Development of a 60 Hz Power Standard using SNS Programmable Josephson Voltage Standards

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Abstract

We are implementing a new standard for 60 Hz power based on precision sinusoidal reference voltages from two independent Programmable Josephson Voltage Standards (PJVS) (one for voltage and one for current). The NIST PJVS systems are based on superconductor - normal metal - superconductor (SNS) junctions. Using step-wise approximation synthesis, the PJVS systems produce sinewaves with precisely calculable rms voltage and spectral content. The uncertainty contributions from the Josephson references are expected to be a few parts in 10^7, which will enable the development of an ac power standard with overall uncertainties of a few parts in 10^6.

Introduction

Following the development of series arrays of intrinsically shunted Josephson junctions in the mid 1990's [1,2], there has been considerable work demonstrating their use as Programmable Josephson Voltage Standards to generate waveforms with precisely known rms values for ac metrology. Using step-wise approximation techniques, these devices are used to produce a variety of arbitrary waveforms including high accuracy ac-dc difference measurements at frequencies up to 1 kHz [3, 4], fast reversed dc comparisons (FRDC) between Josephson sources and thermal voltage converters [5, 6], and more recently impedance and power metrology [7].

System Configuration

The sinusoidal Josephson voltages in the new 60 Hz power standard will consist of two independent SNS arrays, each with separate amplitude and phase controls. Figure 1 illustrates one possible configuration of the system, where $V_{PJVS\text{-}V}$ is a 1.2 V_{rms} reference sinewave for the voltage channel and $V_{PJVS\text{-}I}$ is a 0.5 V_{rms} reference sinewave for the current channel. A 100x amplifier scales $V_{PJVS\text{-}V}$ up to 120 V_{rms}, which is applied to the power-meter under test (MUT). This same 120 V signal is divided down by a factor of 100 by use of an inductive voltage divider (IVD), and then compared in real time with $V_{PJVS\text{-}V}$ so that any gain drift in the 100x amplifier can either be calibrated or actively stabilized using servo feedback. For the MUT current channel, $V_{PJVS\text{-}I}$ is fed to a V-to-I converter to generate a current on the order of 5 A. A multi-stage current transformer with a precisely known burden resistance is used to measure this current so that gain drift in the V-to-I conversion can be measured (and again either calibrated out or removed using feedback).

The Josephson circuits for this application are double-stacked $MoSi_2$-junction SNS arrays containing 67 408 SNS junctions connected in series to produce ±2.5 V and divided according to a ternary weighting scheme [8]. The six least significant bits (LSBs) use a standard ternary configuration with a resolution of 16 junctions (612 μV at 18.5 GHz),

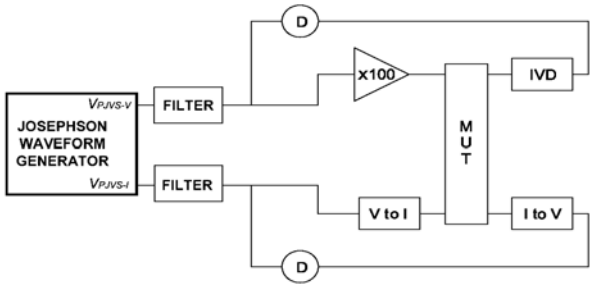

Figure 1. Example of one possible implementation of the power standard with two Josephson reference voltage waveforms. The symbol "D" denotes high precision phase-sensitive detectors.

which enables the array to generate 8427 different quantum output levels. The sizes of the seven most significant bits (MSBs) are not a strict ternary implementation, but this enables the entire chip to have 2 mA current margins by not exceeding 8800 junctions in any array segment. Some MSBs have 2, 4, or 8 junctions removed to improve the effective resolution to just 2 junctions (at less than ¾ full-scale) by use of appropriate pairs of MSBs in opposition to each other. The chips are flex-mounted to ensure uniform microwave power distribution and long-term cryopackage reliability [9].

Sinewave Synthesis

The advantage of using Josephson voltage sources for this 60 Hz power standard (instead of conventional semiconductor waveform synthesizers) is that once the SNS arrays settle into the quantized state for each voltage level in the output waveform, the chip output voltage is precisely known. In a sinewave synthesized using the step-wise approximation method, the harmonic content is reduced by increasing the number of steps. However, since the voltage is not precisely known during transitions between quantum levels, a large number of transitions increases the uncertainty. For this reason, optimizing the number of transitions requires finding the proper balance between high spectral purity and reasonably low uncertainty for the rms voltage.

Consider the case where the number of samples per cycle, N, equals 512. Figure 2 shows the magnitude of the eight largest digitization harmonics relative to the fundamental. The effect on the rms voltage of these eight largest harmonics is summarized in Table 1. Since we aim to produce a pure 60 Hz tone, we refer to any harmonic that contributes more than a part in 10^7 to the rms voltage as an "error". Notice that there are pairs of digitization harmonics at 60Hz * (m*N ± 1) for each integer multiple m of the number of samples.

