Strong Attenuation of the Transients' Effect in Square Waves Synthesized With a Programmable Josephson Voltage Standard

Blaise Jeanneret, Frédéric Overney, Alain Rüfenacht, and Jaani Nissilä

***Abstract*—This paper addresses the effect of transients on the operation of a 1-V programmable Josephson voltage standard for frequencies ranging between 125 Hz and 4 kHz. A detrimental effect of the transients occurring during the transition between different voltage steps is to make the ac Josephson voltage dependent on the bias current in the junctions. In other words, the current margins where the array behaves as a quantum standard are reduced to zero: the voltage steps have a slope. However, by using square waveforms, the effect of the transients can be reduced to a level where this slope is no longer measurable. This observation will probably lead to a simplification in the development of a new type of high-precision Josephson-based waveform synthesizer.**

***Index Terms*—AC measurements, Josephson devices, Josephson voltage standard, waveform synthesizer.**

I. Introduction

The fabrication of large series arrays of overdamped Josephson junctions in the 1990s has lead to the development of the programmable Josephson voltage standard (PJVS) [1], [2], which has now found applications in many different areas of electrical metrology (see [3] and [4] for the latest review articles). The original motivation was to develop a waveform synthesizer with a calculable RMS amplitude by rapidly switching between the different voltage steps available at the array's output. The presence of transient voltages occurring during the step transitions limits the accuracy of the PJVS in two different ways: they produce an error in the RMS value of the signal, and more dramatically, they make the Josephson voltage dependent on various parameters like the current bias settings in the array and the applied microwave power. Therefore, the PJVS system as a waveform synthesizer is no longer working as an intrinsic quantum standard [5]–[7].

The problem of transients has recently received much attention, and different solutions and approaches have been proposed to bring the measurement uncertainty below 1 μV/V up to frequencies of a few kilohertz. The first approach has been to reduce the transition time to a minimum by developing fast bias sources and appropriate wiring to the array [8], [9]. A second approach relies on sampling techniques to probe the Josephson waveform. The great advantage provided by this method is the possibility to ignore the nonquantized voltages occurring during the transients, allowing the PJVS to be used as a true quantum standard. Such a method is being used to develop a quantum-based ac waveform synthesizer [7] and voltmeter [10], [11]. PJVS systems combined with the use of sampling techniques are also involved in the field of low-frequency electrical power metrology [12], [13].

A third method based on square Josephson waveforms is addressed in this paper. With these particular waveforms, the effect of the transients, like in the first approach, cannot completely be cancelled. However, their influence on the value of the fundamental of the signal is drastically attenuated. The insensitivity of the square-waveform approach to the transients was predicted by Helistö *et al.* [14]. With this type of waveform, the fundamental component of the signal is much less affected by the transients than its total RMS value (the sum of the contributions of all the harmonics). An advantage of this method is that the fundamental of the signal can easily be measured with a lock-in amplifier, as proposed by Nissilä *et al.* in the design of a new type of ac synthesizer [15]. These new types of Josephson-based synthesizers, as described in [7] and [15], are instruments where the voltage accuracy and stability of a high-spectral-purity synthesizer is inferred from a Josephson stepwise-approximated reference waveform. In this paper, a systematic experimental and theoretical investigation of the transients' effect on square waveforms generated by a programmable voltage standard is reported.

II. Signal Modeling

The basic idea of the method can be understood by modeling the I–V curve of the array and the desired waveforms. In Fig. 1(a), an ideal I–V curve of a subarray of N Josephson junctions capable of generating a dc voltage of $\pm A$ is depicted. The arrows represent the successive changes in the bias current—supplied by an ideal current source—necessary to generate the quasi-square wave, of period T, which is represented in Fig. 1(b). Although this model is highly idealized, its predictions are in very good agreement with the experimental results, as will be shown in Section IV.

