Bulgarian Journal of Physics 25 Nos 3/4 (1998) 97–103

# PROGRAMMABLE CURRENT REGULATOR

S. KOUTZAROV, G. POPOV
*Faculty of Physics, University of Sofia*
*5 J. Bourchier Blvd, 1164 Sofia, Bulgaria*

Received 14 March 1997

**Abstract.** A flexible circuit of programmable current regulator suitable for computer-controlled equipments is proposed. Its output current changes in steps $\Delta I_0$ can be also programmable. Both theoretical analysis and practical circuit are included.

**PACS number:** 07.07.-a

The current regulators are used in many physical experiments. When computer-controlled measurement and testing has to be done, it is necessary to use programmable regulators. Such type of circuits are given in [1–4]. The output current $I_0$ changes with fixed step value $\Delta I_0$. Some more complicated circuits are considered in [5].

Here a new flexible circuit is proposed, and $\Delta I_0$ can be programmed or adjusted. The circuit description with basic equations and DC analysis is given. By the use of different resistive matrices a great number of practical circuits can be realised. To prove the theory an experimental circuit was realised and tested.

## 1. Basic Circuit

The basic circuit is given in Fig. 1. The SM is a two-port resistive matrix with a transmission gain $K_{SM} = U^+/U_R$ and VM is one-port resistive matrix with resistance $R_{VM}$. By simple analysis with ideal OAs the expression for the output voltage of OA2 is obtained as follows:

$$U_2 = \frac{R_2}{R_3}\left(1 + \frac{R_1}{R_{VM}} + \frac{R_1}{R_2}\right) K_{SM} U_R + \frac{R_1 R_4}{R_2 R_3} U_L \,. \tag{1a}$$

According to Fig. 1 the output current is $I_0(U_2 - U_L)/R_I$ and using Eq. (1$a$) the formula

$$I_0 = \frac{1}{R_I}\left[\frac{R_4}{R_3}\left(1 + \frac{R_1}{R_{VM}} + \frac{R_1}{R_2}\right) K_{SM} U_R + \left(\frac{R_1 R_4}{R_2 R_3} - 1\right) U_L\right] \tag{1b}$$

is obtained. It can be seen that when the condition

$$R_1 R_4 = R_2 R_3 \tag{2a}$$

is satisfied, the output current

$$I_0 = \frac{U_R}{R_I}\left(1 + \frac{R_4}{R_3} + \frac{R_2}{R_{VM}}\right) K_{SM} \tag{2b}$$

is independent from the voltage $U_L$ and the load $R_L$. So under the condition (2*a*) the circuit is an ideal current regulator. For negative voltage $U_R$ the output current goes out from the circuit and it is a current source. With $U_R > 0$ the current $I_0$ enters and the regulator acts as a current sink.

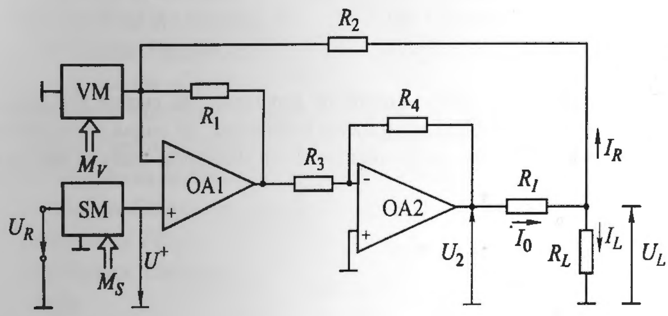


**Fig. 1.** Basic circuit

Realy Eq. (2*a*) is never true (due to the tolerances of the resistors $R_1 - R_4$) and can be written as $R_1R_4 = aR_2R_3$, where $a \neq 1$. So the output resistance of the real current regulator is

$$R_0 = \frac{R_I + R_{02}}{1 - a} \tag{3}$$

where $R_{02} = \dfrac{R_{0(OA2)}}{1 + \dfrac{R_6R_{02}}{R_5 + R_6}}$ and $R_{0(OA2)}$ and $A_{02}$ are the output resistance and the DC gain of the OA2 respectively. The real output current depends on the load $R_L$ according to the equation

$$I_{0r(L)} = \frac{I_0}{1 + \dfrac{R_0}{R_L}}. \tag{4}$$

Supposing $R_1 - R_4$ with equal tolerances $\delta_R$ for the worst case ($R_1$ and $R_4$ are with tolerance $+\delta_R$ and $R_2$ and $R_3$ with tolerance $-\delta_R$) the coefficient $a = (1 - \delta_R)^2/(1 + \delta_R)^2$. To obtain a great $R_0$ and a real current $I_{0r(L)}$ close to $I_0$, resistors with small tolerances ($\delta_R \leq 1\,\%$) have to be used. In this case $1 - a \approx 4\delta_R$, which permits an easy calculation of $R_0$ and $I_{0r(L)}$.

