Chapter 10
Electrical and Electronics Metrology: From Quantum Standard to Applications in Industry and Strategic Sectors

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Abstract CSIR-NPL is the custodian of National standards of electrical and electronic parameters. These include DC parameters such as voltage, current and resistance; low frequency and high frequency impedance related quantities such as capacitance, inductance and AC resistance; AC/DC high voltage and AC high current; AC power and energy; and quantum standard which includes quantum hall resistance

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(QHR), quantum current (QC) and quantum nanophotonics (QN). The metrological traceability of the electrical and electronics parameters to SI units is derived from Josephson Voltage Standard (JVS), Quantum Hall Resistance (QHR) standard and frequency (time) standards; all of them are being maintained at CSIR-NPL with metrological precision at par with international standards. The traceability of the aforementioned parameters is disseminated through an unbroken chain of apex level calibrations and testing at par with international level to the industries and strategic sectors of the country to improve the quality of life, which in turn will lead to the inclusive growth of the country and economic development. R&D efforts on the development of quantum standards is a constant endeavour and continues to be at the forefront. Specifically, CSIR-NPL focuses on the development of quantum standards related to the unit of current (ampere), the unit of resistance (ohm) and quantum nanophotonics which aims for detection of few photons (or even single photons) using the novel concept of superconducting nanowire single photon detectors (SNSPD). Among these the research on QC needs special mention, as this will lead to realisation of the SI unit of electric current (ampere), the only unit out of the seven base units of SI system. The quantum current standard (QCS) realisation is bifurcated into two approaches, (i) based on the single electron tunnelling effect (SET) observable in semiconductor quantum dot (QD) structures and (ii) the quantum phase slip phenomenon (QPS) observable in superconducting nanowires of cross-sectional area of the order of coherence length of the system. The realisation of the resistance unit (ohm) is based on the quantum hall effect observable in semiconductor 2DEG structures such as GaAs/AlGaAs systems. Recently there has been tremendous evidence emerging for the use of monolayer graphene for the use of

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QHR metrology. CSIR-NPL also started the growth of “epitaxial graphene anchored on SiC” and have obtained encouraging results. The nano-photonics measurement research is also taken up actively for its applications to realize quantum standards for optical radiation and device fabrication.

The discovery of the Quantized Hall Effect (QHE) was the result of systematic measurements on silicon field effect transistors – the most important device in microelectronics.

– Klaus von Klitzing (1943-)

10.1 Introduction

Quantum metrology defines the process of measurement as a discrete phenomenon compared to the analogue process of classical metrology. As per the latest revision of SI units [1] all the base units are related to the respective fundamental constants of nature, thus defining the basis quantum metrology in all physical quantities and associated measurements. In the case of EEM, superconductivity plays a vital role in defining the constants of nature. For example, the unit of voltage is defined with respect to the well-known Josephson effect [2], wherein Cooper pairs tunnel through an insulating barrier sandwiched between two superconducting electrodes. Josephson also have predicted that if a superconductor-insulator-superconductor (SIS) junction is being irradiated with energy (usually in the microwave region) constant voltage plateaus appear in the current-voltage characteristics of the junction with the level of voltage plateaus directly proportional to the frequency of irradiated energy \( V = n \cdot \Phi_0 f \). This becomes the basis for quantum voltage metrology, where in the voltage measurement is linked to fundamental constants of \( h \) and \( e \) \( (\Phi_0 = h/2e) \). Programmable Josephson voltage standards are now available with values of 1 and 10 V, with an uncertainty better than \( 10^{-9} \). Similarly, the realisation of the unit of current (ampere) is based on the quantum mechanical phenomenon of coulomb blockade wherein tunnelling of discrete amount of charges takes place through quantum dot (QD) structure. The number of charges tunneled across the dot depends on the cyclic potential difference applied on the gate terminals of the QD. The exploitation of quantum phase slip (QPS) phenomenon in a superconducting nanowire is also being pursued as an alternative for the SET effect. For the case of resistance metrology, the well-known quantum hall effect (QHE) observable in a 2D electron gas is being harnessed. Recently a renewed school of thought is emerging among metrologists to utilise the AC QHE effect to directly link the capacitance (impedance) standards, thus, reducing the uncertainty in the impedance metrology.
As the realisation of current, voltage and resistance are based on quantum effects, the rest of the EEM measurements and standards are also directly or indirectly linked to quantum effects, thus quantum standards become the pillars of modern EEM. In a different approach superconducting nanowire single photon detectors (SNSPD) are used for counting of a few photons or even single photons. The SNSPD technology has the potential to revolutionise the way the single photons can be captured, manipulated or transported.

