Fig. 3 gives the amplifier with $N$ gain values programmed. It uses ($N + 2$) switches, one more than the minimum value. However, the on-resistances $R_s$ of the switches affect the gain accuracy. The effect can be made negligible by
choosing the lowest resistance much higher than maximum \( R_s \), but this means using high-valued resistances, increasing the total resistance. To fully compensate for the effect of \( R_s \), an alternative implementation is given in Fig. 4. Now, each resistance has a switch in series. Thus, the effect of on-resistance of each switch can be compensated for by reducing the resistance value by the on-resistance of the switch in series with it. Assuming that all the switches have equal drift-free on-resistance \( R_s \), another circuit implementation is shown in Fig. 5 where

\[
\begin{align*}
  r_{3n} &= \begin{cases} 
    R_{3n} - R_{3n-1}, & 2 \leq n \leq N \\
    R_{31}, & n = 1 
  \end{cases} \\
  r_{4n} &= \begin{cases} 
    R_{4n} - R_{4n+1}, & 1 \leq n \leq N-1, \quad K_1 \neq 1 \\
    R_{4n} - R_{4n+1}, & 2 \leq n \leq N-1, \quad K_1 = 1 \\
    \infty, & n = 1, \quad K_1 = 1 
  \end{cases}
\end{align*}
\]

(14a) \hspace{1cm} (14b)

The total resistance of the circuit is now given by

\[
R_t = \left( 1.9 + \frac{K_N}{10} + \frac{K_0}{10(K_0 - 1)} \right) R
\]

(15)

where \( K_0 = K_{\min} > 1, \quad K_n > K_{n-1} \quad (n = 1, 2, \cdots, N) \). To have a quantitative feel,
Switch $S$ is replaced by the internal switch of 555.

(a)

(b)

FIGURE 6 (a) Digitally programmable function generator (b) Waveforms for (i) Digital input $D_1$ (ii) Digital input $D_2$, $D_2 > D_1$. 
the $R$, for implementing 10 gain values (gain 1, 2, 10 and the remaining seven of arbitrary values lying between 2 and 10) and choosing $R = 10K$, eqn. (15) gives $R = 31K \Omega$.

4. APPLICATION

A typical application of a dual-polarity controlled amplifier is shown in Fig. 6 in realizing a function generator whose frequency can be digitally programmed.

5. CONCLUSION

A digitally programmable, dual-polarity gain amplifier has been presented. Though it uses more resistors, the total resistance is less than those in Ref. [1]. Thus, the former amplifier is superior to the latter ones for integration. The amplifier can be fully compensated for individual on-resistances of the switches (as shown in Fig. 4). If the on-resistance is assumed to be the same for all the switches, the total resistance can be further reduced (as shown in Fig. 5). An application of a dual-polarity programmable amplifier in realizing a programmable function generator has been given.

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REFERENCE