As the transition time between two different current states is finite (settling time τ), the generated waveform is not precisely a square wave, and a small zero-voltage state occurs at each

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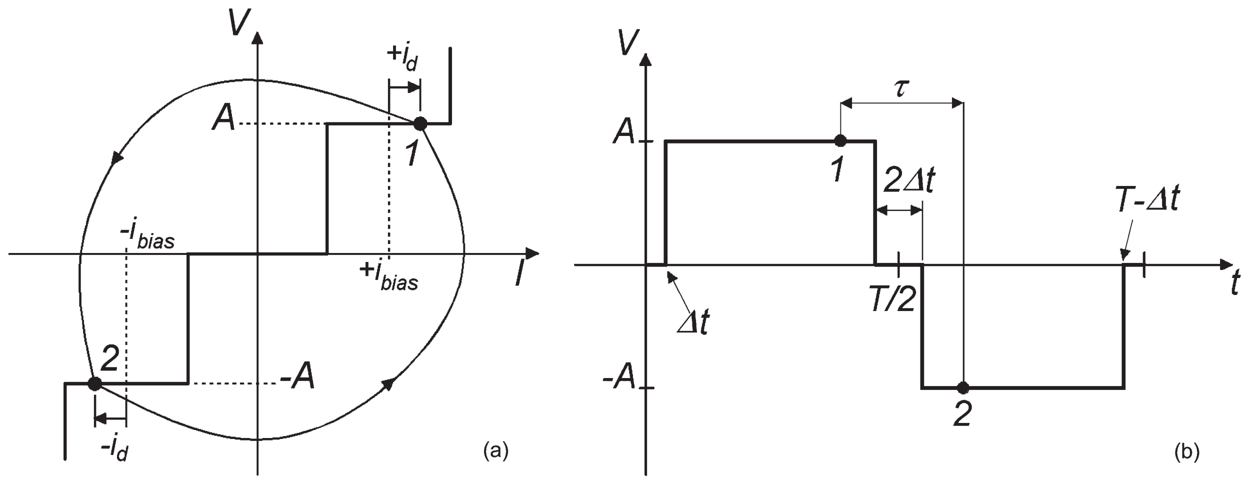

Fig. 1. (a) Idealized I–V curve showing the two transitions necessary to generate the square waveform shown in (b). The dither current i_d is the offset current from the center of the voltage step $i_{\rm bias}$. (b) Idealized quasi-square wave $V(t)$ generated by the output of the N-Josephson-junction array when the bias current successively switched between state 1 and state 2 with a period of T. See text for details.

transition [see Fig. 1(b)]. The duration of the zero-voltage state is proportional to τ and can be approximated by

$$2\Delta t = \frac{\Delta i_0}{2(i_{\rm bias} + i_d)}\tau \tag{1}$$

where Δi_0 is the width of the zero-voltage step of the I–V curve in Fig. 1(a), $i_{\rm bias}$ is the current corresponding to the center of the step, and i_d is the dither current, which is measured from $i_{\rm bias}$. If the time spent on the zero-voltage step is equal to $\Delta t = T/8$, the square wave is transformed into a staircase signal consisting of a waveform with four steps per period. This particular situation has previously been analyzed in detail [7].

Like every periodic function, the waveform in Fig. 1(b) can be represented by its Fourier series

$$V(t) = a_0 + \sum_{k=1}^{\infty}\left(a_k \cos\left(\frac{2\pi}{T}kt\right) + b_k \sin\left(\frac{2\pi}{T}kt\right)\right). \tag{2}$$

Since $V(t)$ is odd, the only nonzero Fourier coefficients are

$$\begin{aligned} b_k &= \frac{2}{T}\int_0^T V(t)\sin\left(\frac{2\pi}{T}kt\right)dt \\ &= -\frac{2A}{k\pi}\cos\left(\frac{2\pi}{T}k\Delta t\right)\left[(-1)^k - 1\right]. \end{aligned} \tag{3}$$

