Linking Primary Power Standards and Programmable Josephson Arrays

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Abstract

Sampling systems have been employed as primary power standards at a number of National metrology institutes all over the world for a long time [1]. The PTB primary standard [2] uses a programmable, highly stable two channel source, whose outputs are amplified to provide the voltage and current signals, *U* at the 120 V level and *I* at 5 A, to the device under test. An inductive voltage divider and a current-to-voltage converter then adapt these signals to the 10 V input range of a sampling voltmeter. The power at the device under test is calculated from the sampled data and compared to the reading from the device under test.

Recently, precision waveforms with accuracies better than 1 part in 10^7 at power frequencies have been available [3] from series arrays of shunted Josephson junctions operated as digital to analog converters with fundamental accuracy [4].

PTB is currently continuing its efforts to integrate such a Josephson waveform synthesizer into its primary power standard [5] in order to continuously calibrate the sampling voltmeter and thus reduce the uncertainty for the measurement of active, reactive and apparent power at the 120 V and 5 A levels.

1. Introduction

PTB started the effort linking ac Josephson Waveform Synthesizers (JWS) with power standards by using the JWS to characterize the digital sampling voltmeter (DSV) used in the PTB primary power standard [5]. This work provided further motivation to the present endeavor to integrate a JWS into the PTB primary power standard. As a result of these initial studies, it was decided to employ the inherent characteristics of Josephson derived voltages and waveforms to continuously calibrate the DSV in the primary power standard.

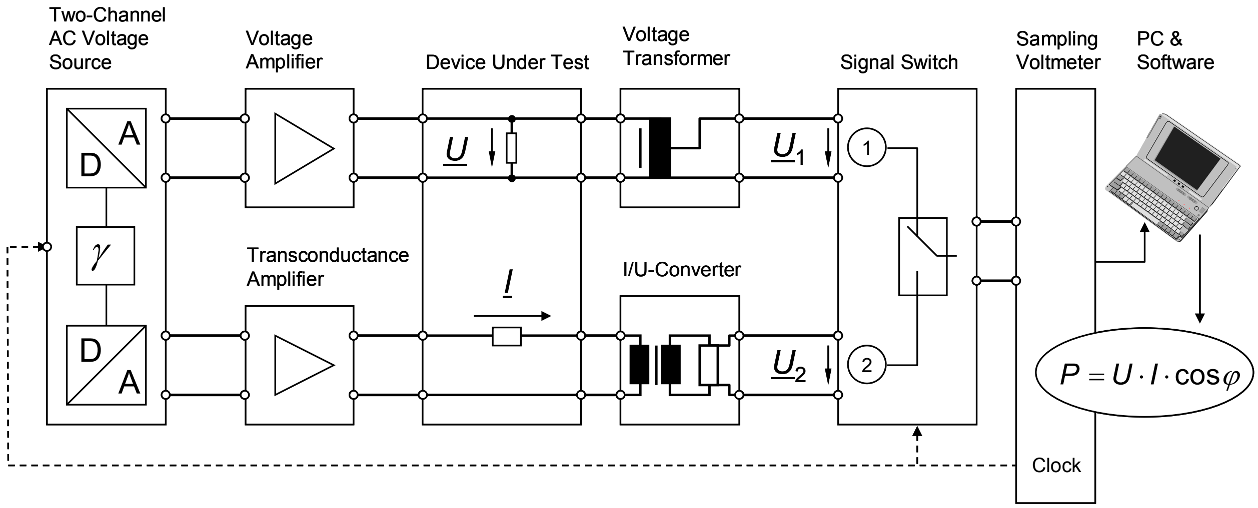

Figure 1. Block diagram of the PTB primary power standard.

This article presents initial results for the integration of a JWS into the PTB primary power standard. There are at least two alternatives for integrating a JWS into a power standard: as a double source or as an additional generator used to calibrate the sampling voltmeter "in-situ". The investigations which led PTB to select this second option are summarized in this article. Apart from reducing the traceability chain for the voltmeter to a minimum, this approach uses the JWS to calibrate the DSV as part of each measurement, therefore reducing the dominant uncertainty contribution.

