Measurement of Leakage Current to Ground in Programmable Josephson Voltage Standards

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***Abstract* — The voltage error associated with the leakage current of programmable Josephson voltage standards (PJVS) is one of the largest contributions to the uncertainty in direct comparison of voltage standards. Due to the parallel biasing scheme of the PJVS and the resulting multiple leakage paths, the quantities "leakage resistance" and "leakage current" are not necessarily equivalent. A method to measure and model the leakage current to ground for a given PJVS output voltage is presented. By upgrading simple components of the NIST system, the leakage current to ground can be reduced from 250 pA to 50 pA at 10 V.**

***Index Terms* — Digital-analog conversion, Josephson arrays, standards, superconducting integrated circuits, voltage measurement.**

I. Introduction

A voltage standard that floats relative to Earth potential offers the flexibility to choose the grounding node of a measurement circuit. This feature is important both for a programmable voltage standard (**PJVS**) [1] used with Kibble balances [2] and more generally for the measurement of a voltage source that is, by construction, referenced to Earth ground (for example a Zener standard on line-power). The leakage resistance to ground of a PJVS system is not infinite. Because a PJVS array requires a current bias, it is always connected to its bias electronics. The bias electronics have an unavoidable leakage current to ground (LCG) error which must be evaluated and reported as a measurement uncertainty. This effect may constitute the largest contributor to the uncertainty budget of direct PJVS comparisons.

This paper explores the effects of the complex leakage current paths of PJVS systems with a simple model and method to measure the LCG for a given PJVS voltage and presents two different methods to derive the equivalent leakage resistance to ground (LRG) of the entire system. This detailed analysis of the various leakage current contributors has allowed us to reduce the LCG of our PJVS system by a factor five.

II. LCG and LRG Measurements

The determination of the individual contribution of each possible leakage path to the total LRG of a PJVS system is not an easy or practical option given 24 current bias leads (in the NIST system) [3]. The multiple parallel leakage paths are shown schematically in Fig. 1 as orange shaded areas surrounding the various components of the current bias electronics and wiring. However, we can measure the combined contribution of all the individual leakage currents to ground for a given PJVS voltage (I_{LCG}). After connecting either the low side or high side of the PJVS output leads to Earth ground potential (GND) through a 2 kΩ resistor (Fig.1A), I_{LCG} is determined by measuring the voltage drop across the resistor with a digital voltmeter (DVM) [4]. During the measurement acquisition, the voltage polarity of the PJVS is switched back and forth and the DVM acquisition starts after a delay of about 1 minute to remove both the influence of the thermal electromotive forces and the dielectric absorption. This method is highly sensitive to perturbations (electrostatic fields and microphonic noise) and this limits the overall relative accuracy to a few percent. The results of our LCG measurements versus PJVS voltage are shown in Fig. 2. Black circles and red squares represent the LCG measured when connecting the GND respectively to the low side (LO) and to the high side (HI) of the PJVS output leads. The measured LCG dependence is not entirely linear with the PJVS output voltage because the potential at the various bias nodes of the array do not necessarily increase linearly with the output voltage due to the ternary nature of the PJVS bias.

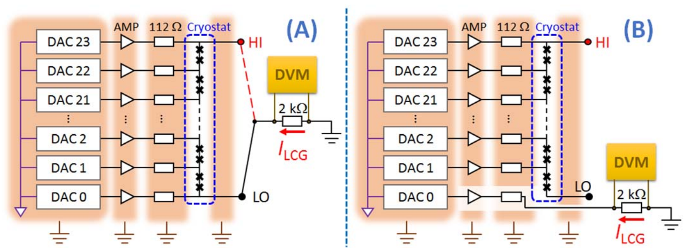

Fig. 1. Schematic of the LCG measurement (I_{LCG}) made by connecting the ground (A) to respectively the low side (LO) and the high side (HI) of the output voltage leads, and (B) to one of the DAC leads. The common node of the bias electronics is shown as a solid triangle symbol.

Another factor influencing the LCG is the potential difference ΔV between the common node (CMN) of the bias electronics and GND. The potential at the bottom node of the array is normally fixed at 0 V with respect to CMN. However, during this measurement the potential at the low side of the PJVS is adjusted first to −1 V and then −2 V with respect to CMN to produce voltages above respectively 8.5 V and 9.5 V. This is required due to the ±10 V dynamic range of the digital-to-analog converter (DAC). Grounding the high side of the array produces a larger LCG, mainly due to increased value of ΔV and the leakage path associated with the CMN node.