Equation (3) shows that even harmonics are not present in the waveform in Fig. 1 ($b_k = 0$ for an even k). The advantage of using a square waveform can very easily be understood from (3). The calculation of the amplitude b_k involves a product of the type $V(t)\sin((2\pi/T)kt)$. The trick is that the transients in the quasi-square waves are exactly located at the zero of the sinus. Therefore, the contribution of the transients in the calculation of the integral is suppressed by a factor $\sin((2\pi/T)kt)$, which is close to zero in the region of interest. The error due to the transients $[1 - \cos((2\pi/T)k\Delta t)]$ is proportional to $(\tau/T)^2$ and can be minimized to give corrections below one part in 10^6 in a practical experiment. In Fig. 2, the RMS amplitude, which is defined as $B_k = |b_k|/\sqrt{2}$, is plotted between $\Delta t = 0$ and

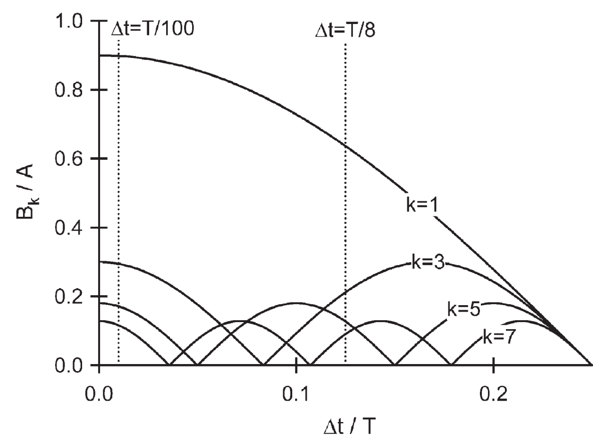

Fig. 2. Normalized RMS amplitude B_k/A of harmonics $k = 1$ to 7 as a function of $\Delta t/T$.

$\Delta t = T/4$ for harmonics $k = 1$ to 7. The vertical dashed lines represent the situation for two different waveforms: a quasi-square wave with $\Delta t = T/100$ and the staircase waveform previously mentioned with $\Delta t = T/8$. In addition, this figure shows that any particular harmonic contribution can be nulled by carefully selecting Δt.

Another detrimental effect of the transients, in addition to introducing an error in B_k, is to make the Josephson voltage dependent on the bias current [5], [7]: the array no longer works as an intrinsic quantum standard, and the voltage steps have a slope s_k defined as

$$s_k = \left.\frac{\partial B_k}{\partial i_d}\right|_{i_d=0} = \frac{\partial B_k}{\partial \Delta t}\cdot\left.\frac{\partial \Delta t}{\partial i_d}\right|_{i_d=0} \tag{4}$$

where $\partial B_k/\partial\Delta t$ is the slope of the curves plotted in Fig. 2.

Using (1) and (3), the slopes s_k become

$$\begin{aligned} s_k = \sqrt{2}A\frac{\Delta i_0}{i_{\rm bias}^2}\frac{\tau}{T}\sin\left(\frac{\pi}{2T}k\frac{\Delta i_0}{i_{\rm bias}}\tau\right) \\ \cdot\,\mathrm{sgn}\left[\cos\left(\frac{\pi}{2T}k\frac{\Delta i_0}{i_{\rm bias}}\tau\right)\right] \end{aligned} \tag{5}$$

TABLE I
JOSEPHSON-JUNCTION ARRAY MARGINS MEASURED AT DC. THE ROWS IN BOLD ARE THE SUBARRAYS INVOLVED IN THE SQUARE WAVEFORM USED IN THIS PAPER. THE FIRST COLUMN IS THE SUBARRAY NUMBER, N IS THE NUMBER OF JOSEPHSON JUNCTIONS IN EACH SUBARRAY, Δi IS THE WIDTH OF THE VOLTAGE STEPS, Δi_0 IS THE WIDTH OF THE ZERO-VOLTAGE STEPS