The availability of digital to analog converters with fundamental accuracy, first proposed in [4] and since then developed by a number of National metrology institutes, has resulted in a considerable effort being devoted to the generation of precision ac waveforms and their applications in metrology [6]. Pulse driven Josephson arrays generate ac waveforms with highly pure frequency spectra but are at present limited to amplitudes below 500 mV [7]. On the other hand, programmable series arrays of Josephson junctions divided into segments whose number of junctions follow a binary sequence (binary arrays) have offered 10 V amplitudes for a few years [8]. Biased by suitable electronics, the voltage across a binary array can be changed quickly – in a matter of 10 ns or 100 ns – thus generating staircase approximations of voltage waveforms.

2. Synthesis of precision waveforms

Precision ac waveforms consisting of steps of constant amplitude, or samples, with quantum accuracy and amplitudes in the 1 V region can significantly improve the accuracy of a number of metrology applications. Previous investigations have shown that precision ac waveforms can be generated using 1 V binary SINIS Josephson arrays with uncertainties below 1 x 10^{-7} for frequencies up to 200 Hz [3]. Applications include calibrating dc voltage reference standards, characterizing Analog to Digital Converters (ADCs) [5], Sigma-Delta analog to digital signal conversion [9] and, as reported in this article, their inclusion into power standards.

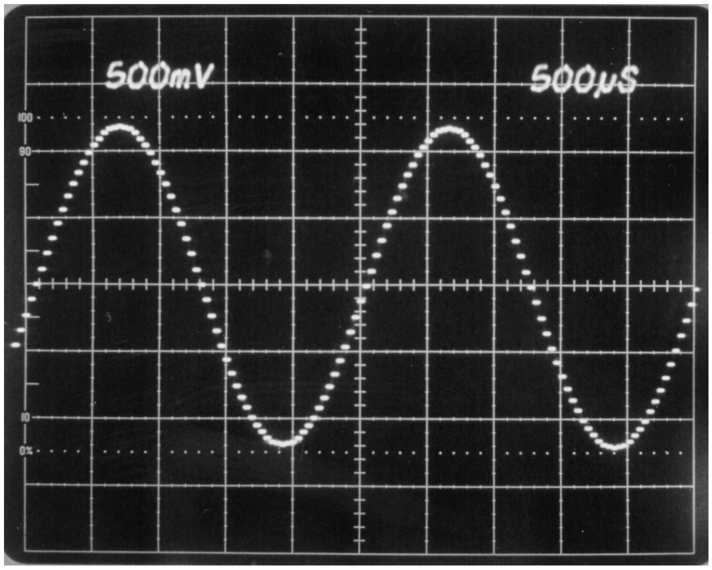

Figure 2. 400 Hz sine wave generated with a JWS and 64 samples per period.

The superconductor–insulator–normal metal–insulator–superconductor (SINIS) Josephson arrays are operated at a frequency of 70 GHz and require approximately 15 mW of microwave power, measured at the finline antenna. A more detailed description of the layout and the fabrication process is given in [8] and [10].

The latest fabrication runs have confirmed the availability of arrays with steps of constant voltage over the whole operating range and with a width in excess of 1.2 mA centered at currents between 2 mA and 4 mA. Furthermore, they also have shown promising results towards achieving 10 V programmable arrays with similar step widths in the coming months.

PTB is devoting a considerable effort to the development of 10 V arrays with operating parameters optimized for their use in Josephson Waveform Synthesizers (JWS) but operating at microwave powers comparable to those from dc voltage standards region with superconductor–insulator–superconductor Josephson arrays. The current design has 13 segments which can be individually biased to the -1, 0 or +1 step, hence allowing 2^{14} (16 384) voltage levels of quantum accuracy.

At the same time, NPL in the UK has developed fast bias electronics suitable for generating precision waveforms with amplitudes in the region of 1 V [11]. Building on from the experience gained from Josephson dc voltage standards, the ground potential of the electronics, and thus of the array, can be connected to any desired potential or “floated”. A sample 400 Hz waveform from the JWS is shown in Figure 2. Depending on the number of constant amplitude samples per period N used, the bias source allows generating waveforms between 1 Hz and approximately 3 kHz for N = 256 or 10 kHz for N = 64. Furthermore, dc voltages can also be generated.

