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Traceability of DC high voltage measurements using the Josephson voltage standard

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ABSTRACT

This paper introduces a new methodology for obtaining high voltage DC measurements traceability to the International System of Units (SI) at the Egyptian National Institute for Standards (NIS). The traceability has been achieved via the NIS automated 10 V DC Josephson Voltage Standard (JVS). A 100 kV DC voltage divider with a nominal voltage ratio of 10,000:1 is being used with its display in parallel with a high sensitive digital voltmeter. The traceability has been realized by calibrating this digital voltmeter via the JVS system and then it has been used to calibrate the divider display readings. Moreover, the divider ratio has been accurately calibrated using a traceable calibrator source on its high voltage side and the calibrated digital voltmeter on its low voltage side. Accurate and traceable high voltage values have been obtained associated with their expanded uncertainties. Highly improved uncertainties have been achieved using this new calibration technique.

1. Introduction

Accurate high voltage measurements are required by the electric power industry for instrumentation, metering, and testing applications. DC high voltage has several applications including high voltage cables testing, X-ray generators, electron microscopes, electro-static precipitators, particles accelerator in nuclear physics, and dielectric testing [1]. For long distance power transmission, economic studies proved that high voltage DC transmission is preferred to AC one [2]. For these usages, accurate measurements are required on the output voltage of high voltage sources. DC high voltage measurements is done through several methods, the series resistance micro-ammeter, the resistance potential divider, the generating voltmeter and the sphere gaps are all possible methods; however a high voltage divider remains the most common method to measure the high voltage output of a high DC voltage source [3].

In this work, the NIS Josephson primary standard [4–8] for the DC volt has been used to provide traceability for 100 kV high DC voltage measurements to the SI units. This is achieved by calibrating a HP 3458A high precision digital voltmeter (DVM) up to 10 V via JVS; then this high precise DVM is placed in parallel with the display of a Phenix High Voltage divider (KVM100) with a full range of 100 kV DC.

The Fluke 5720A calibrator which is traceable to the SI units by a recent DKD accredited calibration certificate is used to produce 1 kV at the high voltage side of the Phenix divider, while the voltage at the low voltage side is measured via the HP 3458A DVM; this is done to accurately determine the Phenix divider transformation ratio (TR). A Haefely Trench 100 kV DC source of one/two stages (PZT100) is used to supply the high voltage side of the KVM100 with a voltage up to 100 kV, the Phenix display reading as well as the DVM readings are recorded. The measurement of the DVM is then multiplied by the estimated transformation ratio to determine the

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Fig. 1. Arrangement for TR estimation of the KVM100.

corresponding high voltage DC readings. The sources of uncertainty and the uncertainty budget have been estimated. Enhanced uncertainties have been obtained in this traceable calibration.

2. Estimation of the transformation ratio

In determining the voltage transformation ratio of the Phenix KVM100 several methods might be used, the binary step up method [9] is one method that relies on a sequence of steps that combine and separate the used dividers to accurately determine the values of the used resistors. One other method is to use a turn's ratio meter that can estimate the turns' ratio of the voltage divider at different test voltages. In this paper, the TR of the KVM100 has been determined. The 5720A calibrator supplies the high voltage side of the KVM100 with 1000 V_{DC}, while the DVM is measuring its output voltage from the low voltage side terminals. The TR is estimated from the equation:

$$\mathrm{TR} = \frac{V_{\mathrm{Calibrator}}}{V_{\mathrm{DVM}}} \qquad (1)$$

where $V_{\mathrm{Calibrator}}$ is the actual value of the calibrator voltage and V_{DVM} is the actual value of the average for 40 DVM voltage readings corresponding to the calibrator voltage, Fig. 1 shows the arrangement for the Phenix divider turns' ratio estimation. Table 1 lists the actual values of the calibrator, DVM and the estimated TR as well. The calibration of Fluke 5720A calibrator was performed through comparison of known values against its output readings. Basis is the realization of units in the PTB-Germany. The calibration results of the calibrator are within a confidence level of 95%. The temperature and relative humidity of the calibration laboratory were adjusted and fairly controlled to (23 ± 1) °C and (50 ± 10%) respectively.

Table 1
Transformation Ratio (TR).

$V_{\mathrm{Calibrator}}$	V_{DVM}	(TR)
999.983 V	0.100235 V	9976.488011

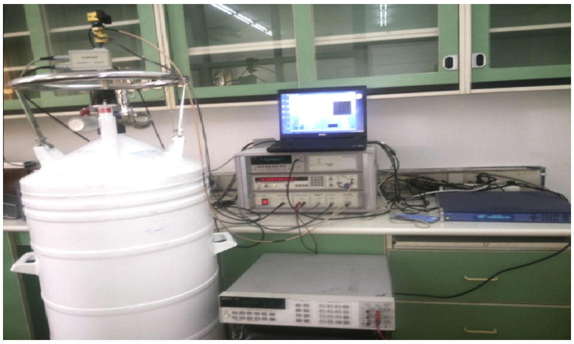

Fig. 2. Calibration of the HP 3458A DVM via the JVS system.