Though we have described very briefly about the quantum standards of EEM, it is worth mentioning about the practical realizations of the SI units related to electrical parameters such as ampere, volt and ohm as per the latest revision of SI units. These recommendations are adapted from the SI Brochure: The International System of Units (SI), Nineth edition (2019): appendix 2 [1].

**Practical realization of the ampere, A:** Realization of a unit generally means to establish the value and associated uncertainty of a quantity of the same kind as the unit that is consistent with the definition of the unit. In practice, the ampere A can be realized by,

1. Using Ohm’s law, the unit relation \( A = V/\Omega \), and using practical realizations of the SI derived units the volt \( V \) and the ohm \( \Omega \), based on the Josephson and quantum Hall effects, respectively; or
2. Using a SET or similar device, the unit relation \( A = C/s \), the value of \( e \) \((e = 1.602176634 \times 10^{-19} \text{ A s}) \) given in the definition of the ampere and a practical realization of the SI base unit the second s; or
3. Using the relation, \( I = C \cdot dU/dt \), the unit relation \( A = F \cdot V/s \), and practical realizations of the SI derived units the volt \( V \) and the farad \( F \) and of the SI base unit second s.

SET implementations still have certain technical limitations and often produce larger relative uncertainties than some other competitive techniques. However, SET offer unique and elegant approaches to realize SI units. The uncertainties have improved in recent years, and continues to be better, in future. Alternatively, there is growing evidence of QPS which appears promising towards the realization of quantum current standards (QCS). QPS is observable in superconducting nanowires of cross-sectional area compared to the coherence length of the superconducting materials. As compared to Josephson effect, a superconductor nanowire exposed to microwave radiation is predicted to give constant current plateaus (dual to the voltage plateaus of the Shapiro steps in Josephson Junctions) as a function of applied frequency. The measurement of current becomes a measurement of frequency which can be realized with uncertainty to the level of better than \( 10^{-9} \). CSIR–NPL is actively working towards the realization of QCS through QPS observable in superconducting nanowires. Efforts have also been started for the realization of SET devices and associated quantum phenomena of Coulomb blockade.

**Practical realization of the volt, V:** The volt \( V \) is the SI derived unit of electric potential difference (voltage) and electromotive force. The Josephson effect, with the Josephson constant \( K_J \) where \( K_J = 483, 597.848 416 984 \text{ GHz V}^{-1} \) is used to
realize the Volt, with $K_J = 2e/\hbar$. The latter relation is strongly supported by several theoretical and experimental works. The values of both $e$ and $\hbar$ and are given in the new adaption of SI units. Although “$2e/\hbar$” is a universal constant and can obviously calculated to any significant digits, the recommended value is in error by $10^{-15}$, thereby negligible to majority of applications. Having a particular value of $K_J$ for practical use, ensures that all realizations of the volt based on the Josephson effect, would employ exactly the same value.

However, it may be noted that $K_J$ is smaller than the value $K_{J-90} = 483,597.9$ GHz $V^{-1}$, the latter which was adopted by the CIPM in 1990 for the international realization of the volt using the Josephson effect. This amounts to a fraction of $106.665 \times 10^{-9}$, implying that the unit of voltage realized using $K_{J-90}$ was larger than present SI unit.

**Practical realization of the ohm, $\Omega$:** The SI derived unit of electric resistance and impedance is ohm ($\Omega$) and is realized as follows:

1. By using the quantum Hall effect, consistent with the CCEM Guidelines [3] with von Klitzing constant $R_K$, ($=25,812.8074593045$ $\Omega$) to 15 significant digits. A large body of experiments and theory shows that $R_K = h/e^2$, with values of $e$ and $\hbar$ as per the new SI units based on quantum phenomena. Since $h/e^2$ represents ratio of two universal constants, the value is however, truncated to 1 part in $10^{15}$, thereby providing negligible variation in majority of applications. The advantage of recommending a particular value of $R_K$ for practical use is that it ensures, all measurements of the ohm are based on the quantum Hall effect.