♯	N	i_{bias} (mA)	Δi (mA)	Δi_0 (mA)
1	**4096**	**4.65**	**2.50**	**6.00**
2	2048	4.63	2.53	6.00
3	1024	4.64	2.52	6.00
4	512	4.77	2.41	6.00
5	**256**	**4.64**	**2.80**	**5.60**
6	**128**	**4.81**	**2.04**	**6.70**
7	1	4.34	2.81	5.86
8	1	4.47	2.41	6.24
9	**2**	**4.68**	**1.97**	**7.22**
10	4	4.71	2.44	6.80
11	8	4.35	4.15	4.20
12	**16**	**4.61**	**3.08**	**5.82**
13	32	4.60	2.83	6.00
14	64	4.76	2.62	5.66

where $\mathrm{sgn}(x)$ is 1 or -1 for, respectively, a positive or negative x.

The total RMS amplitude for this waveform is given by

$$B_{\mathrm{tot}} = \sqrt{\frac{1}{T}\int_0^T V^2(t)dt} = A\sqrt{1 - \frac{\Delta i_0}{i_{\mathrm{bias}} + i_d}\frac{\tau}{T}}. \quad (6)$$

Finally, the slope s_{tot} of the total RMS value is given by

$$s_{\mathrm{tot}} = \left.\frac{\partial B_{\mathrm{tot}}}{\partial i_d}\right|_{i_d=0} = \frac{A}{\sqrt{1 - \frac{\Delta i_0}{i_{\mathrm{bias}}}\frac{\tau}{T}}}\frac{\Delta i_0}{2 i_{\mathrm{bias}}^2}\frac{\tau}{T}. \quad (7)$$

In comparison with the $(\tau/T)^2$ correction related to the harmonics, i.e., B_k and s_k, the correction on the total RMS value, i.e., B_{tot} and s_{tot}, decreases only like τ/T. This calculation emphasizes that, for square waveforms, the fundamental is less affected by the transients than the total RMS value. Therefore, an optimized measurement setup should focus on methods for extracting the fundamental amplitude rather than the total RMS voltage.

III. EXPERIMENTAL SETUP

The measurement system was described in detail in [7]. The Josephson array is a 14-bit superconductor–insulator–normal metal–insulator–superconductor (SINIS) array whose design and operation is fully described in [16]. Table I gives the operating parameters of the array: the number of junctions in each subarray, the bias current of the various steps i_{bias}, the width of the steps Δi, and the width of the zero steps Δi_0.

The electronics driving the array consist of 15 fast (with a rise time of 20 ns) programmable current sources. The output voltage of the array is read by a synchronous sampling system consisting of a commercial digitizer (a 24-bit analog-to-digital converter). The programmable current source supplies the trigger signal to synchronize the digitizer to the Josephson stepwise waveform. Both the bias electronics and the digitizer are frequency locked to a 10-MHz reference signal provided by a cesium clock. All the synchronization and triggering signals are carried by fiber optic links to avoid spurious coupling between the various components of the system. To test the influence of the transients, a Josephson square wave (as represented in Fig. 1) with an amplitude of 0.65 V and a frequency f ranging between 125 Hz and 4 kHz was studied. The digitizer measures the voltage of the SINIS array over eight periods at a sampling frequency of 200 kS/s. Although this sampling frequency does not allow the resolution of the features occuring during the transition, it is sufficient to reveal their influence on the fundamental, as described in Section II. This raw signal is used to calculate the RMS value of the fundamental and the harmonics of the signal using a discrete-Fourier-transform (DFT) algorithm. This procedure is then repeated a hundred times, and the average values are calculated to provide the coefficients B_k.

