An RMS-DC converter based on the dynamical translinear principle

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Abstract

Translinear or log-domain filters are theoretically exact realisations of *linear* differential equations. However, the dynamical translinear principle can also be applied to the implementation of *nonlinear* differential equations. In this paper, an RMS-DC converter is proposed, comprising a direct implementation of the corresponding nonlinear differential equation by means of the dynamical translinear principle. Correct operation of the circuit was verified through measurements.

1 Introduction

The translinear principle [1] plays a key role in conventional implementations of RMS-to-DC conversion [2]. A well-known RMS-DC converter is shown in Fig. 1. The squarer-divider basically comprises a four-transistor, i.e. second-order [3], translinear loop. As the squarer-divider facilitates one-quadrant operation, its input signal is full-wave rectified. It calculates the current I_{in}^2/I_{out}, where I_{out} is the output current of the RMS-DC converter and is equal to the mean value of I_{in}^2/I_{out}:

$$I_{out} = \left\langle \frac{I_{in}^2}{I_{out}} \right\rangle, \tag{1}$$

where $< \ldots >$ represents the averaging operation, i.e. the low-pass filter shown in Fig. 1.

By dividing the square of $|I_{in}|$ by I_{out}, the requirements on the offsets in the system are relaxed.

The low-pass filter is often first-order and can be implemented by a simple RC-section. Another possibility is to implement the filter in the 'log-domain' or 'translinear domain' [4, 5]. Owing to this extension to the translinear principle, theoretically exact filters can be designed comprising only transistors and capacitors. This option is especially interesting for ultra low-power applications, where resistors become too large for on-chip integration [6]. The principle behind translinear filters is explained in Sec. 2.

As both the squarer-divider and the low-pass filter can be realised in the translinear domain, there is actually no reason for these two operations being separate system blocks. The RMS-DC converter proposed in Sec. 3, combines the two mentioned functions into one translinear loop, thus enlarging the key role of the translinear principle in the implementation of RMS-DC conversion.

2 The dynamical translinear principle

The large-signal behaviour of the bipolar transistor is described by the exponential law: $I_C = I_s \exp(V_{BE}/U_T)$, where all symbols have their usual meaning. In translinear or log-domain filters, the exponential law is not only exploited for the implementation of multiplication and division of currents, according to the translinear principle [1], but also to perform an expanding V-to-I conversion of the capacitance voltages. Owing to this expanding V-I conversion, translinear filters inherently perform instantaneous companding [7].

The basic structure of a dynamical translinear circuit is depicted in Fig. 2, where I_{out} is the collector current of the transistor shown. Apart from a possible DC voltage V_{const}, the voltage V_{cap} across the capacitance C is equal to a base-emitter voltage V_{BE}. In general, V_{cap} equals the sum of a number of base-emitter voltages [8]. Applying the exponential law and the constitutive law of the capacitance, $I_{cap} = C\partial V_{cap}/\partial t$, a current-mode description of the capacitance current is found:

$$CU_T\dot{I}_{out} = I_{out} \cdot I_{cap}, \tag{2}$$

where the dot represents differentiation with respect to time. Note that I_{cap} is nonlinearly related to I_{out}. This is a direct consequence of the instantaneous companding inherently performed.

The dimension of both sides of eqn (2) is $[A]^2$. The right hand side consists of a multiplication of two currents. A collector current is multiplied by a capacitance current. As the translinear principle basically facilitates multiplication of currents, it is obvious that the right hand side can be realised by means of this principle. Now, by realising the term $I_{out} \cdot I_{cap}$, we have actually implemented the term $CU_T\dot{I}_{out}$ on the left-hand side of eqn (2). In other words, we have implemented the derivative $\dot{I}_{out}$.

The factor CU_T is on the left hand side of eqn (2). It is not part of the translinear implementation, and thus, it is part of the transfer function describing the translinear filter. As a consequence, the transfer function will be temperature dependent through the thermal voltage U_T. This temperature dependency can be compensated for by making some (or all) currents PTAT [9].