3. Calibration of the HP 3458A DVM

During the calibration process, the best possible frequency for the NIS JVS system has been investigated by applying the function of the system "Arbitrary Voltage". The automatic process of the JVS system includes the step selection and the microwave power adjustment. In order to calibrate the HP 3458A DVM, it has been connected to the "EXTERNAL VOLTMETER" of the JVS electronics unit as shown in Fig. 2. The system has different modes of

Fig. 3. Phenix divider and input source.

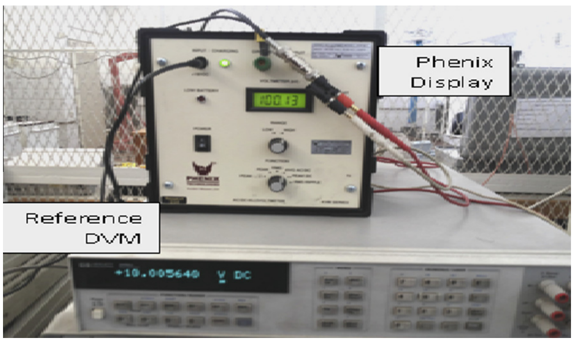

Fig. 4. Phenix display and HP3458A DVM.

Table 2
Uncertainty budget of calibrating the DVM via the JVS system at 10 V range.

Uncertainty sources	Standard uncertainty	Probability distribution	Divider	C_i	Uncertainty contribution
Repeatability of the DVM calibration results	1.50E−7 V	Normal	1	1	1.50E−7 V
Resolution of the DVM calibration results	5.00E−9 V	Rectangular	$\sqrt{3}$	1	2.89E−09 V
Nano-voltmeter gain error voltage	1.00E−8 V	Rectangular	$\sqrt{3}$		5.77E−9 V
Thermal emf	5.00E−9 V	Rectangular	$\sqrt{3}$	1	2.89E−09 V
Voltage due to leakage current	1.00E−7 V	Rectangular	$\sqrt{3}$	1	5.77E−8 V
Environmental effect	5.00E−7 V	Rectangular	$\sqrt{3}$	1	2.89E−07 V
Uncertainty of supra VOLT control system	1.00E−9 V	Normal	1	1	1.00E−9 V
Combined standard uncertainty					±3.3E−7 V
Effective degrees of freedom					∞
Expanded uncertainty at confidence level 95% ($k = 2$)					±660 nV

Table 3
Uncertainty budget of Phenix KVM100 divider calibration at 1 kV range.

Uncertainty sources	Standard uncertainty	Probability distribution	Divider	C_i	Uncertainty contribution
Repeatability of DVM readings	3.67E−6 V	Normal	1	1	3.67E−6 V
Resolution of the DVM	5.00E−6 V	Rectangular	$\sqrt{3}$	1	2.89E−6 V
Drift of the DVM since last calibration	4.07E−4 V	Rectangular	$\sqrt{3}$	1	2.35E−4 V
Uncertainty of calibrating the DVM via the JVS	3.30E−7 V	Normal	1	1	3.30E−7 V
Uncertainty of calibrator	2.30E−2 V	Normal	1	1	2.30E−2 V
Drift of the calibrator since last calibration	−2.10E−2 V	Rectangular	$\sqrt{3}$	1	−0.012 V
Combined standard uncertainty					±0.026 V
Effective degrees of freedom					∞
Expanded uncertainty at confidence level 95% ($k = 2$)					±0.052 V

Table 4
Uncertainty budget of 100 kV range calibration.

Uncertainty sources	Standard uncertainty	Probability distribution	Divider	C_i	Uncertainty contribution
Repeatability of DVM readings	2.219E−3 V	Normal	1	1	2.219E−03 V
Resolution of the DVM	5.00E−7 V	Rectangular	$\sqrt{3}$	1	2.89E−7 V
Drift of the DVM since last calibration	2.112E−3 V	Rectangular	$\sqrt{3}$	1	2.112E−3 V
Repeatability of Phenix display readings	2.274E−3 V	Normal	1	10000	22.74 V
Resolution of the Phenix display	5E−4 V	Rectangular	$\sqrt{3}$	10000	2.89 V
Phenix divider uncertainty	2.6E−2 V	Normal	1	1	2.6E−2 V
Uncertainty of calibrating the DVM via the JVS	3.3E−7 V	Normal	1	1	3.3E−7 V
Combined standard uncertainty					±22.923 V
Effective degrees of freedom					∞
Expanded uncertainty at confidence level 95% ($k = 2$)					±45.85 V

Table 5
Actual values of the voltages from 1 to 10 kV and their expanded uncertainties for one stage input.