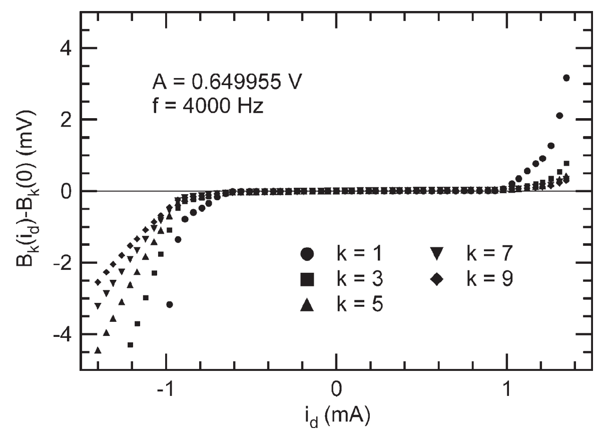

Fig. 3. Effect of the dither current on the RMS amplitude B_k for $k = 1$ to 9 at a frequency of 4 kHz.

IV. RESULTS AND DISCUSSION

The effect of the dither current i_d can be investigated by repeating the B_k measurements for different values of i_d. Corrections for the digitizer drift, which is about 10^{-6}/min, were applied by performing the following measurement sequence: $\{B_k(0), B_k(+i_d), B_k(-i_d), B_k(0)\}$, which was repeated ten times. Fig. 3 shows the RMS amplitude for several harmonics at a frequency of $f = 4$ kHz and an amplitude of $A = 0.65$ V. The departure from the voltage steps is visible around $\pm$ 1 mA. Fig. 4 displays the behavior of the voltage steps in more detail. The measured RMS amplitudes clearly show a slope that increases with the harmonic index k. The line is the result of the model [see (5)] with the parameters mentioned in the legend. In the model, the amplitude A and the frequency f were kept constant. The rise time at the output leads was measured with a fast oscilloscope. Its value, i.e., $\tau = 790$ ns, is much larger than the electronic settling time and is fully dominated by the wiring and filtering properties of the cryoprobe. The parameters Δi_0

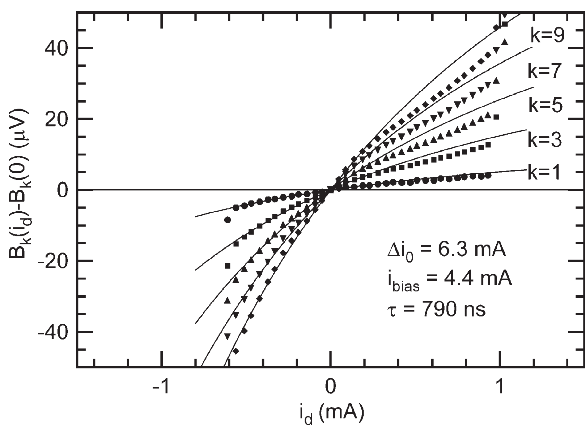

Fig. 4. Same as Fig. 3 with an expanded vertical scale ($\times$ 100) to appreciate the details on the voltage steps. The lines represent the model [see (5)] using the parameters specified in the legend.

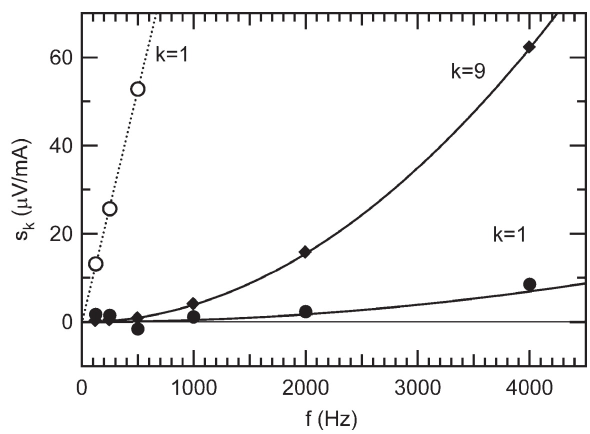

Fig. 5. Solid symbols: frequency dependence of the slope s_k of the quasi-square wave as a function of the frequency for harmonics $k = 1$ and $k = 9$. Solid line: model given by (5) using the parameters in Figs. 3 and 4. Open symbol: for comparison, the slope of the staircase signal of [7] is also given.