3 Dynamical translinear RMS-DC conversion

The dynamical translinear principle forms an elegant possibility for implementing linear filters, or equivalently, linear differential equations. A current-mode description of a translinear first-order low-pass filter is given by [4, 8]:

$$CU_T\dot{I}_y + I_oI_y = I_oI_x, \tag{3}$$

where I_o is a DC bias current and I_y is the low-pass filtered version of I_x.

In contrast with a linear filter, in an RMS-DC converter, the filtering operation is not performed on the input signal I_{in}, but on the current I_{in}^2/I_{out}. That is, the variable I_x in eqn (3) equals I_{in}^2/I_{out}, while I_y equals I_{out}.

We thus obtain a differential equation describing the RMS-DC operation:

$$CU_T\dot{I}_{out}I_{out} + I_oI_{out}^2 = I_oI_{in}^2. \tag{4}$$

The most important aspect of this expression is that it is a *nonlinear* differential equation, in contrast with all existing publications regarding translinear filters.

The term $CU_T\dot{I}_{out}$ can be eliminated from this equation, by substitution of eqn (2). A current-mode polynomial is obtained:

$$(I_{cap} + I_o)I_{out}^2 = I_oI_{in}^2, \tag{5}$$

thus clearing the road for an implementation by means of the translinear principle.

Since all factors in eqn (5) are positive, it can be implemented directly by a six-transistor translinear loop. A possible implementation is shown in Fig. 3. Transistors Q_1 through Q_6 comprise a third-order translinear loop. The small difference between the output structure of the RMS-DC converter and the subcircuit shown in Fig. 2 causes the cut-off frequency to halve with respect to eqn (4).

Two emitter followers, Q_7 and Q_8, are used to reduce the errors introduced by the finite current gain of the transistors.

4 Measurements

To verify the operation of the proposed RMS-DC converter, measurements were performed on a breadboard version of the circuit. V-I conversion, using a 100 $k\Omega$ resistor, and full-wave rectification were established through the circuit shown in Fig. 4 [10], mainly comprising some current mirrors. The output current was measured across a 100 $k\Omega$ resistor.

The cut-off frequency of the filter equals $I_o/(4\pi C U_T)$ Hz, which comes down to 45 Hz for the chosen values: $I_o = 10$ μA and $C = 0.68$ μF. The measured bandwidth was 38 kHz and was mainly limited by the switching full-wave rectifier.

The output current was measured as a function of the amplitude of a sine wave input signal, at a frequency of 1 kHz, and compared with a measuring-instrument. The results, depicted in Fig. 5, demonstrate the correct operation of the proposed RMS-DC converter.

Fig. 6 and 7 show measurements at 75 Hz of $I_C(Q_3)$ and $-I_{out}$ for a sine wave and a pulse wave input signal, respectively. The measured wave forms are in agreement with simulations of the proposed circuit.

Finally, the output signal of the proposed RMS-DC converter as a function of the duty cycle of a 1 kHz, 1 V_{tt} pulse wave is shown in Fig. 8.

5 Conclusions

Translinear or log-domain filters exploit the exponential V-I characteristic of the bipolar transistor to implement multiplication of currents and to perform instantaneous companding. The dynamical translinear principle can not only be used to realise *linear* filters, but can also be applied to implement *nonlinear* differential equations. RMS-DC conversion is one example of an operation described by a nonlinear differential equation and the dynamical translinear principle was used to synthesise a completely-translinear implementation. Measurements verify the correct operation of the proposed RMS-DC converter.

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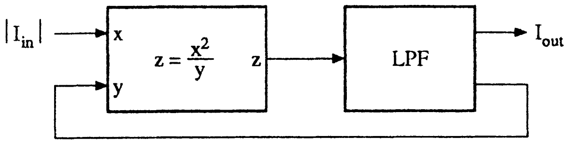

Figure 1: Block schematic of a conventional RMS-DC converter.

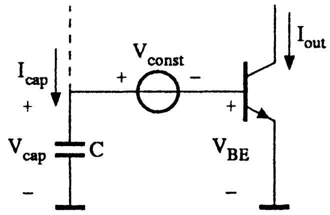

Figure 2: Principle of dynamical translinear circuits.