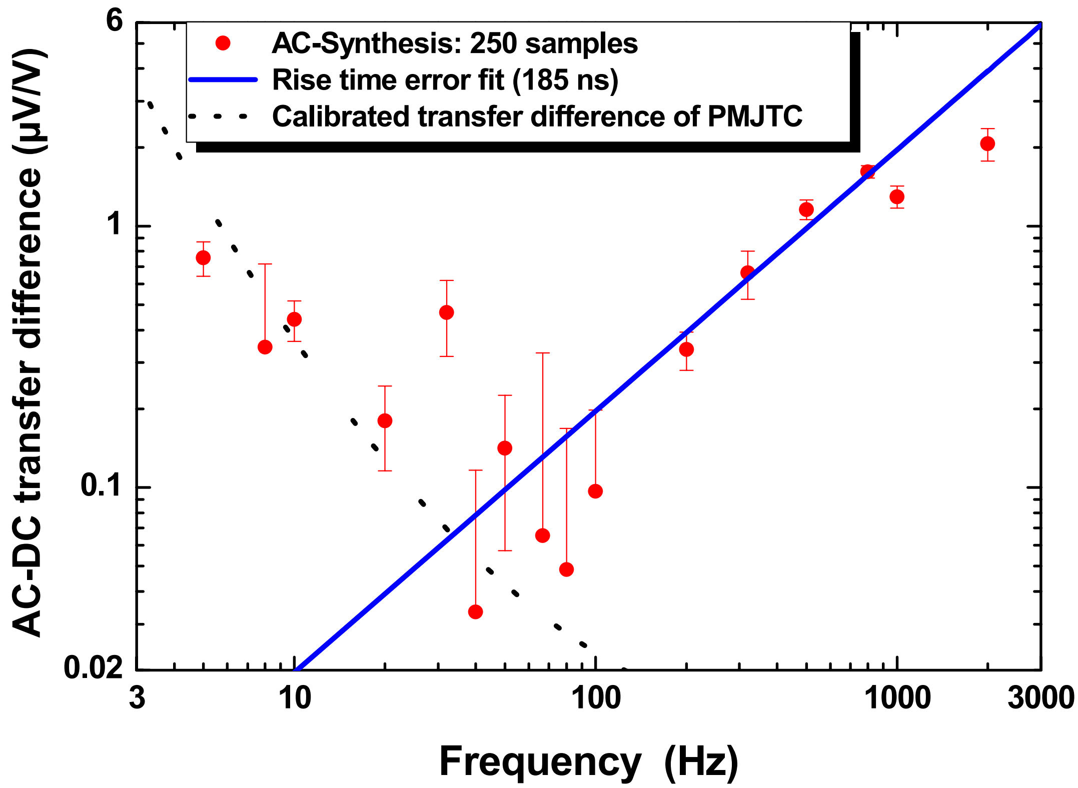

Figure 3. Difference between measured and calculated rms values of synthesized sine waves as a function of frequency. The rms values were measured using a PMJTC.

Figure 3 shows the measured ac–dc transfer differences using a Planar Multi Junction Thermal Converter (PMJTC) in the frequency range of 5 Hz to 2 kHz using 250 samples. The ac–dc transfer difference is given as the difference between and the measured rms value of the synthesized sine wave and the calculated value for an ideal, i.e. with infinitely fast transients, waveform. The error bars indicate an 1 σ standard uncertainty of the transfer measurement which is dominated by noise and drift of the PMJTC.

The solid line is a least squares fit to the expected linear increase with sine wave frequency of the error due to the limited rise time of the bias source. This fit gives an effective risetime of 185 ns in good agreement with a measured 10% to 90% rise time of about 170 ns [11]. At low frequencies, the characteristic increase in the ac–dc transfer difference for these devices [12] is also clearly visible. The measurements are in good agreement with the dotted line which is a fit to a calibration of the same PMJTC using sampling methods [13].

