Seminar on New Opportunities for Testing and Certification in the Age of Technology

Quantum Measurement Standards: New Trends in Electrical Metrology

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Contents

• Introduction
• History of Electrical Metrology
• Recent Developments in Electrical Quantum Measurement Standards
• New Applications in Electrical Metrology
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What is Metrology?

• Metrology is the “science and practice of measurement”
  – **Stable**: Long-term trends can be used for decision making
  – **Comparable**: Results from different laboratories can be brought together
  – **Coherent**: Results from different methods can be brought together

• The objectives of metrology are achieved through providing the framework for **traceable measurements**.
What is traceability?

International System of Units (SI)

Primary Standards of the Primary Standards Laboratory

Secondary Standards of the Primary Standards Laboratory

Working Standards of the Primary Standards Laboratory

Ref./Working Standards of Calibration/Testing Laboratories

Measuring/Testing Instruments

NMI of the Economy (NMI: National Metrology Institute and SCL is HK’s de facto NMI)

NAB Accredited Laboratories (NAB: National Accreditation Body)

- Manufacturing/Trading/Utilities
- Government Departments
- Academic/Research Institutes
- Other Users

Higher Accuracy Calibrations
Introduction of SCL

- Established in 1984
- SCL is the Hong Kong’s custodian of reference standards for physical measurement
History of Electrical Metrology
History of Electrical Metrology

• From 1860:

• Siemens mercury unit
  – Electricity passing through a 1-meter long column of pure mercury

• Silver voltameter
  – “International ampere”
  – Determine the mass of the cathode before and after to indicate current had passed through it

Source: NIST


- **Weston Cells**
  - H-saped glass container filled with chemical for stable voltage

- **Ampere balance**
  - Current pass through a coil will produce a physical motion to move the indicator

Source: NIST
History of Electrical Metrology

• In 1920s:
  – International comparison of Weston cells

• In 1933:
  – CGPM determined to move from “international ampere” to “absolute system” based on length, weight and time.

• In 1948:
  – Officially adopted by CIPM

Source: NIST
Current SI Definition (1948)

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between them a force equal to 2 × 10\(^{-7}\) newtons per meter of length.

Ampere’s Force Law:

\[ \Delta F = \frac{\mu_0 I_1 I_2}{2\pi r} \Delta l \]

\[ \Rightarrow 2 \times 10^{-7} = \frac{\mu_0 \times 1 \times 1}{2\pi \times 1} \times 1 \]

\[ \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \]
In 1960:
  – The “ampere” joined the family of SI base unit.

In 1970-80:
  – Evolution of quantum technologies
Current Practical Realization

**Josephson effect**

\[ V = \frac{nf}{K_{J-90}} \approx nf \frac{h}{2e} \]

**Quantum Hall effect**

\[ R_H = \frac{R_{K-90}}{i} \approx \frac{h}{ie^2} \]
Josephson Effect

- Nobel Prize in Physics in 1973
- Prof. Brian Josephson

- Josephson Array Junction
  - Superconductor
  - Tunneling effect

- At 4.2 K (liquid helium)
  - Cooper pair of electron can tunnel through the insulation barrier giving rise to a DC current
  - No voltage drop across the tunnel barrier
Josephson Voltage

\[ V = nf \frac{h}{2e} = \frac{nf}{K_J} \]

- \( h \approx 6.626 \times 10^{-34} \text{Js} \)
- \( e \approx 1.602 \times 10^{-19} \text{C} \)
- where \( K_J : \text{Josephson constant} = 2e/h \)
  \( \approx 483597 \text{ GHz/V} \)
- \( K_{J-90} = 483597.9 \text{ GHz/V} \)
Quantum Hall Effect

- Nobel Prize in Physics in 1985
- Prof. Klaus von Klitzing

- Two-dimensional (2D) electrons in strong magnetic field at low temperature shows quantized Hall resistance with the universal fundamental constant.

Prof. Dr. Klaus von Klitzing visited SCL on 29 July 2016
Quantum Hall Resistance

\[ R_H = \frac{h}{ie^2} \]

- \( h \approx 6.626 \times 10^{-34} \) Js
- \( e \approx 1.602 \times 10^{-19} \) C
- For \( i=1 \),
  \[ R_k \approx 25812 \) \( \Omega \]
- CIPM conventional defined value \( R_{k-90} = 25812.807 \) \( \Omega \)
- \( R_H = R_{k-90}/i \)
Revised definition of electric current

The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge $e$ to be $1.602\ 176\ 634 \times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta \nu_{Cs}$.

