A Study on Current Conveyors and their Applications

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Abstract

The study presents the basic building block of analog current-mode circuits, namely current conveyor. A comparison has been drawn between the performance of the voltage-mode and current mode circuits. The speed of operation, voltage and power consumption which are the major constraints in circuits are quite better in the current mode circuits. A typical second generation current conveyor circuit has been studied. A variety of applications involving current conveyor as the building block has been listed. It has been inferred that current conveyors are a worthy choice for most analog applications owing to their signification advantages.

Keywords—*current mirror; current conveyor; operational amplifier (OPAMP); current-mode; voltage-mode*

1. INTRODUCTION

The operational amplifiers' invention had caused the voltage mode circuits to be at the forefront of most analog applications. Although a few significant limitations of these circuits were identified but a more suitable alternative was not available. In 1968, with the invention of the concept of current conveying by Sedra and Smith, the concept of current mode circuits came into light. Due to lack of research in the area they did not come into use immediately. However the current mode circuits have been found to be more advantageous than voltage mode circuits in recent times. In current mode circuits, the entire circuit response is determined by the currents at the various circuit nodes and the input-output signals are primarily currents. The operational amplifier acts as a basic building block in many of the voltage mode circuits. In the same way, the current mirror is the replacement of OPAMPs in the current mode circuits [1].

Current conveyors are a current mode equivalent of operational amplifiers. It is a three terminal device (can have 4-6 terminals also) introduced by Sedra and Smith in 1968.It can perform many useful analog signal processing functions when arranged with other electronic components in specific circuit configurations depending on application. We can design current conveyor circuits that work at levels close to their predicted theoretical performance which is a significant advantage over the voltage mode counterparts [2]. The design of current conveyors is prevalent using bipolar junction transistors (BJTs) and complementary MOS (CMOS).

Owing to the advantages the circuits using current conveyors exhibit, there are a variety of applications that can be built around the current conveyors. These involve the use one or more current conveyor blocks along with a few other circuit elements like resistors, capacitors etc. Hybrid circuits involving use of both voltage-mode and current-mode concepts can also be formulated to take up the advantages of both of them. The second generation of the current conveyors popularly known as CCII and its variant current-controlled current conveyor (CCCII), are commonly used all these applications. The third generation of current conveyors is still under study and finds less application in the industry.

The remaining paper has been organized as follows: Section II elucidated the advantages that current mode circuits have over their voltage mode counterparts. Section-III describes the basic characteristics of a current conveyor and its three generations. Section IV and V are dedicated to the current mirror concept and its usage in deriving the current and voltage relations in second generation current conveyor. Section VI summarizes the various applications that make use of CCII as a building block. The conclusion that is drawn from this study has been presented last.

II. ADVANTAGES OF CURRENT CONTROLLED CIRCUITS OVER VOLTAGE MODE CIRCUITS

Conventionally all analog circuits are voltage mode circuits (VMCs) and their circuit performance is evaluated in terms of voltage levels at different nodes including the input and the output example operational amplifier. But all these circuits suffer from the several disadvantages:

- output voltage usually doesn't change instantaneously with input voltage
- Effect of stray and other circuit capacitances.
- Bandwidth of the op amp based circuits is usually low because of finite unity gainbandwidth.
- Slew rate depends on the time constants associated with the circuit.
- Do not have high voltage swings.
- Better SNR requires higher supply voltages

In current mode circuits the circuit response is determined by the currents and all the input/output signals are primarily currents. The voltage levels are irrelevant in determining the circuit performance. Some of the advantages of current-mode circuits over their voltage-mode counterparts are

1) They have low impedance nodes,

2) Summing of current signals is easier as it requires only a circuit node,

3) Replication and scaling of current signals is easier due to presence of current mirrors,

4) Wide bandwidth is available for current mode circuits

5) Dynamic range is less dependent on the supply voltage [1].

Due to the simplicity of the building blocks, current-mode circuits can be compact and operate with low voltages. This leads to reduction in area and power consumption requirements as well as to improved high frequency performance.