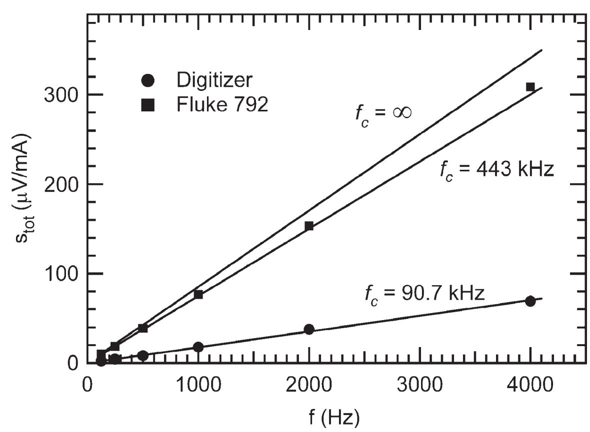

Fig. 6. Measured slope $s_{\rm tot}$ as a function of the frequency for measurements with the digitizer (circle) and the Fluke 792 (square). The solid lines show the results of the model [see (9)] for the cutoff frequency corresponding to the different cases.

and $i_{\rm bias}$ are extracted from a fit to the data. As emphasized in Table I, the voltage of the square waveform is the sum of five active PJVS subarrays, involving ten dc bias parameter settings (Δi_0 and $i_{\rm bias}$). For every polarity change, the current is reversed in nine different bias current lines, each with its own rise time. The model presented in Section II [see (5)] is based on a single idealized I–V curve and does not include the contribution of the individual parameters. Despite the relative simplicity of this model (ideal I–V curve and ideal current source), the values obtained for Δi_0 and $i_{\rm bias}$ are in good agreement with the measured dc bias parameters in Table I.

In reality, the I–V curve is far from ideal, and the ideal current source is, in fact, a voltage source with a 50-Ω impedance. Therefore, the transition region does not really look like what is depicted in Fig. 1(b). To better model the real behavior, we have assumed a transition from +A to −A, which is linear during the lapse of time $2\Delta t$. There is no longer a zero-voltage step. The results of this more realistic model are not analytical; however, they are basically the same as those of the model described in Section II with a slightly different set of parameters. This shows that the precise way the transition takes place has little influence on the dither current dependence of the Fourier coefficients. Rather than the transition shape, the timing effect associated with the transition from one voltage level to another plays a crucial role. The $\tau - 2\Delta t$ transition time where the voltage is still quantized (+A and −A) essentially contributes to the dither current dependence of either the harmonic content or the total RMS voltage [5], [6].

For this square waveform, the amplitude of the slope monotonically increases with k. This behavior is completely different from what was observed with a staircase signal [7], where only the sign of the slope depends on k. This difference in behavior can be observed in detail in Fig. 2 for the case of $\Delta t = T/100$ (quasi-square wave) and $\Delta t = T/8$ (staircase signal).

The frequency dependence of the slope s_k is shown in Fig. 5 for harmonics $k = 1$ and $k = 9$ up to 4 kHz. From (5), it can be seen that, in the limit $\tau \ll T$, $s_k \propto k(\tau/T)^2$, as shown in the graph. The solid lines in Fig. 5 were calculated with the parameters mentioned in the legend of Figs. 3 and 4 without any fitting procedure. As can be seen, the agreement between our data and the model is excellent. For comparison, the results obtained with the staircase signal previously mentioned are also shown for $k = 1$. The staircase signal shows a linear frequency dependence whose magnitude is much larger than the one of the square waveform. At 1 kHz, the square waveform allows for a reduction of s_1 by a factor of 200 in comparison with a staircase signal of identical amplitude and frequency. At 4 kHz, this factor drops to 60, which is still a non-negligible improvement. Since the slope is proportional to τ^2, a further improvement may easily be achieved by removing the filters and improving the wiring of the cryoprobe. Such modifications would bring τ below 100 ns, providing a reduction in the measured slopes by a factor 64. Such an improvement would make the slope so small that it will be difficult to measure within our present resolution of 200 nV/mA.