To be implemented on 20 May 2019
Revised definition of electric current

A = C/s

Count the flow of electrons in a second
Revised definition of electric current

Sources: NIST, PTB, NPL

Single Electron Transport (SET)

(Sources: NIST, PTB, NPL)
Continuity of Electrical Standards

Defining constants:

\[ e = 1.602\,176\,634 \cdot 10^{-19} \text{ C} \]

\[ h = 6.626\,070\,15 \cdot 10^{-34} \text{ J s} \]

\[ K_{J-90} = 483\,597.9 \text{ GHz/V} \]

\[ R_{K-90} = 25\,812.807 \text{ Ω} \]

Revised SI:

\[ K_J = 483\,597.848\,416\,984 \text{ GHz/V} \]

\[ R_K = 25\,812.807\,459\,3045 \text{ Ω} \]

\[ K_J / K_{J-90} - 1 = -1.1 \cdot 10^{-7} \]

\[ R_K / R_{K-90} - 1 = 1.8 \cdot 10^{-8} \]
## Implementation

<table>
<thead>
<tr>
<th>Criteria</th>
<th>CCEM 17-09 recommended actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.5 , d \leq U$</td>
<td>no action is necessary until the next recalibration (or measurement).</td>
</tr>
<tr>
<td>$U &lt; 2.5 , d$</td>
<td>numerical correct or recalibrate before the standard’s next use for traceability.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Instruments</th>
<th>$U \times 10^{-6}$</th>
<th>$d \times 10^{-6}$</th>
<th>$U &lt; 2.5 , d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zener voltage standards</td>
<td>0.06</td>
<td>+0.11</td>
<td>Yes</td>
</tr>
<tr>
<td>Calibrators (DC voltage)</td>
<td>0.7</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>DMM (DC voltage)</td>
<td>1.5</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Standard resistors</td>
<td>0.3</td>
<td>+0.018</td>
<td>No</td>
</tr>
<tr>
<td>Calibrators (Resistance)</td>
<td>1.0</td>
<td>+0.018</td>
<td>No</td>
</tr>
<tr>
<td>DMM (Resistance)</td>
<td>1.0</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Calibrators (DC current)</td>
<td>2.6</td>
<td>+0.087</td>
<td>No</td>
</tr>
<tr>
<td>DMM (DC current)</td>
<td>1.0</td>
<td></td>
<td>No</td>
</tr>
</tbody>
</table>
DC Voltage Metrology

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Mean Difference</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 V</td>
<td>0.22 nV</td>
<td>2.2 nV</td>
</tr>
<tr>
<td>1.018 V</td>
<td>-0.51 nV</td>
<td>1.8 nV</td>
</tr>
</tbody>
</table>

(Source: NIST)
AC Voltage Synthesis

Programmable Josephson Voltage Standard (PJVS)
- step-wise approximated sine waves

\[ V(t) \]

Transitions

Steps

Josephson Arbitrary Waveform Synthesizer (JAWS)
- direct digital synthesis with current pulse sequences

\[ \int V(t) = \frac{h}{2e} \]

(Source: NIST)
AC Voltage Metrology

(Sources: NIST, PTB)
Medical Application

- Synthesis of Normal sinus ECG waveform by JAWS
Medical Application

- Defibrillator
  - High energy
  - Short pulse

- Electrocardiograph
  - Weak differential signal
  - Narrow QRS pulse

- Electrosurgical
  - High energy
  - High frequency
  - Different duty cycle

Arbitrary Waveforms

Sampling Multimeter

In-house developed control program

Digital sampling system
Electrical Testing

- RCD tester
- Insulation resistance
- Clamp meter
- Withstanding voltage
- Electrical safety analyzer
Advanced Sensors

(Sources: Electronicshub.org, logisticsarena.eu)
Future development

- Lower magnetic field for QHR
- Higher operating temperature for quantum standards
- Quantum calibrators (DC/AC)
- SET
- Ultra Low Current Amplifier (ULCA)

Graphene based QHR

(Sources: NIST, PTB)
Conclusions

• The development of quantum measurement standards have evolved rapidly in recent years.
• These measurement standards ensured the accuracy of electrical calibration for new opportunities in the technology age.
Thank you!