In the context of ICs, Current-Mode offers some advantages over Voltage-Mode:

- performances improvement : high signal dynamic range, high speed, low power consumption at high frequency, low cross-talk & switching noise
- structural advantages : current summing without extra components, schematic simplicity, controlled gain without feedback components
- specific features : pseudo conductance networks, well suited for low voltage applications, current switching technique.

Current mode circuits offer lesser delay as compared to voltage mode circuits. The delay can be reduced either by reducing voltage swing or by increasing charging or discharging current. In voltage mode circuits, voltage swing cannot be reduced because it is limited by the signal to noise ratio (SNR) requirements. However charging and discharging current in current mode circuits can be increased due to less parasitic capacitance. This will give lesser delay and hence current mode circuits are capable of giving a faster transient response. The current mode circuits provide higher bandwidth in comparison to voltage mode circuits.

Current mode circuits can be operated for lower voltage swings of input signals as compared to voltage mode circuits. The output of the voltage mode circuits varies directly with the input signal variations. It gives noisy and distorted output at lower input voltage swings. The input voltage swing is limited by signal to noise ratio. It results in slower response of the circuit. The effect of supply voltage and ground fluctuations adversely affects voltage mode circuits. This is because output varies directly with input signal in voltage mode circuits while in current mode, the output is in the form of current and there is very less attenuation due to supply voltage reduction.

As the device size is reducing, the thickness of gate oxide is also scaling down. As a result, there is increase in Electrostatic Discharge induced MOSFET failures due to breakdown of gate oxide insulators. Voltage mode circuits are more affected by this as it has high input impedance. The electrostatic charges gather at the input of gate due to high input impedance of voltage mode circuits. However, low input impedance in current mode circuits avoids the accumulation of electrostatic charges at the input terminal of the gate and is therefore a safer design technique [1].

II. CURRENT CONVEYOR AND ITS GENERATIONS

Sedra and Smith introduced the concept of current conveyors in 1968 but the actual advantages and innovative impact were not clear at that time. But in recent years, with the growing popularity of the current-mode approach as a way to design low voltage, low power circuits, current conveyors are coming into use [2].

In voltage-mode circuits, the main building block for addition, subtraction, amplification, attenuation and filtering voltage signals is the operational amplifier (OP-AMP). In the current-mode circuits, the analogous building block is the current conveyor. The original current conveyor is a three-terminal device with two input terminals X & Y and one output terminal Z with the following properties:

1. The potential that appears at its input terminal (X) is equal to the voltage applied at the other input terminal (Y).

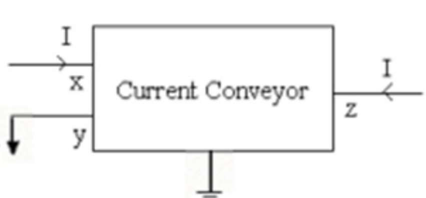

Fig. 1: Basic block diagram Of Current Conveyor

2. An input current forced into node X results in an equal amount of current flowing into the node Y.

3. The input current that flows into node X is conveyed to node Z, which has the characteristics similar to a high output impedance current source [3].

It is desired that a current conveyor should have a large bandwidth and should consume low quiescent power. Ideally a current conveyor should have:

- Infinite input impedance (Rin) at port Y
- Zero input impedance (Rx) at port X for current inputs
- Infinite output impedance (Rout) at port Z
- Unity voltage transfer gains between port Y and X
- Unity current transfer gain between port X and Z
- Infinite bandwidth [4]

A. First Generation Current Conveyor

In the first generation of current conveyors, if a voltage is applied at port Y, an equal potential will appear on the input port X. An input current I being forced into port X will result in an equal amount of current flowing into port Y. The current iz will be conveyed to output terminal Z such that terminal Z will have the characteristics of a current source, of value iz, with high output impedance. The potential at X is set by that of Y, and hence, is independent of the current being forced into port X. Current through port Y is fixed by current that flows into X and is independent of the voltage applied to Y [1].

The relationship between the currents and voltages appearing on the three ports of the first generation current conveyor and its matrix representation is give in the equations (1-3).

