Development of high-frequency true-linear generator for electrochemical purposes

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Abstract

A new design for a true-linear generator suitable for electrochemical measures is presented. The main component of generation system is an MAX038 chip, a high-frequency relaxation-type oscillator. The design is completed with a digital interface for computer control and an output stage to make signal suitable for cyclic voltammetry experiments. A digital circuit is also included to obtain single sweep signals by isolating one period or a half-period from continuous original output. Performance of presented generator is tested up to 1 MV s \(^{-1}\) obtaining good stability and linearity.

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1. Introduction

Microelectrodes have been the object of increasing attention even before the first serious calculations on microelectrode reactions made by Pons and Fleischmann (1987). The experimental approach has been made possible first, by the progress of micromechanics and, secondly, by the improved sensitivity and performance of the electrochemical equipment. Thus, microelectrodes are successfully applied in the fields of biology and medicine (Neher, 1992; Sakmann, 1992) and in a wide variety of both scientific and technical fields (Schultze and Tsakova, 1999). The extremely low current densities (in some cases in the order of a magnitude of pA cm \(^{-2}\)) and the characteristics of mass transport, involve the necessity of achieving very high scan rates, with the obvious instrumental complication (Schultze and Tsakova, 1999). The electrochemical response is so fast that ultra-high speed systems must be used for both generating and recording the signals (Amatore et al., 1989). In the case of digital instrumentation this implies very high-velocity A/D and D/A converters and, in consequence, expensive systems. Centring on waveform generators, digital systems use D/A converters, in many cases of low resolution that generate staircase signals rather than true linear signals. This can be inconvenient due to the non-equivalence of the linear-sweep and staircase voltammetries, even at low values of step potential (Bott, 1997). Thus, an electrochemical system implementing the true linear sweep voltammetry must be available in the electrochemical laboratory.

The aim of this paper was to present a computer-controlled wave generator able to generate true linear ramps at very high scan rates. The interest of this instrumentation resides, first, in its proved versatility, because the amplitude, frequency and symmetry of the triangular wave can be programmed, and, second, in its low cost for virtually any laboratory having computer-based instrumentation. Additional features such as other waveforms can be easily implemented. Moreover,
its assembly is easy and the control program is available on request to the authors.

2. Description

2.1. Generation system

The main component of the generation system is the MAX038 (IC1 in Fig. 1) (Maxim Integrated Circuits Data Book, a), a high-frequency function generator that produces low-distortion sine, triangle, saw tooth, or square (pulse) waveforms at frequencies from less than 1 Hz to 20 MHz or more, using a minimum of external components. Frequency and duty cycle can be independently controlled by programming a current, a voltage or a resistance. The desired output waveform is selected under logic control by setting the appropriate digital code. A SYNC output and a phase detector are included to simplify designs requiring tracking to an external signal source. The output amplitude is $2V_{P-P}$, symmetrical around ground.

The MAX038 operates with $\pm 5$ V power supplies. The basic oscillator is a relaxation type that operates by alternately charging and discharging a capacitor (CF1 or CF2 in Fig. 1) with constant currents, simultaneously producing a triangle wave and a square wave. The charging and discharging currents, and then the frequency, are controlled by the current flowing into $I_{IN}$. Acceptable values of current can range from 2 to 750 $\mu$A, producing more than two decades of frequency for any value of CF.

Once the fundamental, or centre frequency is set by $I_{IN}$, it may be changed further by setting FADJ to a voltage other than 0 V. This voltage can vary from $-2.4$ to $+2.4$ V, causing the output frequency to vary from 1.7 to 0.30 times the value when FADJ is 0 V ($\pm 70\%$).

The voltage on DADJ controls the waveform duty cycle (defined as the percentage of time that the output waveform is positive). Normally, voltage in DADJ is 0 V and the duty cycle is 50%. Varying this voltage from $+2.3$ to $-2.3$ V causes the output duty cycle to vary from 15 to 85%, $\sim -15\%$ per volt. Voltages beyond $\pm 2.3$ V can shift the output frequency and/or cause instability.

