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Traceability of DC and AC high voltage measurements using voltage divider calibration

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Abstract

This paper focuses on achieving traceability of high voltage measurements up to 200 kV at the Egyptian National Institute of Standards. The measurement system consists of an AC/DC voltmeter and a universal resistive/capacitive high voltage divider. The voltmeter shows measured voltage values based on the scale factor of the voltage divider. The divider ensures a stable capacitance for AC voltage measurements and an additional resistive parallel path for DC voltage measurements. Both the divider and the voltmeter are calibrated in AC and DC modes. All uncertainty components are taken into account to obtain measured values with an acceptable accuracy. The calibration results in traceability to the national standards, which make measurements using the international system of units. The proposed calibration method is useful for the theory and practice of high voltage measurements in education, industrial applications, and electrical metrology studies.

Keywords

Calibration, educational engineering, high voltage measurements, metrology, uncertainty, traceability

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Introduction

Regular calibration of high voltage measuring and sourcing systems is an essential need of many governmental, educational, and private sector industries to ensure accurate electricity standards and enable robust measurements.[1]

Commonly used digital voltmeters measure voltages up to 1 kV, while high voltage dividers are used for measurements above 1 kV. Both voltmeters and dividers have to be calibrated regularly to ensure their accuracy.

A high voltage divider is commonly used to calibrate high voltage sources[2] and gives a ratio that relates the unknown high voltage values to the well-known low voltage ranges.[3] This is achieved by reducing the high voltage to a lower value that can be measured with a voltmeter.[4] The most commonly used method to calibrate the division ratio is to obtain the ratio between actual voltages on the high voltage and low voltage arms of the divider.[5–7] In other words, the true voltage values of a high voltage source are obtained by multiplication of the voltages on the low voltage arm with the ratio of the division.

The precision of high voltage DC dividers relies on their resistive design, while high voltage AC dividers are commonly based on a capacitive design.[8] The Josephson voltage standard (JVS) has been used for many years as the DC voltage standard with the best accuracy.[9–11]

Traceability of DC and AC voltage measurements up to 100 kV was previously achieved at the National Institute of Standards (NIS) via a DC-JVS.[4,9] In the studies presented by El-Rifaie et al.[4] and Abdel Mageed et al.,[9] uncertainties in DC and AC high voltage measurements up to 100 kV were significantly enhanced after achieving traceability with the JVS.

In this work, traceability of DC and AC voltages up to 200 kV on the basis of traceable 100 kV measurements is obtained using an enhanced calibration method. The high voltage system considered in this study consists of two main parts, the divider and the display, both of which are calibrated. A two-stage Haefely Trench high voltage AC source (PZT-100) is used to supply the high voltage side of the measurement system.[12]

The division ratio of the divider has to be accurately known at the beginning of the calibration for precise measurement. The display is calibrated in both high voltage and low voltage modes in order to obtain a corrected scale factor that is used in the 200 kV measurement system, according to the following steps:

(i) The display of a traceable 100 kV high voltage measurement system (Phenix-kVM100) is calibrated as presented in Abdel Mageed et al.[9]
(ii) The AC/DC peak voltmeter (MU17) is calibrated in its high voltage mode compared to the display of the traceable Phenix.
(iii) The low voltage mode is calibrated via a traceable calibrator (Fluke 5720A) to acquire its corresponding low voltage readings. Hence, corrected scale factors are obtained in DC and AC modes and then applied to the 200 kV display.

(iv) High voltage values up to 200 kV are calculated by multiplying low voltage readings by the corresponding scale factors.

The most important uncertainty factors are taken into account while determining the final values. The proposed calibration method is useful in high voltage measurements in educational engineering, industrial applications, and electrical metrology studies, as well as courses on measurement theory and practice.

The article is organized into four sections as follows: "Introduction" section presents an introduction to the purpose of the study. "The 200 kV high voltage system setup" section is dedicated to the setup of the 200 kV system. "Calibration of the 200 kV high voltage system" section describes the proposed calibration technique, results, and discussion. "Conclusions" section presents conclusions and future work.