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix} \quad (1)$$

$$ix = iy = iz \quad (2)$$

$$vx = vy \quad (3)$$

B. Second Generation Current Conveyor

It was published by Sedra in 1970. If a voltage is applied at port Y, an equal potential appears at the input port X. The current flowing into port Y is 0. The current iz will be conveyed to output port Z such that terminal Z acquires the characteristics of a current source, of value iz, with high output impedance. The port Y exhibits infinite input impedance [2].

The relationship between the currents and voltages appearing on the three ports of the second generation current conveyor and its matrix representation is give in the equations (4-7).

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \pm 1 & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix} \quad (4)$$

$$iy = 0 \quad (5)$$

$$vx = vy \quad (6)$$

$$iz = \pm ix \quad (7)$$

The ± sign denotes whether it is a positive transfer conveyor (CCII+) or a negative transfer conveyor (CCII-). The difference is in the direction of current iz with respect to ix. If both the currents are flowing into the circuit or both are flowing out of the circuit then the sign would be positive; otherwise it would be negative.

A. Third Generation Current Conveyor

This was published by Fabre in 1995. It is quite similar to CCI with the exception that the current in port X and Y flow in opposite direction. Its main application is current measurement [4].

The relationship between the currents and voltages appearing on the three ports of the third generation current conveyor and its matrix representation is give in the equations (8-11).

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix} \quad (8)$$

$$iy = - ix \quad (9)$$

$$vx = vy \quad (10)$$

$$iz = ix \quad (11)$$

IV. CURRENT MIRROR CONCEPT

For studying the circuit of a current conveyor, it is important to understand what a current mirror is and how it works. In a current mirror, the output current is the mirror reflection of the input current. The advantages of current mirror are that it offers extremely large resistance under ac conditions and provides high value of common mode rejection ratio (CMRR).

It is very simple and uses less number of transistors. It makes use of the fact that for a transistor in the active mode of operation, the collector current is relatively independent of the collector voltage (i.e. we are ignoring Early effect). The Early effect is variation in the width of the base of a bipolar junction transistor (BJT) due to a variation in the applied base-to-collector voltage. Base-narrowing has two consequences that affect the current. The chance for recombination within the base (effectively smaller) region reduces. The charge gradient is increased across the base, and this causes the current of minority carriers that are injected across the emitter junction to increase. Both these factors lead to an increase in the collector current of the transistor with an increase in the collector voltage [5].

Q1 and Q2 are matched i.e. the bases and emitters of Q1 and Q2 are tied together. Q2 is connected as a diode i.e. self biasing. It means that only one voltage source is used and the Base-Emitter junction is forward biased while Collector-Emitter junction becomes reverse biased. Iref establishes a voltage across Q2. Since Q1 and Q2 are identical, therefore this VBE2 appears as VBE1 across Q1 making their emitter currents equal. Q1 operates in active mode. Mirror effect is valid only for large value of β (transistor gain).

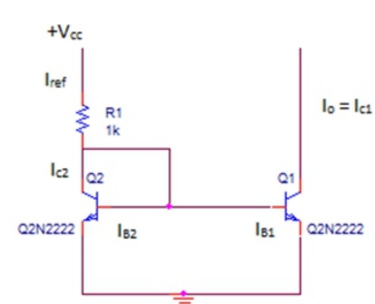

Fig. 2: Basic BJT current mirror

If the source current is denoted by Iref and the sink current by Io = IC1. As both transistors have the same biasing, therefore VBE2 = VBE1.

The emitter currents are equal and the base currents are also equal as they are tied together, hence the collector currents will also be equal.

$$IC2 = \alpha F.IES.eVBE2/VT \quad (12)$$

$$IC1 = \alpha F.IES.eVBE1/VT \quad (13)$$

where IES is the saturation current and αF.IES is the same for both transistors.