Recently, the model for the JWS waveform has been refined and a new electronic design for the bias sources has reduced the duration of the transients to some 50 ns. As the Josephson array defines the voltage during the duration of the samples, the length, shape and reproducibility of the transients becomes the dominant contribution to the uncertainty of the waveform. The evaluation improvement resulting from this significant reduction is currently being evaluated [14].

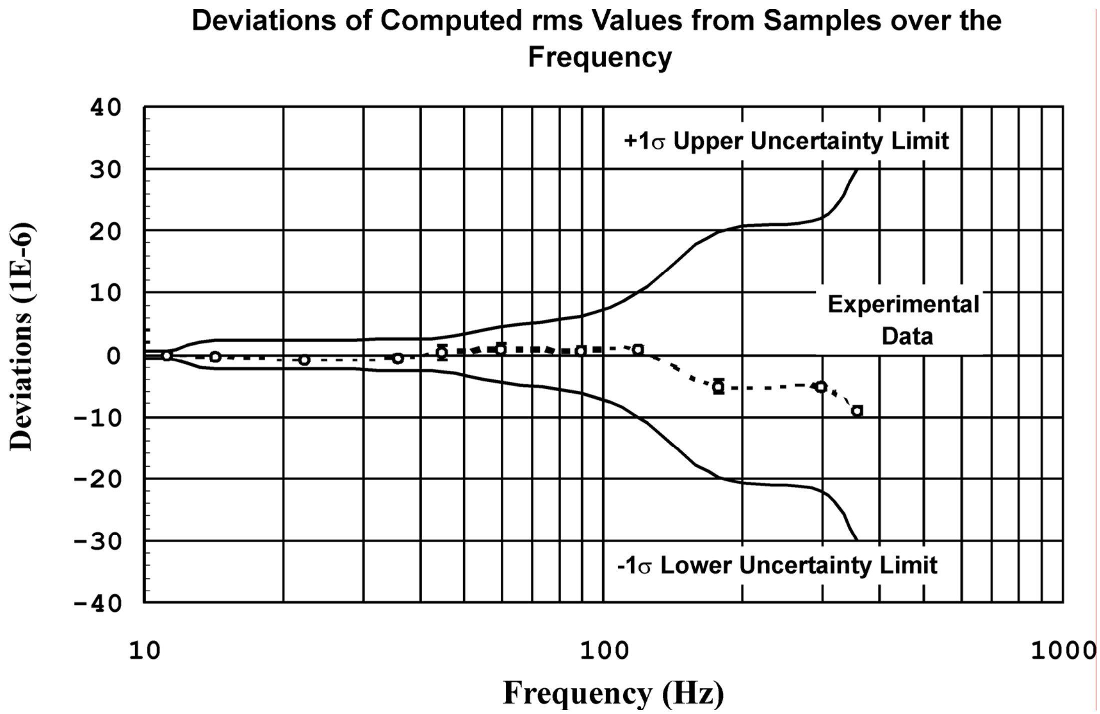

Figure 4. Deviation of the rms value computed from samples from the true rms value determined from the amplified quantized steps in the time domain in the 10 V input range of a DSV. The standard deviations of the measurements are also shown, although not readily apparent.

3. Characterization of the sampling ADC

Initial studies at PTB employed triangular waves generated by a JWS to characterize the DSV used in the primary power standard. As shown in Figure 4 for the effective value calculated from the voltage samples, the performance of the JWS allows characterizing the DSV significantly beyond the performance specifications provided by the manufacturer.

Introducing a JWS into the primary power standard would provide direct traceability to a Josephson voltage standard, eliminating intermediate links currently employed.

At present, the voltage at the device under test results in a signal with 8.5 V amplitude and would thus profit from the availability of 10 V binary arrays and the corresponding biasing electronics.

The current through the device under test is converted to a voltage signal of 1.5 V amplitude and is nearly matched by the voltages presently delivered by JWS.