It is also instructive to measure the slope of the total RMS value $s_{\rm tot}$, which is given by (7). The measurements were performed with either the digitizer or a thermal transfer standard (Fluke 792). The RMS value $B_{\rm tot}$ obtained with the digitizer was directly calculated from the raw data i.e., without performing the DFT. The results displayed in Fig. 6 show a large difference between the two methods. This difference can be explained by the bandwidth of the measuring system, which is always finite and introduces a cutoff frequency f_c. The RMS value of the voltage with a limited bandwidth is given by

$$B_c = \sqrt{\sum_{k=1}^{k_{\max}} B_k^2} \tag{8}$$

where $k_{\max}$ is related to the cutoff frequency by $k_{\max} = \mathrm{round}(f_c/2f - 1)$. This gives the following relation for the slope s_c:

$$s_c = \left.\frac{\partial B_c}{\partial i_d}\right|_{i_d=0} = \frac{\sum_{k=1}^{k_{\max}} s_k B_k}{\sqrt{\sum_{k=1}^{k_{\max}} B_k^2}}. \tag{9}$$

This last expression can be compared with the measurement in Fig. 6. Although the thermal transfer standard (Fluke 792) has a broad bandwidth, we measure a relatively low cutoff frequency ($f_c = 443$ kHz) due to the filtering effect of the measurement system. In the other case, the digitizer itself further limits the bandwidth to $f_c = 90.7$ kHz, according to its specifications. As can be seen in Fig. 6, this model describes the data extremely well. For completeness, the calculation for an infinite bandwidth obtained with (7) and the parameters in Fig. 4 is also included. By comparing the vertical scale in Figs. 5 and 6, the benefit of measuring the fundamental clearly appears: the slope s_1 is much smaller than the slope of the total RMS value s_{tot}.

The aforementioned results clearly show that the effects of the transients are drastically reduced with the use of square waveforms. In fact, their impact can be decreased to a level where it is no longer measurable for $k = 1$ at frequencies between 1 kHz and 4 kHz. These results emphasize that, for square waveforms, the fundamental component of the signal is much less affected by the transients than its total RMS value. Therefore, an optimized measurement setup should focus on methods for extracting the fundamental amplitude rather than the total RMS voltage. This observation will probably lead to a simplification in the development of a new type of high-precision Josephson-based waveform synthesizer. For square-wave generation, the bias electronic no longer needs to be a sophisticated 15-channel current source, and since the first harmonic is calculable, a lock-in amplifier detection will be sufficient to measure the voltage. This approach has been proposed earlier by Nissilä *et al.* [14], [15]. This paper shows that the RMS amplitude of the fundamental of the square waveform is independent of the bias current over a certain range. The existence of such margins is the first requirement for the feasibility of such a Josephson-based synthesizer.

V. Conclusion

This paper has addressed the effect of the transients on the operation of a 1-V PJVS for frequencies ranging between 125 Hz and 4 kHz. A dramatic effect of these transients is to make the Josephson voltage dependent on the bias current in the junctions. In other words, the current margins where the array behaves as a quantum standard are reduced to zero: the voltage steps have a slope. However, by using square waveforms, the effect of the transients can be reduced to a level where this slope is no longer measurable within our present detection limit of 200 nV/mA. These results emphasize that, for square waveforms, the fundamental component of the signal is much less affected by the transients than its total RMS value. Therefore, an optimized measurement setup should focus on methods for extracting the fundamental amplitude rather than the total RMS voltage. This observation will probably lead to a simplification in the development of a new type of high-precision Josephson-based waveform synthesizer.

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