Now dividing the two, we get

$$\frac{IC1}{IC2} = e^{(VBE1-VBE2)/VT} \quad (14)$$

As VBE1 = VBE2 therefore from equation (14),

$$I_{C1} = I_{C2} = I_o \quad (15)$$

Both the transistors are matched hence, β2 = β1 = β

Now applying KCL at collector of Q2

$$I_{ref} = I_{C2} + I_{B2} + I_{b1} \quad (16)$$

Using (15),

$$I_{B1} = I_{B2} = \frac{IC1}{\beta} = \frac{Io}{\beta} \quad (17)$$

Therefore, from (16) and (17), we get

$$I_{ref} = I_o.(1 + \frac{2}{\beta}) \quad (18)$$

Hence,

$$I_o = I_{ref}.(\frac{\beta}{\beta+2}) \quad (19)$$

If β is large, then it can be said that I0 ≈ Iref.

$$I_{ref} = \frac{VCC-VBE2}{R1} \quad (20)$$

Therefore the current mirror gives us the relation I0 = Iref i.e. the input current is reflected at the output [5].

If we have only one source then it can be used to provide current to multiple sinks. This is called a Current repeater.

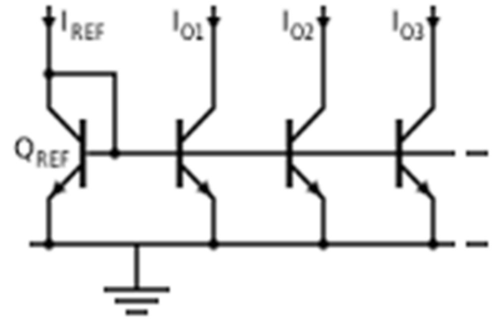

Fig. 3: Current repeater using BJT

$$Iref = IC + IB + NIB \quad (21)$$

$$I_{ref} = I_C + (1 + N).\frac{IC}{\beta} \quad (22)$$

All transistors are identical and have same value of β.

$$I_C = \frac{Iref}{1+\frac{1+N}{\beta}} = \frac{Iref.\beta}{\beta+1+N} \quad (23)$$

For large values of β, we can say that for all the sink transistors

$$IC = I_{ref} \quad (24)$$

V. Second Generation Current Conveyor Circuit Using

BJT

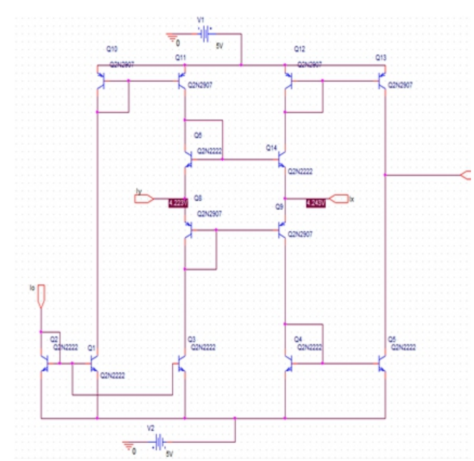

Fig. 4: Current conveyor II circuit using BJT

Fig. 4 shows the circuit diagram of a current conveyor of second generation designed using BJTs. The two relations between the currents at port X and port Z; and between the voltages at port X and Y can be derived using the following procedure. The circuit has many pairs of current mirrors and repeaters and the concept of current mirroring seen in section IV can be used to derive the relations easily [2][4].

Applying KCL at node A

$$I_x + I_{E14} = I_{E9} \quad (25)$$

(Assuming IC = IE for all transistors neglecting IB)

$$I_x + I_{C14} = I_{C9} \quad (26)$$

Also IC9 = IC4 (Same branch)

As transistors Q4 and Q5 form a current mirror, so

$$I_{C4} = I_{C5} \quad (27)$$

Therefore, $I_{C9} = I_{C5}$ (28)

Similarly $I_{C14} = I_{C12}$ (Same branch)

As transistors Q13 and Q12 form a current mirror, so

$$I_{C13} = I_{C12} \quad (29)$$

Therefore, $I_{C14} = I_{C13}$ (30)

Put values of IC14 and IC9 from (30) and (28) into (26)

$$I_x + I_{C13} = I_{C5} \quad (31)$$

$$I_x = I_{C5} - I_{C13} \quad (32)$$

Now apply KCL at node B, we get

$$I_z + I_{C13} = I_{C5} \quad (33)$$

$$I_z = I_{C5} - I_{C13} \quad (34)$$

Therefore from (32) and (34), we get

$$I_z = I_x \quad (35)$$

Hence the current that we give at port X, appears at the port Z of the current conveyor.