The 200 kV high voltage system setup

The measurement system consists of an AC/DC voltmeter and a universal resistive/capacitive high voltage divider. The capacitor in this divider is designed to ensure that the capacitance is stable during AC voltage measurements. This divider also has an additional resistive parallel path for DC voltage measurements. The two parts are connected to a two-stage Haefely Trench high voltage AC source (PZT-100) that supplies the high voltage side of the measurement system up to 200 kV. A flexible connection with appropriate probes connects the two AC voltage source stages. For DC sourcing, two 140 kV half-wave rectifiers are connected in parallel to the source to acquire 200 kV DC voltage. Figures 1 and 2 show the AC and DC connections, respectively.

Figure 1. High voltage AC connections (courtesy of the Egyptian NIS).

Figure 2. High voltage DC connections (courtesy of the Egyptian NIS).

Figure 3. MU17 voltmeter and the Phenix display.

The NIS 200 kV high voltage measurement system is used for accurate and precise AC and DC high voltages calibrations according to the IEC 60060-2:2010 international standard.[13,14] The voltmeter displays measured DC and AC voltage readings while taking into account the scale factor of the voltage divider.

As previously mentioned, for the 200 kV high voltage measurement system, high voltage readings have been calibrated based on a 100 kV Phenix (KVM100) reference system that is traceable to the NIS-JVS. The root-mean-square (rms) setting at the fundamental frequency (50 Hz) is used throughout calibration of AC voltages for both systems. Figure 3 shows the MU17 voltmeter versus the Phenix display. Corresponding low voltages are calibrated using a Fluke traceable calibrator.

Table 1. Uncertainty budget of the calibrated divider at the 100 kV DC range.

Uncertainty sources	Standard uncertainty	Probability distribution	*M*	C_i	Uncertainty contribution
Repeatability of voltmeter	4.00E−02 V	Normal	1.00	1.00	4.00E−02 V
Resolution of voltmeter	5.00E−02 V	Rectangular	$\sqrt{3}$	1.00	2.89E−02 V
Calibration certificate of the calibrator	4.45E−05 V	Normal	1.00	1.00	4.45E−05 V
Drift of the calibrator (since last calibration)	2.10E−2 V	Rectangular	$\sqrt{3}$	1.00	1.20E−02 V
Calibration certificate of Phenix	2.29E+01 V	Normal	1.00	1.00	2.29E+01 V
Repeatability of Phenix display readings	9.55E+00 V	Normal	1.00	1.00	9.55E+00 V
Combined standard uncertainty					±2.48E+01 V
Effective degrees of freedom					∞
Expanded uncertainty at 95% confidence level ($k = 2$)					±4.97E+01 V

Any quantitative measurement has two components: the value which gives the best estimation of the quantity being measured (called as measurand in the literature) from the mean value of a series of measurement and the uncertainty associated with this estimated value. According to the International Vocabulary of Metrology (VIM), uncertainty of measurement is “a non-negative parameter characterizing the dispersion of the quantity values being attributed to a ‘measurand’”. The two manifestations of uncertainty are categorized as Type-A and Type-B.[15–19]

Type-A uncertainty is based on statistical analysis of a series of measurements, while Type-B uncertainty can be obtained by non-statistical procedures. The final result is obtained by combining components of both types. The combination is usually based on rms summation. In this work, Type-A and Type-B uncertainties have been taken into account in all calibrations. As is common, the overall expanded uncertainty is scaled using a coverage factor (k), which is set to 2 to give a level of confidence of approximately 95%. Table 1 illustrates the uncertainty budget of the calibrated divider at the 100 kV DC range while Table 2 enumerates the uncertainty budget in the AC mode at the 100 kV AC range. Uncertainty sources, standard uncertainties, probability distributions, division factors (M), coefficients of sensitivity (C_i), and uncertainty contributions are given in details. The reader can refer to Joint Committee for Guides in Metrology International Vocabulary of Metrology[15] and Farrance and Frenke[16] for more details on uncertainty components.