The parameter line regulation of the circuit is defined as $LR = (\Delta I_0/I_0)/(\Delta U_C/U_C)$, where $\Delta I_0/I_0$ is the relative change of $I_0$ due to the relative change $\Delta U_C/U_C$ of both supply voltages of OA2. Using the parameters power supply rejection ratio $PSRR_1$ of OA1 and $PSRR_2$ of OA2 with simple analysis of the circuit the expression

$$LR = \frac{BU_C}{\left(1 + \frac{R_L}{R_I}\right) I_0} \tag{5a}$$

is obtained. In Eq. (5*a*) the coefficient $B$ is

$$B = \frac{R_4}{R_3}\left[1 + \frac{R_1}{R_{VM}||(R_2 + R_0)}\right] \times 10^{-0.05\mathrm{PSRR}_1} + \left(1 + \frac{R_4}{R_3}\right) \times 10^{-0.05\mathrm{PSRR}_2} \tag{5b}$$

and $I_0$ is given by Eq. (2*b*). Obviously $LR$ changes during the programmation of $I_0$.

The offset voltage $U_{IO}$, the bias current $I_{IB}$ and the offset current $I_{IO}$ of both OAs have influence on the output current, creating its component $I_{O(R)}$. According to the explanations in [6] these three parameters give the component

$$U_{O(B1)} = \frac{U_{IO(1)} + \left(R_{O(SM)} - R_{1(-)}\right) I_{IB(1)} + R_{1(-)} I_{IO(1)}}{1 + \frac{R_2}{R_{VM}} + \frac{R_2}{R_1}} \tag{6a}$$

in the output voltage of OA1, where $R_{O(SM)}$ is the output resistance of SM and $R_{1(-)} = R_1||R_2||R_{VM}$. In the voltage $U_2$ there is a component

$$U_{2(B2)} = -\frac{R_4}{R_3} U_{0(B1)} + \left(1 + \frac{R_4}{R_3}\right)\left[U_{IO(2)} - \frac{R_3 R_4}{R_3 + R_4}\left(I_{IB(2)} - I_{IO(2)}\right)\right]. \tag{6b}$$

So to $I_{0r}$ is added

$$I_{0(B)} = \frac{U_{0(B2)}}{R_I}. \tag{6c}$$

It is recommended to choose both OAs so that $I_{0(B)} \le 0.5\Delta I_0$.

From Fig. 1 can be seen that $I_0 = I_L + I_R$ and $I_R = (U_L + U^+)/R_3$. When the load $R_I$ varies, the voltage $U_L$ and the current $I_R$ change too.

These changes cause an error in the load current $I_L$ (the circuit maintains constant the value of $I_0$). The error is maximal for $U_{L\max}$ (which can be supposed for instant equal to the maximal output voltage $U_{2\max}$ of OA2) and $K_{SM} = 1$ or $U^+ = U_R$. With the choice of

$$R_3 \ge \frac{U_{2\max} + |U_R|}{k\Delta I_0} \tag{7}$$

the difference $I_L - I_0$, i. e. the error due to $R_3$ is smaller than that of $k\Delta I_0$. The coefficient $k$ must be chosen too.

## 2. Practical Considerations

The step matrix SM can be any digital-to-analog converter (DAC) with voltage output. In this case

$$K_{SM} = \frac{m_S}{2^{n_S}}, \qquad R_{i(SM)} = R_{SM} \tag{8a}$$

where $m_S$ is the decimal number corresponding to the step word $M_S$, and $n_S$ and $R_{SM}$ are the resolution and the resistance of the DAC respectively. Ordinary the output resistance is $R_{0(SM)} \approx 0$. So the output current is

$$I_0 = m_S \Delta I_0 \tag{8b}$$

where

$$\Delta I_0 = \frac{U_R}{2^{n_S} R_I}\left(1 + \frac{R_4}{R_3} + \frac{R_2}{R_{VM}}\right). \tag{8c}$$

The value of $I_0$ can be programmed by $M_S$ from 0 (with $m_S = 0$) to $I_{0\max} = -(2^{n_S} - 1)\,\Delta I_0$ in $2^{n_S}$ steps $\Delta I_0$.