Apply KVL in loop I,

$$(0 - V_y) - V_{BE6} + V_{BE14} + (V_x - 0) = 0 \quad (36)$$

As the transistors are matched, therefore

$$V_{BE6} = V_{BE14} \quad (37)$$

Therefore on solving (36) we get,

$$V_x = V_y \quad (38)$$

Hence, we see that if a voltage is applied at terminal Y, the same potential appears on the terminal X

VI. APPLICATIONS OF CURRENT CONVEYORS

Due to the advantages stated in Section II, the current conveyors are being used in a number of applications. Similar to OP-AMPs, the current conveyor block can be used along with a few other active/passive elements like diodes, resistors, capacitors etc. [6][7]. Several applications were proposed by Sedra and Smith, out of which the block diagram representation of a few is given in Fig. (5-13)..

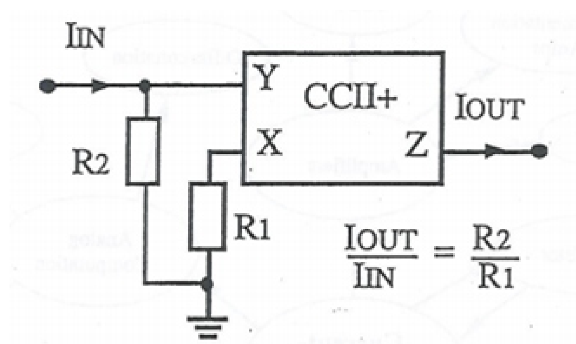

Fig. 5: Current amplifier using CCII

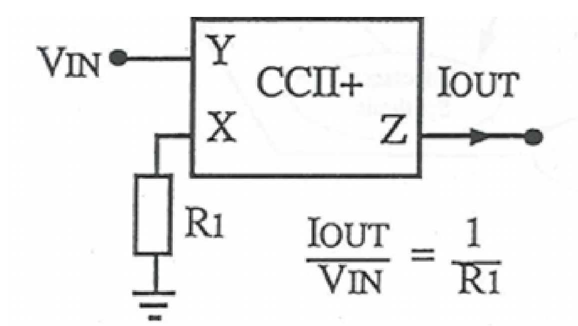

Fig. 6: Voltage to Current converter using CCII

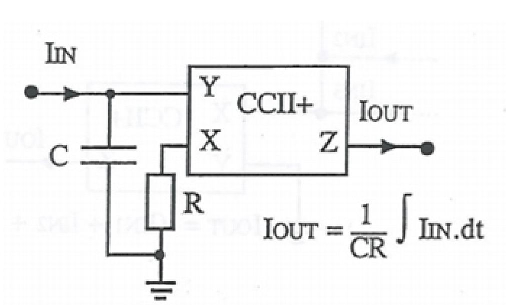

Fig. 7: Current integrator using CCII

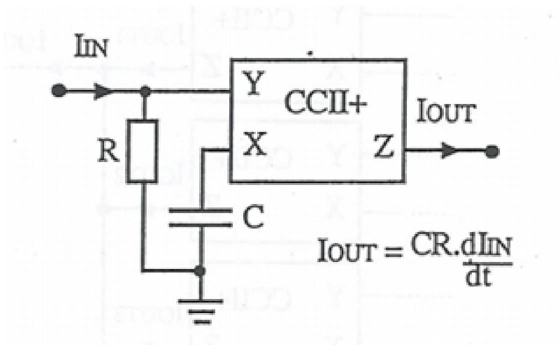

Fig. 8: Current differentiator using CCII

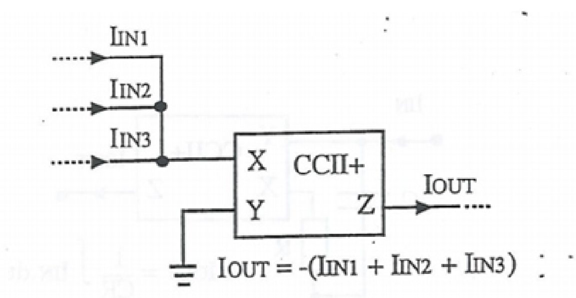

Fig. 9: Current summer (I) using CCII

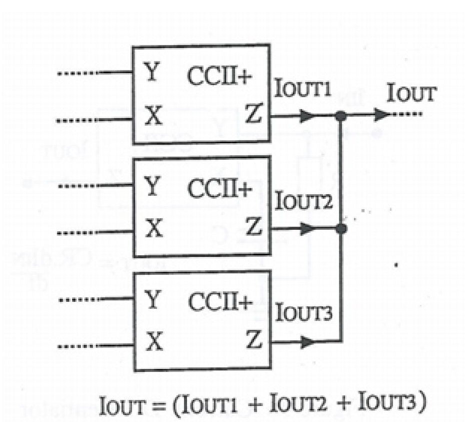

Fig. 10: Current summer (II) using CCII