Nominal values (kV)	Measured values (kV)	Actual values (kV)	± Expanded uncertainty (V)	± Expanded uncertainty (%)
1	1.009	1.004	0.638	0.064
2	2.007	2.002	1.154	0.058
3	3.005	2.997	1.834	0.061
4	4.016	4.004	2.325	0.058
5	5.004	4.990	2.838	0.057
6	6.005	5.989	3.738	0.062
7	7.015	7.002	4.144	0.059
8	8.005	7.974	4.420	0.055
9	9.006	8.985	5.051	0.056
10	9.999	9.968	5.677	0.057

Table 6
Actual values of the voltages from 1 to 10 kV and their expanded uncertainties for two stages input.

Nominal values (kV)	Measured values (kV)	Actual values (kV)	± Expanded uncertainty (V)	± Expanded uncertainty (%)
1	1.015	1.012	0.655	0.065
2	2.004	1.997	1.273	0.064
3	2.977	2.969	1.765	0.059
4	4.047	4.033	2.275	0.056
5	5.003	4.992	3.169	0.063
6	6.007	5.989	3.897	0.065
7	7.012	6.996	4.277	0.061
8	8.038	8.012	4.504	0.056
9	9.009	8.987	5.051	0.056
10	10.006	9.977	5.804	0.058

operation, predefined within the software. For this task, the function of the system "External Voltmeter" has been applied.

For automatic operation, the data acquisition of the connected DVM is realized via GPIB bus. Twenty one data points in each DC range (from 100 mV to 10 V) of the DVM have been carried out. The Josephson voltage, the voltage measured by the DVM, and their standard deviations are calculated from ten measurements.

Table 7
Actual values of the voltages from 20 to 100 kV and their expanded uncertainties for one stage input.

Nominal values (kV)	Measured values (kV)	Actual values (kV)	± Expanded uncertainty (V)	± Expanded uncertainty (%)
20	19.994	19.945	9.866	0.049
30	30.067	29.989	15.144	0.050
40	40.040	39.877	20.385	0.051
50	50.128	49.956	24.139	0.048
60	60.051	59.867	29.545	0.049
70	70.084	69.900	31.686	0.045
80	80.104	79.828	36.387	0.045
90	90.096	89.751	41.414	0.046
100	100.118	99.786	45.855	0.046

Table 8
Actual values of the voltages from 20 to 100 kV and their expanded uncertainties for two stages input.

Nominal values (kV)	Measured values (kV)	Actual values (kV)	± Expanded uncertainty (V)	± Expanded uncertainty (%)
20	19.932	19.880	10.133	0.051
30	30.051	29.971	15.261	0.051
40	39.952	39.776	20.559	0.051
50	50.013	49.823	25.087	0.050
60	60.122	59.895	30.192	0.050
70	70.084	69.899	31.686	0.045
80	80.052	79.730	36.216	0.045
90	90.135	89.775	40.988	0.046
100	100.073	99.764	45.196	0.045

4. Calibration of the KVM100

The Phenix KVM100 consists of a high voltage divider and 4½ digit LCD display (with both low and high voltage ranges). Its two main parts are connected by connecting cables. The calibrated HP 3458A DVM is used as a reference standard to calibrate the KVM100. Fig. 3 shows the Phenix KVM100 divider connected to the PZT100 DC source of one/two stages. Fig. 4 shows the KVM100 display (under calibration) connected to the standard DVM. By applying the divider ratio, the actual values of the input high voltages from 1 kV to 10 kV (at the low range) and from 20 kV up to 100 kV (at the high range) have been acquired.

5. Calibration results

The uncertainties of the calibration results of the DVM via the JVS system up to 10 V, the Phenix KVM100 divider and the Phenix KVM100 display results up to 100 kV DC have been investigated. The uncertainty budgets have been evaluated for all calibrations. All components of the combined standard uncertainty (Type A and Type B) have been taken into consideration. The expanded uncertainty has been calculated by using the coverage factor $k = 2$, to give a level of confidence of approximately 95% according to the ISO GUM [10,11]. The uncertainty budget of calibrating the DVM via the JVS system at 10 V range is listed in Table 2. Table 3 shows the uncertainty budget of Phenix divider calibration at 1 kV range while the uncertainty budget of calibrating the 100 kV range is illustrated in Table 4. According to the uncertainty budgets, the repeatability of the Phenix display readings is the dominate uncertainty component. The actual values of the voltages from 1 kV up to 10 kV (low range) and their expanded uncertainties for both input stages are listed in Tables 5 and 6 respectively. Tables 7 and 8 illustrate the actual values of the voltages from 20 kV up to 100 kV (high range) and their expanded uncertainties for one stage and two stages respectively.