2. By comparing an unknown resistance to the impedance of a known capacitance for example, a quadrature bridge, where, for example, the capacitance has been determined by means of a calculable capacitor and the value of the electric constant.

Note that the value of $R_K$ is larger than the value $R_{K-90} = 25,812.807$ $\Omega$, the latter which was adopted by the CIPM in 1990 for the international realization of the ohm using the Quantum Hall effect. The new adoption therefore differs by a fractional amount of $17.793 \times 10^{-9}$, implying that the unit of resistance determined by using $R_{K-90}$ would be larger than the present $h$ and $e$ based SI unit. Thus, the numerical value of a resistance measured in terms of $R_{K-90}$ with respect to $R_K$ would be smaller by the same fractional amount.

This chapter discusses in detail about how accurate and precise measurements are realised for electrical and electronics parameters such as impedance, voltage, current, power and energy quantum hall resistance and quantum current. It includes impedance parameters up to radio frequencies, DC Voltage, Current, resistance, AC & DC high voltage and high current and power and energy.

The traceability of these parameters is being disseminated through apex level calibration and testing at par with international level to the power sector, public sector undertakings, MSMEs, electrical and electronic equipment manufacturers, strategic sector, accredited calibration and test laboratories and R&D organization and institutes.
In addition, fundamental and applied research in particular to the quantum metrology for JVS, QHR, realisation of quantum current and on-going research in field of nano-photonics metrology are further discussed. The R&D associated with QHR, QC and nano-photonics is the part of a continuous process to further enhance the measurement capabilities.

The impact of the electrical and electronics metrology on industrial growth, missions of the Government and quality infrastructure of the country is also discussed. Details of training and human resources development related to EEM are also briefly provided.

10.2 DC Metrology (Voltage, Resistance, and Current)

The traceability chart for the electrical quantities linking with the respective primary standards is shown in Fig. 10.1. The primary standard of voltage and resistance are JAVS/JVS and 1 kΩ reference standard respectively, from where the unit of volt and current are being disseminated. The unit of ampere is derived from voltage and current using the Ohm’s law of electrical conductivity.

10.2.1 Metrological Traceability

The calibration and measurement capabilities (CMC) of the DC metrology are listed in Table 10.1. The laboratory have DC voltage measurement capability in the range from 10 μV to 1000 V with a maximum uncertainty of ~5 μV, DC current in the
Table 10.1 Calibration and measurement capabilities of DC metrology (Voltage, resistance and current)

| Parameter        | Range            | Uncertainty levels |
|------------------|------------------|--------------------|
| DC voltage       | 10 μV–1000 V     | (1.5–4.5) μV       |
| DC current       | 1 μA–20 A        | (5.5–100) ppm      |
| DC resistance    | 0.1 μΩ–1 GΩ      | (1.5–1000) ppm     |

range from 1 μA to 20 A with a maximum uncertainty of 100 ppm and DC resistance in the range from 0.1 μΩ to 1 GΩ with an uncertainty of 1000 ppm. There are about 27 CMCs related to the DC metrology which are approved under CIPM-MRA and are listed at BIPM key comparison database (KCDB) [4].

The traceability of DC voltage is primarily dependent on the DC Voltage Reference standard with output voltages of 1.018 and 10 V. The stability of 10 V output is 0.3 ppm/month and 2.0 ppm/year. Similarly, the measurement traceability of DC resistance in the range from 0.1 μΩ to 1 TΩ and DC current is disseminated with standard reference resistors and high precision multifunction calibrators and digital multimeter respectively. Ratio measurements for voltage and resistance are being performed with the help of voltage dividers and direct current comparator (DCC) bridges.