Tables 3 and 4 present the calibrated true values of the high voltage that correspond to the calibrated true low voltage ranges, in addition to the corrected scale factors for both DC and AC voltages.

The relation between high voltages and the corresponding low voltages is linear in both the DC and AC modes, as shown in Figure 4.

Table 2. Uncertainty budget of the calibrated divider at 100 kV AC range.[15]

Uncertainty sources	Standard uncertainty	Probability distribution	M	C_i	Uncertainty contribution
Repeatability of voltmeter	2.58E−02 V	Normal	1.00	1.00	2.58E−02 V
Resolution of voltmeter	5.00E−02 V	Rectangular	$\sqrt{3}$	1	2.89E−02 V
Calibration certificate of the calibrator	1.55E−03 V	Normal	1.00	1.00	1.55E−03 V
Drift of the calibrator (since last calibration)	1.00E−2 V	Rectangular	$\sqrt{3}$	1.00	5.80E−03 V
Calibration certificate of Phenix	5.00E+00 V	Normal	1.00	1.00	5.00E+00 V
Repeatability of Phenix display readings	6.70E+00 V	Normal	1.00	1.00	6.70E+00 V
Combined standard uncertainty					±8.36E+00 V
Effective degrees of freedom					∞
Expanded uncertainty at 95% confidence level ($k=2$)					±1.67E+01 V

Table 3. Calibrated true values of the high voltage and low voltage ranges, and the corrected scale factor for the DC voltages.

True high voltage ranges (kV)	True low voltage ranges (V)	Corrected scale factors	±Expanded uncertainty (V)
10.017	19.344	517.835	6.55E+00
20.074	39.085	513.599	1.37E+01
30.027	58.678	511.725	1.81E+01
40.098	78.665	509.731	2.40E+01
50.115	98.359	509.511	2.90E+01
60.154	118.100	509.348	4.03E+01
70.336	138.088	509.356	3.49E+01
80.133	157.738	508.013	4.51E+01
90.610	178.318	508.137	4.38E+01
99.970	196.657	508.347	4.97E+01
Corrected scale factor = 510.6:1			

The divider's linearity check shows that the ripple factor of the DC voltages is less than 1% and for the AC voltages, the form factor does not exceed 1 ± 0.05 at the investigated values. Thus, the scale factors are 510.6:1 for the DC mode and 497.0:1 for the AC mode. These scale factors are used in the display of the 200 kV measurement system in both modes.

Calibration of the 200 kV high voltage system

Applying the DC and AC scale factors to the display of the 200 kV measurement system completes its high voltage calibration. The system voltmeter has been

Table 4. Calibrated true values of the high voltage and low voltage ranges, and the corrected scale factor for the AC voltages (rms voltages at 50 Hz).

True high voltage ranges (kV)	True low voltage ranges (V)	Corrected scale factor	±Expanded uncertainty (V)
10.063	20.151	499.373	3.35E+00
20.091	40.530	495.706	1.21E+01
30.122	60.795	495.470	1.53E+01
40.393	81.398	496.235	1.81E+01
50.452	101.521	496.964	1.57E+01
60.142	121.041	496.870	1.82E+01
70.186	141.101	497.416	1.97E+01
80.277	161.220	497.931	1.65E+01
89.953	180.959	497.091	1.50E+01
99.972	200.999	497.374	1.67E+01
Corrected scale factor = 497.0:1			

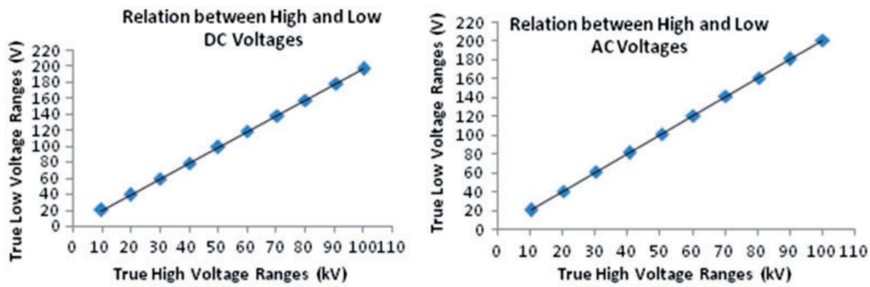

Figure 4. Relationship between the DC and AC high voltages and their corresponding low voltages.