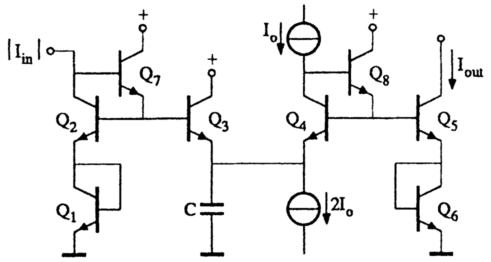

Figure 3: A nonlinear-dynamical translinear RMS-DC converter.

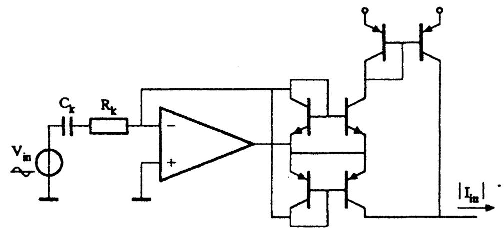

Figure 4: V-I conversion and full-wave rectification.

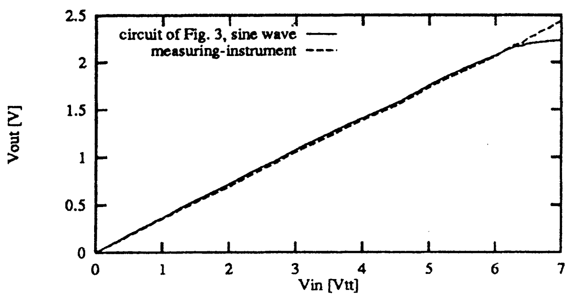

Figure 5: Transfer function for a sine wave.

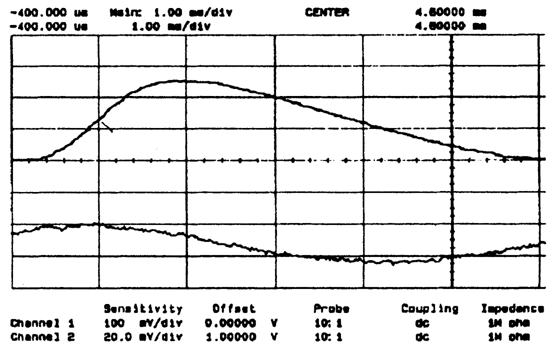

Figure 6: $I_C(Q_3)$ (upper trace) and $-I_{out}$ for a 75 Hz sine wave.

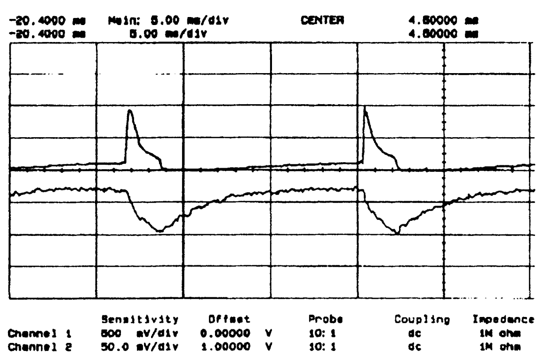

Figure 7: $I_C(Q_3)$ (upper trace) and $-I_{out}$ for a 75 Hz pulse wave.

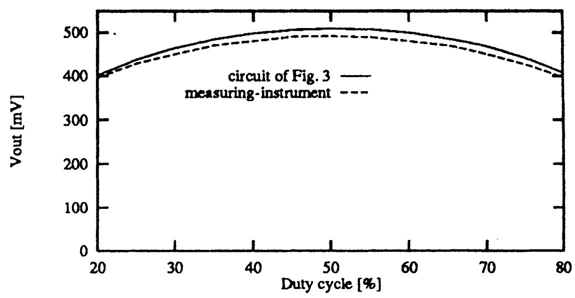

Figure 8: RMS value versus duty cycle of a 1 kHz pulse wave.