4. Integration of the JWS into the power standard

The PTB power standard, shown in Figure 1 and explained in detail in [2], uses a two-channel ac voltage source to generate two sinusoidal voltages with a defined phase shift γ in the range 0° to 180° between them. A voltage amplifier supplies the voltage (e.g. 120 V) to be applied to the

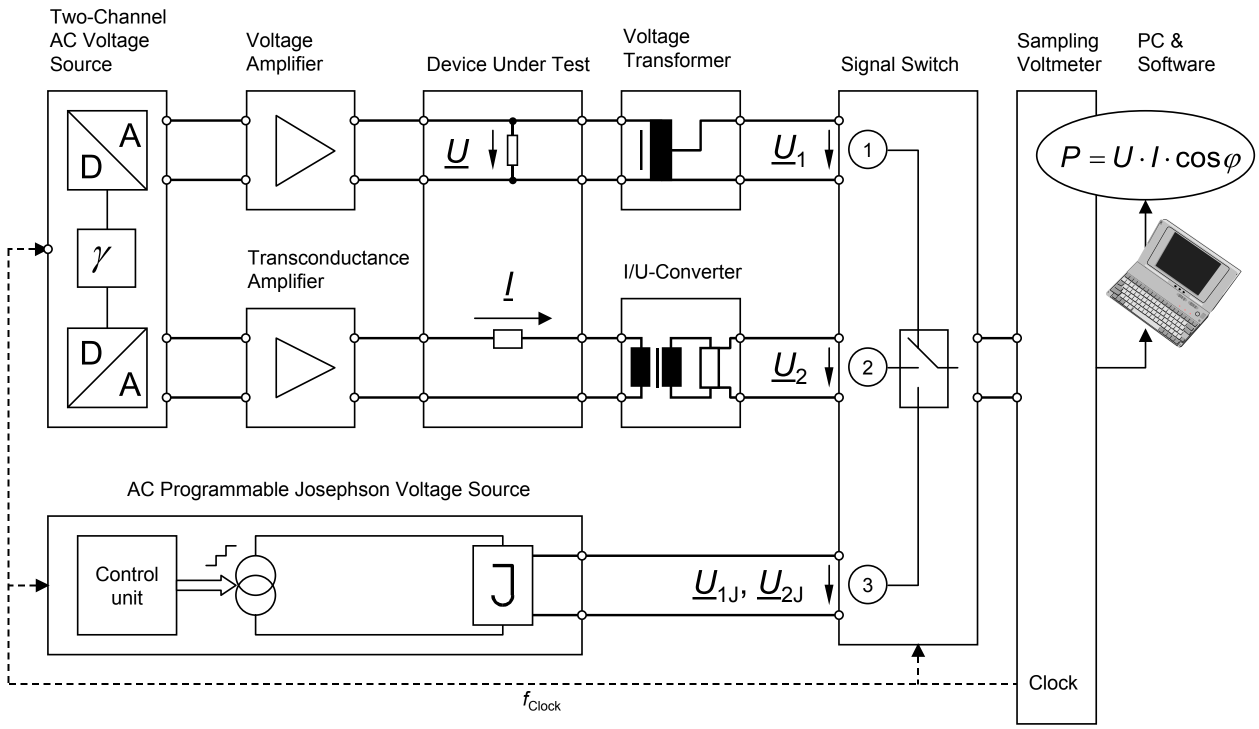

Figure 5. Block diagram of the proposed integration of a Josephson Waveform Synthesizer into the PTB power standard.

device under test and in parallel to the voltage transformer. A transconductance amplifier generates the current (e.g. 5 A) to be supplied to the load and which is also routed to the primary

of a current transformer burdened with an ac shunt The two voltages $\underline{U}_1$ and $\underline{U}_2$ with nominal peak values of ±8.5 V and ±1.5 V respectively (from the secondary of the voltage transformer and from the burden at the secondary of the current transformer), are connected to the sampling voltmeter in succession by means of a signal switch.

The dominant contribution to the uncertainty for power measurements is due to the sampling voltmeter [2]. It was therefore decided to investigate first the improvement which results from integrating a JWS according to the block diagram in Figure 5. With this arrangement, the DSV can be calibrated immediately before and after measurements. Furthermore, ratio measurements relative to the voltage steps generated by the JWS can be performed for each set of measured data.