calibrated via the traceable Fluke calibrator in low voltage ranges from 20 V to 400 V with 20 V steps. The temperature of the laboratory during calibration was maintained at 23 ± 1°C, while the relative humidity was 50 ± 10%. An average of 10 readings was taken in each voltage range. It should be mentioned that other factors may affect the uncertainty budget, such as corona discharge, the power coefficient, and the divider's temperature rise. However, their impacts on the uncertainty budget are insignificant compared to the dominant factors used in this work.[4,9] Tables 5 and 6 show the uncertainty budgets for the 200 kV DC and AC calibrations, respectively.

The final calibration results of the 200 kV system with their expanded uncertainties in both volts and percentages for the DC and AC modes are listed in Tables 7 and 8, respectively.

Figure 5 shows the DC and AC voltages associated with their expanded uncertainties. Calibration results show that the expanded uncertainties for the 20 kV DC

Table 5. Uncertainty budget of the 200 kV DC system.

Uncertainty sources	Standard uncertainty	Probability distribution	*M*	C_i	Uncertainty contribution
Repeatability of the low voltage readings	2.41E−02 V	Normal	1.00	1.00	2.41E−02 V
Calibration certificate of the voltmeter	2.89E−02 V	Normal	1.00	1.00	2.89E−02 V
Influence of the temperature on the scale factor	3.41E−01 V	Rectangular	$\sqrt{3}$	1.00	1.97E−01 V
Influence of the proximity effect	3.41E−01 V	Rectangular	$\sqrt{3}$	1.00	1.97E−01 V
Short-term instability	5.12E−01 V	Rectangular	$\sqrt{3}$	1.00	2.95E−01 V
Repeatability of high voltage readings	1.20E−01 V	Normal	1.00	1000	1.20E+02 V
Resolution of high voltage readings	5.01E−02 V	Rectangular	$\sqrt{3}$	1000	2.89E+01 V
Uncertainty of the voltage divider scale factor	2.49E−02 V	Normal	1.00	1000	2.49E+01 V
Combined standard uncertainty					±1.26E+02 V
Effective degrees of freedom					∞
Expanded uncertainty at confidence level 95% ($k = 2$)					±2.53E+02 V

Table 6. Uncertainty budget of the 200 kV AC system (rms voltages at 50 Hz).

Uncertainty sources	Standard uncertainty	Probability distribution	*M*	C_i	Uncertainty contribution
Repeatability of the low voltage readings	1.42E−01 V	Normal	1.00	1.00	1.42E−01 V
Calibration certificate of the voltmeter	2.89E−02 V	Normal	1.00	1.00	2.89E−02 V
Influence of the temperature on the scale factor	3.41E−01 V	Rectangular	$\sqrt{3}$	1.00	1.97E−01 V
Influence of the proximity effect	3.41E−01 V	Rectangular	$\sqrt{3}$	1.00	1.97E−01 V
Short-term instability	5.12E−01 V	Rectangular	$\sqrt{3}$	1.00	2.95E−01 V
Repeatability of high voltage readings	1.45E−01 V	Normal	1.00	1000	1.45E+02 V
Resolution of high voltage readings	5.01E−02 V	Rectangular	$\sqrt{3}$	1000	2.89E+01 V
Uncertainty of the voltage divider scale factor	9.07E−03 V	Normal	1.00	1000	9.07E+00 V
Combined standard uncertainty					±1.48E+02 V
Effective degrees of freedom					∞
Expanded uncertainty at confidence level 95% ($k = 2$)					±2.96E+02 V

Table 7. Calibration results of the 200 kV system in the DC mode.