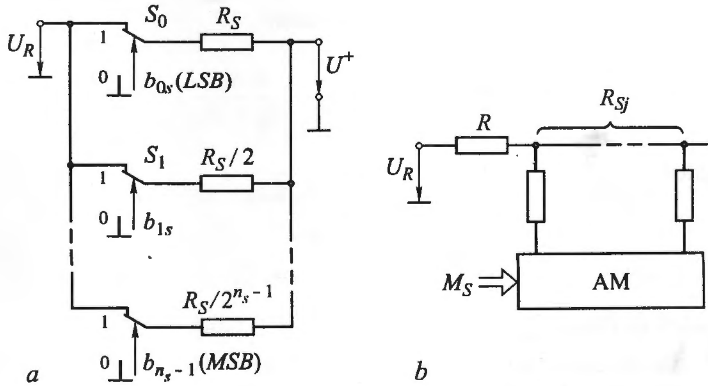


**Fig. 2.** Resistive matrices for SM
(*a*) weight matrix; (*b*) matrix for arbitrary values

For smaller number of steps (i. e. below 100) different types of resistive matrices as SM can be used. The weight matrix in Fig. 2*a* [7] uses $n$ analog switches $S_i$. Each of them is controlled by one bit $b_i$ of $M_S$ and is in position "1" for $b_i = 1$. The step word is $M_S = b_{n-1} \ldots b_1 b_0$ and the matrix parameters are

$$K_{SM} = \frac{m_S}{N_{ms}}, \quad R_{i(SM)} = \frac{R_S}{m_S}\left(1 - \frac{m_S}{N_{ms}}\right), \quad R_{0(SM)} = \frac{R_S}{N_{ms}} \tag{9a}$$

where $N_{ms} = 2^{ns-1}$ and $R_{i(SM)}$ is the input resistance. The output current is given by Eq. (8*b*) with

$$\Delta I_0 = \frac{U_R}{N_{ms} R_I} \left(1 + \frac{R_4}{R_3} + \frac{R_2}{R_{VM}}\right) . \tag{9b}$$

The number of steps of $I_0$ is $2^{ns}$ with first step ($m_S = 0$ or all $S_i$ in position "0") $I_0 - 0$. A variant of this matrix with four analog switches and resistance $R_S/2$ in a series with $S_3$ ensures $N_{ms} = 9$. It is suitable for digital instruments.

For arbitrary values of $I_0$ the circuit from Fig. 2*b* is recommended as SM. Its transmission gain in the $j$-th position of the analog multiplexer AM is $K_{Sj} = R_{Sj}/\left(R + R_{Sj}\right)$, which must be submitted in Eq. (2*b*) to obtain the value $I_{0j}$ of the output current.

It is possible to use as SM the digital potentiometers [8, 9] or digital attenuators [10], provided by different firms.

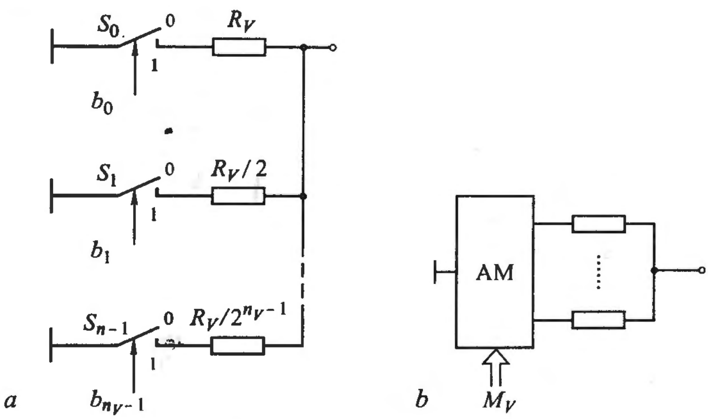


**Fig. 3.** Resistive matrices for VM
(*a*) weight matrix; (*b*) matrix for arbitrary values

The step value $\Delta I_0$ can be programmed according to Eqs (8*c*) and (9*b*) througth the value matrix VM. A suitable choice for VM is the matrix in Fig. 3*a*. Its resistance $R_{VM} = R_V/m_V$ is controlled by the value word $M_V = b_{n-1} \ldots b_1 b_0$ to which corresponds the decimal number $m_V$. So the step $\Delta I_0$ is directly proportional to $m_V$. For arbitrary steps the circuit in Fig. 3*b* must be used. In the $j$-th position of the AM the resistance is $R_{VM} R_{Vj}$.