10.2.2 R&D and Future Road Map

Recently there has been tremendous interest in realisation of very low values of voltage, current and resistance for upcoming applications such as IoT and radiation dosimetry. Looking into these aspects and after receiving many industry feedbacks the laboratory started extending and enhancing the measurement capabilities to the limit of low values. For DC current, the range has been extended up to 1 pA utilizing the method of capacitance charging with known value of voltage ramp. The current measurement is performed using an electrometer and pre-amplifier [5]. For a capacitor of known capacitance value \(C\), and for applied voltage ramp of \(dV/dt\), the current is generated in the capacitor as \(I = C \cdot dV/dt\). Capacitance values of less than 1 nF are suitable for this technique, that too with gas or air dielectric as the medium. To implement the technique a suitable ramp generator (AD549) is fed by constant voltage pulses from the multifunction calibrator. The current developed across the capacitor is measured using the electrometer. The generation and measurements of currents in the range from 1 to 100 pA respectively has been demonstrated with and uncertainty of less than ppm.
10.3 Impedance Metrology

Electrical impedance, $Z$ is a complex quantity and can be expressed in terms of resistance ($R$), reactance ($X$); where, the reactance can be capacitive or inductive or a combination of both.

$$Z = R + jX$$

$$X_C = (\omega C)^{-1} \text{ or } X_L = \omega L$$

The frequency behaviour of impedance is severely affected by the parasitic and stray components. The electrical impedance at a specified frequency is defined as the complex ratio of phasor voltage across the terminals and the phasor current flowing between the terminals of a component. This is a frequency-dependent complex quantity and dependent on the material and dimensions of component/device.

While AC resistance differs from DC resistance as it is affected by the skin effect, which increases the effective resistance of conducting wire. Capacitance is related to the electric field and it is affected by the fringing field that occurs at the boundaries of the electrodes separated by dielectric material. Inductance is related to the magnetic field and is therefore susceptible with environment conditions. A variety of bridge circuits are used to measure the impedance parameters and mostly are discussed further in detail.

10.3.1 Metrological Traceability

The traceability chart for the respective impedance parameters are shown in Fig. 10.2. The coaxial bridges discussed below are generally used for the measurement of impedance, which includes the ac resistance, capacitance and inductance parameters.

10.3.1.1 Primary Standard of Capacitance

Thompson-Lampard theorem (1956) allows the calculation of capacitance directly from dimension. Referring to Fig. 10.3, The relationship between capacitance $C_1$ and $C_2$ for infinite length system in vacuum $[6, 7]$ can be written as

$$e^{-C_1 \frac{\pi}{\eta}} + e^{-C_2 \frac{\pi}{\eta}} = 1$$

For symmetrical cylindrical electrodes $C_1 = C_2$, then capacitance per unit length can be defined as:

$$C_0 = \varepsilon_0 \frac{\ln 2}{\pi}$$
\[ \varepsilon_0 = \frac{1}{\mu_0 c^2} \]

with \( c \) defined as the velocity of electromagnetic wave in vacuum, which is a constant.

In practice, the cylindrical electrodes are not fully symmetrical but if the \( C_1 - C_2/(C_1 + C_2/2) \) is less than \( 10^{-4} \) then uncertainty of 1 part per \( 10^8 \) can be achieved. The capacitance of the calculable cross capacitor was found to be frequency independent, but self-inductance and mutual inductance of the electrodes are frequency dependent and linearly proportional to the inverse square root of the frequency in the

Fig. 10.2 Traceability chart for the impedance metrology laboratory at CSIR-NPL

Fig. 10.3 Cross-section of cylindrical electrodes
examined frequency range. Cross-calculable capacitor is a complex system and its capacitance is limited to the fractions of pF. It also requires the frequency correction term in the uncertainty calculation as it is defined for electrostatic case.

10.3.1.2 Fused-Silica Capacitor

The fused-silica capacitor standards of 10 and 100 pF drives the traceability of impedance standards and the scaling of capacitance is performed through the various capacitance bridges. The quadrature bridge is used to assign the resistance standard in terms of capacitance standards. Thereafter, the inductor standards are defined in terms of resistance and capacitance standards through Maxwell-Wein Bridge. The laboratory utilizes the high value capacitance bridge for 10 to 10 mF values while low value inductance-bridge is used to measure inductance values equal to below 10 μH.

10.3.1.3 Quadrature Bridge

The quadrature bridge is a product bridge (Fig. 10.4), which compares two resistors $R_1$ and $R_2$ with two capacitors $C_1$ and $C_2$ at a single angular frequency $\omega$ [8]. The equilibrium condition does not rely on voltage or current ratios given by electromagnetic dividers. Quadrature bridge is balanced using the balance condition provided by the equation below.