Although some other factors including divider temperature rise, Corona discharge and power coefficient

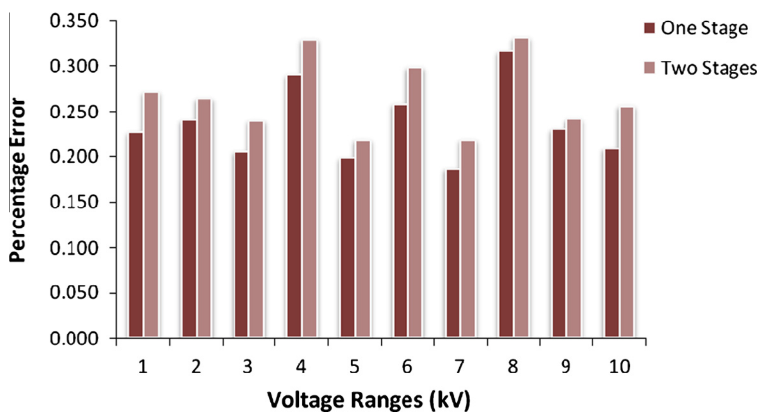

Fig. 5. Percentage error deviation when using one/ two stages' source for 1–10 kV range.

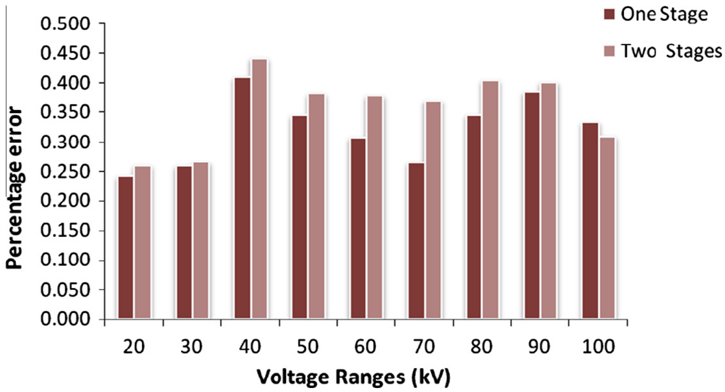

Fig. 6. Percentage error deviation when using one/two stages' source for 20–100 kV range.

might affect the uncertainty budget of Phenix KVM100 calibration; still these factors have neglected effect compared to the dominant one owed to the repeatability of the Phenix display readings.

It is clearly shown that the expanded uncertainties of the low range measurements (from 1 kV to 10 kV) do not exceed 0.06% of their values while, the high range uncertainties (from 20 kV up to 100 kV) are within 0.05%. Fig. 5 shows the deviation in the percentage error of the 100 kV Phenix readings when using one stage or two stages' supply up to 10 kV. The Percentage error (PE) is calculated using the equation:

$$PE = \frac{MV - AV}{AV} \times 100 \quad (2)$$

where *MV* and *AV* are the measured and actual voltage values respectively. Fig. 6 shows the deviation in the percentage error for the high voltage range of 20–100 kV. It clearly appears that a supply with one stage transformer gives lower PE all over the low range up to 10 kV. In the high range the usage of one stage supply still gives better results; however it is better to use a two stage supply for the 100 kV as it gives less *PE*. Besides, it is preferred to obtain the 100 kV from two stages to avoid stressing the step up transformer by operating it on its full range.

6. Conclusion

A new calibration technique has been used at NIS for disseminating the traceability to the high voltage DC measurements (up to 100 kV). The traceability has been provided via the NIS DC Josephson primary standard. Measurements have been carried out using a high voltage meter (KVM100) at two different supply stages. The KVM100 divider and its display have been accurately calibrated. The percentage error as well as calibration uncertainties have been calculated for both input stages. The uncertainty budget of the Phenix calibration shows that the repeatability of its readings is the dominant affecting factor. Therefore, all the other factors will not effectively influence the total budget. The percentage error results show that it is better to use a one stage supply for all DC voltage values up to 90 kV, while it is better to use two stages for the 100 kV value. The expanded uncertainty has a maximum value of 0.06% for the low range measurements (1–10 kV), while it decreases to about 0.05% for the high range measurements (20–100 kV). Enhanced uncertainty results have been attained using this calibration methodology.

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