A stable 2.5 V reference voltage output, REF, allows simple determination of $I_{IN}$, FADJ, or DADJ with fixed resistors, and permits adjustable operation when potentiometers are connected from each of these inputs to

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Fig. 1. Schematics of the generation system. IC1 = MAX038; IC2 = DAC8408; IC3 = X9C103; IC4 = MAX312; U1,2,3,4,5 = AD712.
REF. FADJ and/or DADJ can be grounded, producing the nominal frequency with a 50% duty cycle.

To control the setting of these parameters by a computer-controlled system, a ‘digital configuration interface’ is used based on a multiplier D/A converter DAC8408 (IC2 in Fig. 1) (Precision Monolithics Data Book).\(^2\) This quad converter allows the use of independent reference voltages for each converter and includes the feedback resistors and the data register for each converter. In this way it is possible to apply a different multiplying factor to any reference voltage used.

By setting a different operational amplifier configuration at the output stage, the output signal may be unipolar (from 0 V to \(+V_{\text{ref}}\)) or bipolar (from \(-V_{\text{ref}}\) to \(+V_{\text{ref}}\)). Moreover, it may be interpreted as a voltage or as a current.

The \(I_{\text{IN}}\) signal is obtained from a D/A in unipolar mode and current output (Eq. (1)). Voltages DADJ and FADJ are obtained from two D/A’s in bipolar mode and voltage output (Eq. (2)). All cases use the 2.5 V REF signal by MAX038 as reference voltage for converters (see Ref. Fig. 1 for details).

The conversion rate for the parameters is given by:

\[
I_{\text{IN}} = \frac{V_{\text{ref}}}{R_{\text{in}}} \cdot \frac{\text{NUM}}{256}
\]

(1)

\[
\text{DADJ} = \pm V_{\text{ref}} \cdot \frac{\text{NUM} - 128}{128}
\]

(2)

where NUM is a digital value (0–255) applied to the converter and Rin the value of the resistor through which the current \(I_{\text{IN}}\) flows.

To obtain the largest range of accessible frequencies, the system has been implemented with two 1% polycarbonate CF capacitors (CF1 and CF2 in Fig. 1), both components are connected to the MAX038 and are also tied to ground by an analog computer-controlled switch.

By using 330 pF and 33 nF values it is possible to obtain 200 Hz–2 MHz signals (four decades of frequency) without reaching the operational limits for each capacitor. Other proposed values are 1 and 100 nF for frequencies 70 Hz–700 kHz. Many other pairs are possible depending on desired frequency range.

To fit the output signal for electrochemical purposes an ‘output stage’ has been included for two purposes: modify sweep amplitude and select sweep sign. To obtain ramp signal with amplitude other than \(2V_{P-P}\), an inverter operational amplifier (U5A in Fig. 1) with a digitally-controlled potentiometer in the feedback loop is used. The X9C103 (IC3 in Fig. 1) (Xicor Data Book)\(^3\) is a 10 kΩ potentiometer whose effective resistance may be digitally controlled by a three-wire bus. The potentiometer is implemented by a resistor array composed of 99 elements and a wiper-switching network. The position of the wiper element is controlled by a three-wire bus (the CS, U/D and INC inputs). This device can be used as a three-terminal potentiometer or, as in this case, as a two-terminal variable resistor. As part of an inverter operational amplifier it may obtain gain factors from 5 (10 K) to 0.02 (0 K) if the wiper resistance of 40 Ω is considered. The gain factor may be modified by steps of 0.0505 U.

The output signal from inverter is applied to another operational amplifier (U5B) to permit selection over sweep sign. This section is configurable by an analog switch which is digitally-controlled by setting gain 1 or \(-1\). This configuration has been used before by the authors (Roldán et al., 1986).

The unused 1/4DAC8408 (IC2D) may be employed to add a bias level to the sweep signal. The original output from the MAX038 is centred around ground and it is convenient to modify this condition for most electrochemical experiments. The converter is bipolar voltage-output configured and uses the REF output from MAX038 as voltage reference. Therefore, it is possible to obtain voltages from \(-2.5\) to \(2.5\) V in 20 mV steps. The final output obtained may be centred over this bias value if desired.