Nominal voltage (kV)	Measured value (kV)	Actual value (kV)	±Expanded uncertainty (V)	±Expanded uncertainty (%)
20	20.026	20.049	20.84	0.10
40	40.031	40.039	38.56	0.10
60	60.065	60.284	60.43	0.10
80	80.085	80.231	87.22	0.11
100	100.330	100.141	122.01	0.12
120	120.420	120.221	150.11	0.12
140	140.120	139.850	168.47	0.12
160	160.310	160.006	201.06	0.13
180	180.430	180.858	227.02	0.13
200	196.350	196.906	252.59	0.13

Table 8. Calibration results of the 200 kV system in the AC mode (rms voltages at 50 Hz).

Nominal voltage (kV)	Measured value (kV)	Actual value (kV)	±Expanded uncertainty (V)	±Expanded uncertainty (%)
20	20.155	20.301	20.29	0.10
40	40.095	40.458	42.53	0.11
60	59.765	59.611	64.93	0.11
80	80.262	80.152	88.71	0.11
100	99.940	99.792	123.75	0.12
120	120.010	119.561	153.69	0.13
140	139.620	139.898	193.19	0.14
160	159.970	159.827	231.14	0.14
180	180.000	180.139	265.00	0.15
200	199.840	199.753	295.63	0.15

and AC voltages are about 0.10% of their actual values. However, the expanded uncertainties increase gradually with an increase in voltage to finally reach 252.59 V at 200 kV DC, while the uncertainty for the 200 kV AC reaches 295.63 V. The expanded uncertainties therefore did not exceed 0.13% in the 200 kV DC range and 0.15% in the 200 kV AC range. It is clear that measurement uncertainties using this calibration technique up to 200 kV are acceptably small compared to the voltages measured.

The presented high voltage divider calibration method improves the calibration and measurement capabilities of the NIS high voltage laboratory. The proposed calibration method can also be beneficial for high voltage measurements in laboratories, engineering classes, industrial applications, and electrical metrology studies.

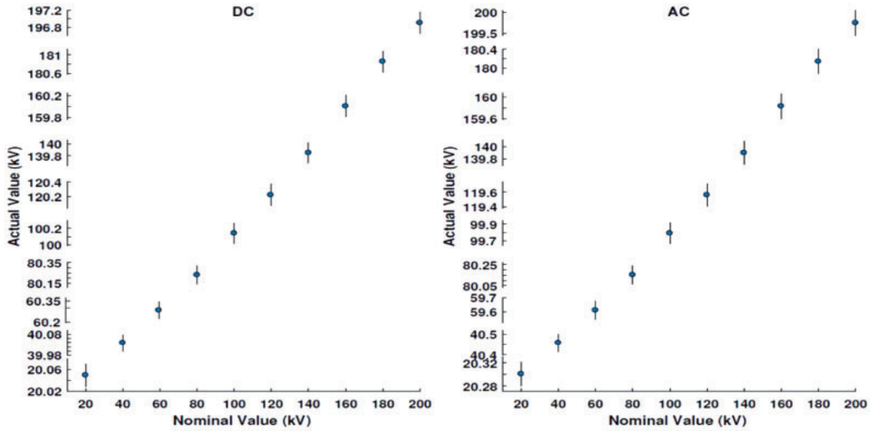

Figure 5. Measured DC and AC voltages and their expanded uncertainties.

Conclusions

Traceability of high voltage measurements up to 200 kV at NIS has been achieved. A high voltage divider calibration method has been used to calibrate the 200 kV measurement system in both DC and AC modes. The calibration was performed by calibrating the two main parts of the 200 kV measurement system (the voltmeter and the high voltage divider). DC and AC voltages and their expanded uncertainties were measured.

The repeatability of high voltage measurements is the most significant component in the uncertainty budget. Expanded uncertainties do not exceed 0.13% of the 200 kV DC range and 0.15% of the 200 kV AC range, which is small compared to the voltage ranges. The principles of this method may also be applied to higher voltages (up to 400 kV), but the uncertainty may be greater.

Declaration of Conflicting Interests

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