The choice of the OA2 depends on the maximal output current $I_{0\max}$ of the regulator. It is the recommended power OAs or audio power amplifiers. For $U_L > 20$ V must be used high- voltage OAs. The power dissipated on OA2 is

$$P_{D2} = U_{C2} I_0 - \left(R_I + R_L\right) I_0^2 \tag{10a}$$

where $U_{C2}$ is the supply voltage of OA2. The value of $P_{D2}$ depends on $R_L$ and is maximal for $R_L = 0$. In this case the inequalities

$$U_{C2} \leq 2I_{\mathrm{OA2max}}R_I \text{ and } U_{C2} \leq 2\sqrt{P_{\mathrm{OA2max}}R_I} \tag{10b}$$

must be satisfied, where $I_{\mathrm{OA2max}}$ and $P_{\mathrm{OA2max}}$ are the maximal output current and power of OA2.

A special attention should be paid to the resistor $R_I$. Its power dissipation is $I_0^2R_I$ and can attain values up to 10 W or more. A tolerance not great than 0.1 % is recommended to obtain a sufficiently exact value of $I_0$.

The load resistance $R_L$ vary between 0 and

$$R_{L\max} - \frac{U_{2\max}}{I_0} - R_I \tag{11}$$

where $U_{2\max}$ depends on $O_{A2}$ and $U_{C2}$.

## 3. Simplified Circuits

When the programming of $\Delta I_0$ is not necessary, then the VM can be eliminated, which means $R_{VM} \to \infty$ in Eq. (1*b*), (2*b*), (8*c*) and (9*b*).

For $\Delta I_0 = \mathrm{const}$ and necessary adjustment of $I_0$ the matrix VM is replaced by a series connection of the resistor $R_V$ and trimmer-potentiometer $P_V$. The value of $I_0$ according to Eq. (2*b*) must be obtained with $R_{VM} = R_V + 0.5P_V$. An increase of $I_0$ with $q$ % when the potentiometer is short-circuited needs

$$\frac{P_V}{R_V} = 0.02q\left(1 + \frac{1 + R_4/R_3}{R_2/R_{VM}}\right). \tag{12}$$

## 4. Experimental Results

The circuit was realised with LM357 as OA1 and TDA2030 as OA2. The matrix SM is a simple resistive voltage divider and VM is a resistor 16 kΩ. The resistors $R_1 = R_2 = R_3 = R_4 = 4.99$ kΩ/1 % and $R_I = 3.966$ Ω (measured value) are used too. To prevent possible oscillations a capacitor $C$ is placed in parallel with $R_4$. The time constant $R_4C$ must be approximately 0.5 μs.

The maximal difference between the calculated values of $I_0$ according to Eq. (2*b*) and the measured ones is 1.3 %. It was measured $R_0 = 423$ Ω and $LR = 8.64 \times 10^{-3}$ (for change of $U_C$ from ±6 V to ±18 V).

To verify the programming possibility of the circuit the matrix SM was replaced by a simple multiplying DAC (Fig. 2*a*) with $n_S = 4$, $K_{SM} = m_S/16$ and $R_{SM} = 2$ kΩ. So the Eq. (8*c*) is transformed to $\Delta I_0 = \frac{U_R}{63.5}\left(2 + \frac{4.99}{R_{VM}[k\Omega]}\right)$ A. For step change $\Delta I_0 = 50$ mA with $R_{VM} = 16$ kΩ the reference voltage must be $U_R = 1.372$ V. The differences between the calculated and experimentally measured values are not greater than 2 %. A step $\Delta I_0 = 100$ mA with the chosen value of $UR$ can be obtained by

$R_{VM} = \dfrac{4.99}{\dfrac{63.5\Delta I_0}{U_R} - 2} = 1.90\,\text{k}\Omega$. This value is easy realised with resistor $2.2\,\text{k}\Omega$ in parallel to $16\,\text{k}\Omega$. The connection is ensured by simple analog switch.

## References


1. D. Soderquist. *Electron. Engr.* **49** (1977) 32.
2. R. M. Fisher. *Electronics* **57** (1979) 116.
3. A. Olesin. *Electronics* **53** (1975) 95.
4. Dahlmann. *Electronik* **28** (1979) 56.
5. S. Koutzarov. Thesis for Doctor of Sciences, Univ. of Sofia (1995).
6. G. B. Clayton. Operational Amplifiers. (Butterworth & Co Ltd, 1979).
7. N. T. Abdulaev, M. G. Markatun. *Izvestia VUZ - priborostr.* (1974) 26.
8. L. Sherman. *EDN* **31** (1983) 143.
9. J. Randal. *EDN* **32** (1987) 177.
10. E. Hall. *EDN* **29** (1981) 212.