![Transformer-based quadrature bridge assembly to define resistance standard in terms of capacitance at CSIR-NPL for audio frequency range. The assembly includes the stable oscillator as signal generator, inductive-voltage dividers, frequency counter, chokes, precise capacitance standards, oil bath, signal detector and unknown resistances](image)
$$\omega^2 R_1 R_2 C_1 C_2 = 1$$

A quadrature bridge is based on the known fact that the phase angle of the impedance, ratio between a resistor and a capacitor is $\pi/2$. Implementation of two such ratio circuits give a total phase shift of $\pi$. Ratios with phase angle near to $\pi$, can be measured precisely with Inductive-voltage-divider.

### 10.3.1.4 Transformer Ratio Bridge

Transformer ratio bridges are versatile bridge circuits with wide measurement range and these bridges are used for precision measurement of impedance parameters especially in audio frequency ranges. Primary and secondary transformer ratio in the source and detector side may be tapped to provide the variable internal standards. This mainly removes the requirements of variable resistor and capacitor. These bridges can be used for precise measurements up to 1 MHz. It offers wide measurement range for resistance, capacitance, and inductance. The typical schematic diagram of transformer-ratio bridge and two terminal pair bridge are shown in Figs. 10.5 and 10.6, respectively. The balance condition can be written as (Fig. 10.5).

\[
G_X = \left( \frac{N_X}{N_S} \frac{n_X}{n_S} \right) G_S \\
C_X = \left( \frac{N_X}{N_S} \frac{n_X}{n_S} \right) C_S
\]

The accuracy of the transformer-based bridge is limited by the stray components, electrostatic and electromagnetic field nearby. Electrical and magnetic shielding is
the common method that is used to minimize the impact of fields nearby the circuit and devices [8]. Shielding is essential in both DC and AC bridges. Guarding of bridge circuits is also important to reduce the capacitive coupling between the signal and low path. Coaxial circuit helps to confine the electrical and magnetic field well within the inner and outer conductor of coaxial system.

### 10.3.1.5 Coaxial Bridge

AC coaxial bridges are mainly derived from the conventional DC Wheatstone Bridge. It replaces battery from oscillator (AC source) while galvanometer from sensitive AC detector (tuned detector, vibration galvanometer, electro-mechanical meter, headphone, oscilloscope). Both magnitude and phase are required to be adjusted independently in order to balance the AC bridge. This balance condition is also the function of frequency. Thus, AC bridges are more complex than DC bridges. The bridge circuits can be classified as shown in Fig. 10.7.

The accuracy of the coaxial bridges is limited by the stray and residual components. The contribution from stray capacitance can be minimized by shielding the bridge arms that may reduce the effect of stray capacitance. Wagner balance is also used to eliminate some effects of stray capacitance in a bridge circuit [9]. The laboratory maintains the transformer-based coaxial analog bridges to measure impedance parameters at par with leading NMI’s of the world.

### 10.3.1.6 Maxwell-Wien Bridge

This transformer-based bridge is used to define the inductance in terms of standard resistance and standard capacitance. This bridge can achieved uncertainty better than
10 ppm for the 10 and 100 mH inductor at 1 kHz. It requires additional shielding and Wagner balance to adjust the shield potential to detector [10, 11]. The requirement of internal shielding is stringent. Maxwell-Wien bridge is slow and difficult to operate. The connecting leads should be as short as possible, and precautions must be taken to minimize the connection error especially while connecting the unknown with bridge.

10.3.1.7 High Frequency Impedance

The ultra-high-precision air dielectric coaxial transmission lines utilized as national standard of capacitance up to radio frequency range. The set of seven coaxial reference air-lines (Type 900-LZ series) exhibiting capacitance values varying from 2 to 20 pF have been realized as a capacitance standard at high frequency (1–200 MHz). The dimensions of coaxial air-lines; the outer diameter of inner conductor, inner diameter of outer conductor and geometrical length of air-line have been measured precisely and are traceable to the primary standard of length being maintained at the laboratory.