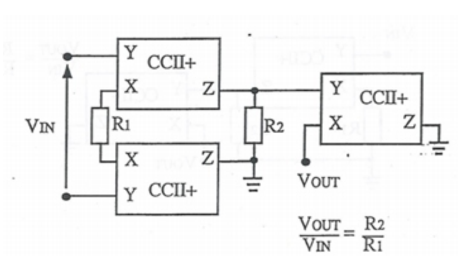

Fig. 11: Instrumentation amplifier using CCII

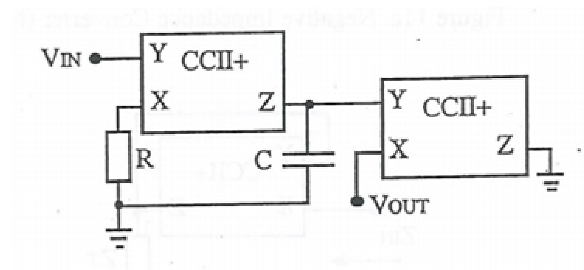

Fig. 12: Voltage Integrator using CCII

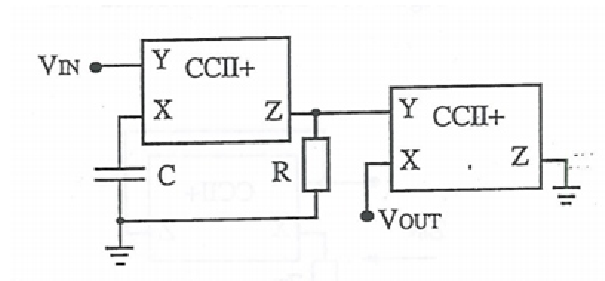

Fig. 12: Voltage differentiator using CCII

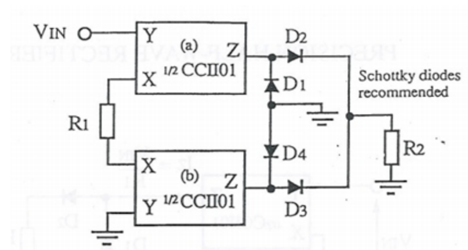

Fig. 13: Full wave precision rectifier using CCII

It can be concluded from the study that current mode devices offer many significant advantages due to which they become a natural choice in many analog applications over the voltage mode circuits. The basic building block in current mode circuits is the current conveyor, which is analogous to OPAMPs in voltage mode circuits. There are three generations of current conveyors with minor differences in their operation. The circuit of the second generation current conveyor using BJTs has been studied and the current and voltage relationships among the three ports have been derived using the current mirror concept, which has also been explained in detail. Lastly we have seen the various application that can be implemented by making use of one or two current conveyors only, which not only gives the advantages of using current-mode, but also circuit simplicity and modularity.

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