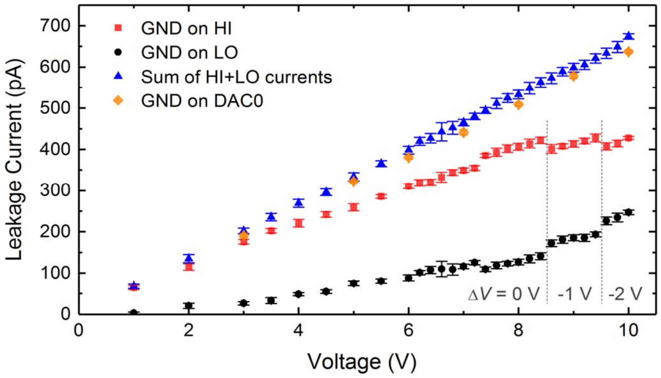

Fig. 2. Measured LCG as a function of the PJVS voltage for the two grounding configurations associated with the method A. Measured LCG as a function of the DAC0 voltage for the method B (orange diamonds).

The two independent measurements of LCG provide different values of the equivalent LRG (Table 1). However, these two measurements are complementary and by combining them (sum of the HI and LO LCG for a given PJVS voltage), each node of the system is virtually biased at the same voltage. As a result, the voltage dependence of the current sum (blue triangles) is now linear, as expected for a true leakage resistance measurement.

A second method, shown in Fig. 1B, allows a direct measurement of the LRG with a single measurement. One of the 24 DAC lines is disconnected from the PJVS array and connected through the sense resistor to ground (DAC0 line). Applying a voltage only on the DAC0 line elevates the potential difference of the whole system with respect to GND by the opposite voltage. The orange triangle symbols in Fig. 2 show the measured LCG as a function of the DAC0 voltage. The voltage dependence is linear and the LRG is comparable to the summed currents measured with the first method. Note that the two different LRG measurements were performed at different times.

PJVS Voltage	GND on	ΔV	Leakage current I_{LCG}	Equivalent Leakage Resistance
10 V	HI	+8 V	■ 427 pA	23 GΩ
10 V	LO	-2 V	● 246 pA	41 GΩ
10 V	SUM	(10 V)	▲ 673 pA	14.9 GΩ

Table 1. Measured LCG and LRG at 10 V.

III. Reduction of the LCG

After measuring the LRG of various components of the NIST system, we found that the LCG can be drastically reduced by replacing the commercial bias cables connecting the DAC to the amplifier board and the cable connecting the cryoprobe to the amplifier board with custom-made Teflon isolated cables. Figure 3 shows the LRG measurement after the cable replacement. No modification was applied to the commercially available DAC cards, the amplifier board (AMP), or the cryostat. The LCG at 10 V for the GND on LO configuration is

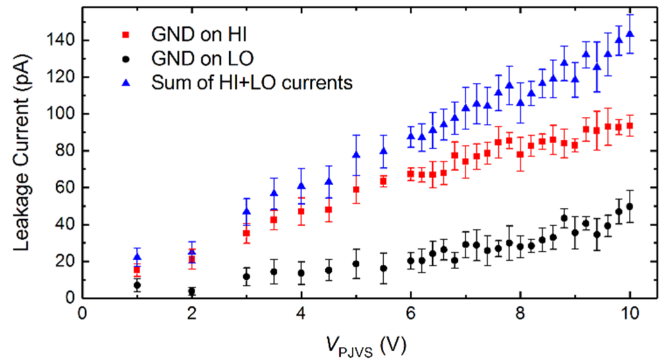

Fig 3. Measured LCG as a function of the PJVS voltage for the two grounding configurations associated with the method A, after replacement of the commercial bias cables with low leakage cables.

reduced by a factor five to around 50 pA. For a typical PJVS comparison at 10 V (assuming the GND is connected to the LO side of the opposite PJVS array and 2 Ω output lead resistance connecting the two systems), the 0.1 nV (or 1 part in in 10^{11}) voltage error due to such LCG is smaller than the noise floor of the digital nanovoltmeters currently used for such typical comparison measurement.

IV. Conclusion

Leakage currents to ground in the PJVS are often ignored or poorly estimated. An understanding of the contributions of the different elements of the bias electronics to the leakage resistance to ground of the entire system is the first step to improving the error due to leakage to ground. For metrology applications, the important quantity to measure is the leakage current to ground and its influence on the measurement circuit. The leakage current cannot be derived directly from the leakage resistance and must be measured independently for each PJVS output voltage. However, the leakage resistance to ground is a good indicator of the worst-case scenario; we are currently developing tools to automatically measure this quantity. To be compressive, the leakage current to ground from the bias electronics is not the only leakage effect: the leakage current due to the isolation resistance of the output leads must also be accounted for.

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