The MAX038 is only for continuous signal generation. To obtain a sweep one period long or perhaps a half-period it is necessary to use an analog switch digitally controlled to shoot down continuous output. An MAX312 (IC4C in Fig. 1) (Maxim Integrated Circuits Data Book, b)\(^4\) is used for this purpose. The switch is closed only when a period or a half-period is generated. This operation mode implies obtaining an appropriate digital signal to control the switch, a signal like this should be one period long or a half-period long and should be synchronised with a period start. A digital circuit has been developed for this purpose, the so called single-sweep controller (see Fig. 2). This circuit takes the SINC TTL-output from the MAX038 and, by applying a narrow pulse SET, produces the desired signal.

A falling edge in SET signal leads to high level output at RS flip–flop (IC5A and IC5B). This output is tied to data input from D flip–flop (IC6A) and prepares for high at Q output when the SINC rises. At this moment Q and SINC signals are high and then IC5D output is low, resetting RS flip–flop and closes D (see time diagram in Fig. 2 for explanations).

While Q output is high, output for IC5D follows SINC signal by inverting. When a rising edge occurs at SINC, D is low and Q goes low returning to a rest state. IC5C is used as inverter to obtain the SS-CTRL signal.

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\(^3\) X9C103 Data sheet. Xicor Inc. (www.xicor.com).

that controls the analog switch for a half-period long sweep (Fig. 3c). A one period long sweep may be obtained by applying the Q signal to control the switch (Fig. 3a).

A debouncing circuit with a pair of 7414 trigger-smith inverters (IC7B and IC7C) must be included to clean edges on SINC signal. Due to high-speed TTL output circuit for SINC, a narrow spike may appear at transitions, this spike affects the correct operation of the single-sweep controller and must be eliminated.

Also, an 7474 inverter (IC7A) is included in SET signal to produce a narrow pulse at RS flip–flop input. The length of SET pulse is set by the time constant of an RC circuit. For the proposed values 1 μs was obtained. For proper operation SET pulse must be narrower than the SINC period at highest frequencies.

### 2.2. Digital control

To control the generation system a commercial board inserted on a PC is used. A CIO-DIO24 model from ComputerBoards has been chosen (ComputerBoards Technical Data Sheet). It is based on a 85C22 VIA chip which includes three eight-bit digital ports and an 85C56 timer-counter chip not used in this case. Bit assignation and use is shown in Table 1.

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**Table 1**

<table>
<thead>
<tr>
<th>85C22 Port</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port A (output)</td>
<td>Range control, SET and DAC8408 control (6 bits): A0 = CF2; A1 = CF1; A2 = SET; A5 = A/B; A6 = DS2; A7 = DS1</td>
</tr>
<tr>
<td>Port B (output)</td>
<td>DAC8408 data bus (8 bits)</td>
</tr>
<tr>
<td>Port C (output)</td>
<td>X9C103 and output stage control (4 bits): C0 = U = D; C1 = INC; C2 = CS; C3 = INV</td>
</tr>
</tbody>
</table>

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Software programmed for generation control is developed in Windows® by using the VisualBasic® compiler and the DLL files supplied by CIO-DIO24 buyers for administration, configuration and control of the board. This software runs under all Windows OS versions and its use is easy and friendly. It consists of a control panel to program the few parameters of generation (frequency output, bias level, amplitude output, duty cycle) and a button to start generation (Fig. 4 is a configuration example). This software and the masks to construct the complete IC board are available on demand to the authors.

3. Results

In general aspects, the performance of the generator is acceptable with respect to reproducibility and stability. It presents good linearity in test conditions (up to 1 MV s⁻¹). Only when signal period and response time of analog switch are comparable the generator performance falls drastically. There are a large number of analog switches available with a wide range of electrical characteristics (voltage switch range, stray resistance and capacitance, current leakage...). Therefore, if a DG211 (Intersil Data Book)⁶ is used and the sweep rate is about 1 MV s⁻¹ the resulting signal is strongly distorted at starting stages (Fig. 5). Time response for this device is 0.3–0.5μs, and is different for open and closed operations. Use of switches with shorter response times allows satisfactory results to be obtained for sweep rates up to MV s⁻¹. The MAX312 has lower response delay (<0.1 μs) and is pin-to-pin compatible with DG211.

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References


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Fig. 4. Control panel example for software configuration of generation system.

Fig. 5. Effect of analog switch’s electrical performance on output signal at the MV s⁻¹ range.

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