The signal at the input of the DSV when the second channel is connected to a JWS is shown in Figure 6. The sampled data from $\underline{U}_1$ -on the left hand side- and $\underline{U}_2$ are used to calculate $\underline{U}$, $\underline{I}$, and the phase angle between them at the device under test, φ. The power $P = U \cdot I \cdot \cos\varphi$ is then calculated and compared to the reading from the device under test.

The internal connection between the ground terminal for the clock, trigger in- and output signals and the array reference potential in the NPL bias source has been removed by using optoelectrical and electro-optical converters. Furthermore, additional commands have been programmed into the control software for synchronizing it with an external source.

The system proposed for continuously calibrating the DSV is shown Figure 5. in would enable reducing the uncertainty contribution from the voltmeter, which is the dominant contribution for the primary standard [2]. The proposed system is shown in Figure 5.

6. First results

The sampling voltmeter, the double source and the JWS shown in have been successfully synchronized. Initial measurements have been performed by connecting the JWS instead of the "current" signal, $\underline{U}_2$ in Figure 6. For clarity, only a small time window around the transition between the two waveforms, with the JWS output on the right hand side, is shown. The switching transient is smoothed by adjusting the phase of the JWS in order to match both voltage levels when the switch is toggled. The stability of the phase relationship between the two waveforms and also relative to the sampling clock in the DSV was confirmed by the overlapping data points corresponding to acquisitions performed with three different initial delays relative to the edge of the trigger pulse.

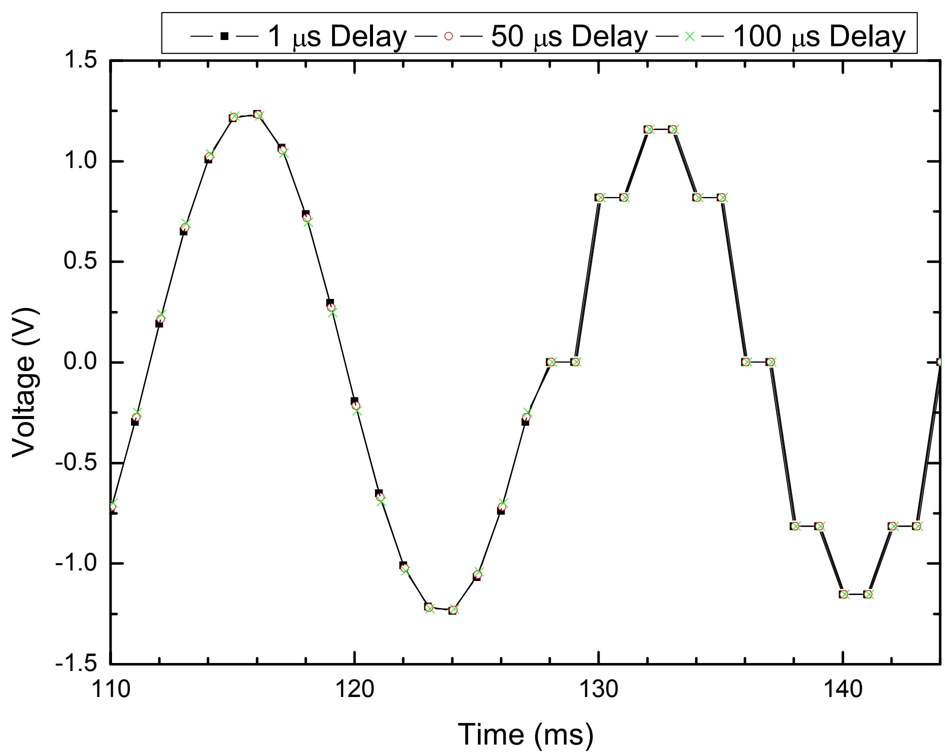

Figure 6. Typical signal at the DSV input around the switching transient from a sine wave to a JWS signal for three initial delays relative to the trigger pulse. The constant voltage samples from the JWS are clearly visible on the right hand side.

Initial analysis of the two data points acquired during each sample of the JWS waveforms (see Figure 6) shows that an uncertainty in the region of 400 nV is attainable by averaging Josephson voltage readings from successive single sampling windows within a few minutes. This corresponds to a relative uncertainty of $3x10^{-7}$ for the "current" signal $\underline{U}_2$.

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