Another important feature in Fig 2 is the structure of all the other harmonics at integer multiples n of 60 Hz (from n = 2 to 2500 on this scale). These harmonics are due to waveform distortion caused primarily by the finite transition time between levels. Finite rise-times for these step-wise approximated waveforms will always create harmonic

distortion and affect the amplitude of the fundamental. In fact, our proposed Josephson source will also have finite transition times (on the order of 10 nSec), and we plan to address this critical issue in a later paper.

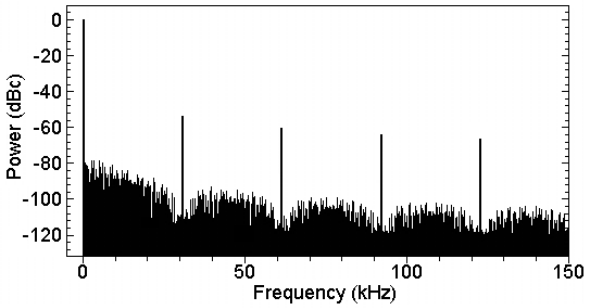

Figure 2. Fourier transform of a 512-sample sinewave at 60 Hz showing the magnitudes and frequencies of the first eight digitization harmonics (i.e. the first four pairs, the dominant harmonics for this particular application). This measurement was made using a commercial semiconductor waveform generator, and the spectrum shown is consistent with theoretical calculations.

In this example, the eight largest digitization harmonics cause the total rms voltage to be 5.4 μV/V higher than the fundamental itself (i.e., the square-root of the sum of the squares (RSS) of the 1 V_{rms} fundamental and the eight mV_{rms} values in Table 1). This would be a real measured error for instruments with a bandwidth of a few megahertz or higher. The effects of these digitization harmonics can be managed in several ways, including (a) Adding a carefully characterized low-pass filter to the SNS array output that attenuates these harmonics without appreciably changing the fundamental, thus taking advantage of the large gap in frequency between 60 Hz and the first digitization harmonic; (b) Modifying the 100x amplifier and the V-to-I converter in Fig. 1 to perform this same low-pass operation; (c) Increasing the number of samples so that the digitization harmonics are at higher frequencies and easier to filter. The latter approach requires that transitions between quantum levels be more carefully characterized and/or directly measured because the SNS arrays would be spending more time in transitions and less time in quantized voltage states.

Table 1 – Calculated values of the first eight digitization harmonics for a 1 V_{rms} synthesized sinewave at 60 Hz using $N = 512$ samples. The last column (the error that each harmonic would individually produce in the total rms voltage) decreases rapidly for increasing harmonic number.

Harmonic	Harmonic Number	Frequency (kHz)	Power (dBc)	Voltage (mV_{rms})	Error (μV/V)
N-1	511	30.66	-54.2	1.95	1.9
N+1	513	30.78	-54.2	1.95	1.9
2N-1	1023	61.38	-60.2	0.97	0.48
2N+1	1025	61.50	-60.2	0.97	0.48
3N-1	1535	92.10	-63.7	0.65	0.21
3N+1	1537	92.22	-63.7	0.65	0.21
4N-1	2047	122.82	-66.2	0.49	0.12
4N+1	2049	122.94	-66.2	0.49	0.12

Filter Design

Final implementation of a power standard utilizing step-wise approximated sinewaves from SNS arrays will most likely include filters on both PJVS outputs. The number of poles and cut-off frequency for those filters will depend upon how we balance the errors associated with the number of samples and the fraction of time the arrays are on quantized voltage levels. To select the proper filter cutoff frequency consider Table 2, which shows the magnitude of the largest digitization harmonics (i.e. the first pair: N-1 and N+1) and their combined rms voltage error for different numbers of samples.

At $N = 2048$ samples, the error from the first pair of digitization harmonics is only 0.24 μV/V, even without any filtering. Decreasing N to 512 samples reduces the total time of transitions by a factor of 4 (reducing the total uncertainty due to transitions by the same factor), but requires a filter with a 3 dB point around 10 kHz (recall from Table 1 that we need to suppress the 5.4 μV/V combined error from the first eight digitization harmonics). For $N = 256$ and below, the digitization harmonics are large enough that it would be difficult to filter them without negatively impacting the uncertainty at the fundamental. We will probably choose a value of $512 \le N \le 1024$.

Table 2 – Frequencies and error contribution of the most significant digitization harmonics (the first pair) for a 60 Hz sinewave with various numbers of samples.

Number of Samples	Freqs of the first pair of Digitization Harmonics (kHz)	Power at each of those freq (dBc)	Combined Error (μV/V)
256	15.30 and 15.42	-48.2	15.3
512	30.66 and 30.78	-54.2	3.8
1024	61.38 and 61.50	-60.2	0.95
2048	122.82 and 122.94	-66.2	0.24
4096	245.70 and 245.82	-72.2	0.06

Conclusion

We have discussed the feasibility of using SNS arrays to construct a new standard for 60 Hz power based on Josephson sinusoidal sources. With optimized filter design and digitization harmonic placement, this system should be able to generate reference sinewaves with suitably low errors due to harmonics. Future work will include careful characterization of the transitions to determine how to provide the best total uncertainty at the 60 Hz fundamental.

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