10.3.2 Calibration Measurement Capability

The mandate of the laboratory is to maintain and disseminate the unit’s related capacitance, inductance, AC resistance, ac voltage ratio and transformers ratio. All these quantities are linked to the respective primary/national standards through an unbroken chain of traceability. Traceability of impedance parameters are maintained through coaxial bridges, which are at par with international standards. The measurement
Table 10.2 Measurement capabilities of LF, HF impedance metrology laboratory at CSIR-NPL

| Parameters       | Range                        | Exp. uncertainty ($k = 2$) |
|------------------|------------------------------|-----------------------------|
| AC resistance    | 1 Ω–1 MΩ @ 1 kHz             | 5–300 ppm                   |
| Capacitance      | 10 pF–1 μF                   | 0.6–100 ppm                 |
| Inductance       | 1–100 mH                     | 30–100 ppm                  |
| AC voltage ratio (IVD) | 0–1 (1–50 V) @57 Hz, 1 and 10 kHz | 0.05–1 ppm                  |

capacities of quantities are approved under CIPM-MRA and are listed at BIPM key comparison database (KCDB) [4]. The uncertainty associated with impedance parameters are given in Table 10.2.

The laboratory has participated in various international inter key comparison [12–14] with different NMIs for the degree of equivalence in impedance and associated parameters are listed below (Table 10.3).

Table 10.3 List of key comparison of Impedance parameters CSIR-NPL

| Parameter       | Artifact and range                        | Year  | Country/program          |
|-----------------|-------------------------------------------|-------|--------------------------|
| Capacitance     | 10 pF Quartz capacitor (at 1592 Hz)       | 1986  | VNIIM (USSR)             |
|                 | 10 pF Quartz capacitor (at 1592 Hz)       | 1990  | VNIIM (USSR)             |
|                 | 10 pF Quartz capacitor (at 1592 Hz)       | 1984  | APMP                     |
|                 | 1 nF Air capacitor (at 1592 Hz)           | 1984  | NML (South Africa)       |
|                 | 10 pF Air capacitor (at 1592 Hz)          | 1994  | PTB (Germany)            |
|                 | 100 pF, Air capacitor (at 1592 Hz)        | 1994  | BIPM                     |
|                 | 1000 pF Air capacitor (at 1592 Hz)        | 1994  | BIPM                     |
|                 | 10 pF Quartz capacitor (at 1000, 1592 Hz) | 2004  | NIM China (APMP EM-S15)  |
|                 | 100 pF Quartz capacitor (at 1000, 1592 Hz)| 2004  |                          |
| Inductance      | 10 mH (at 1000 Hz)                        | 1984  | VNIIM (USSR)             |
|                 |                                           | 1988  | VNIIM (USSR)             |
|                 |                                           | 1998  | PTB (Germany)            |
| AC resistance   | 1 kΩ Resistor (at 1592 Hz)                | 1986  | VNIIM (USSR)             |
| AC ratio        | Inductive voltage dividers at 1 kHz and 55 Hz | 2001 | CCEM K7                  |
| DC resistance   | 1 Ω and 10 kΩ                            | 2013  | BIPM (France)            |
|                 | 1 Ω Standard                              | 1987  | Indo-Soviet Prog.        |
|                 | 1 Ω and 10 kΩ                             | 1986  | APMP                     |
| DC current      | 1 pA, 10 pA and 100 pA                    | 2012  | KRISS (Korea)            |
| DC voltage      | 1000:10, 100:10 (Voltage ratios)          | 2011  | IEN Italy                |
10.3.3 R&D and Future Roadmap

10.3.3.1 Development of AC–DC Calculable Resistance Standard

Cross calculable capacitance standard based on Thomson-Lampard theorem, was being used as a primary standard of impedance in leading NMI’s. These capacitance standards were able to provide the uncertainty of the order of $10^{-7}$ but are bulky and complex in operation and it has other limitations as well. The laboratory is working on to establish traceability of impedance standards from AC–DC calculable resistance standard that will be traceable to QHR as shown in Fig. 10.8. It is compact, simple to design, and easy to operate and its uncertainty is better than the cross-calculable capacitance standards, considering these factors it has become the first choice for a primary standard.

10.3.3.2 Frequency Characterization of Four Terminal Pair Air Capacitance Standards

Frequency Characterization of four-terminal-pair (4TP) air capacitance standards have been explored using extrapolation technique from 1 to 1000 pF up to 30 MHz. The approach used for the evaluation is based on the determination of capacitive and inductive residual components of electrical equivalent circuit model of four-terminal-pair air capacitance standards [15–19]. S-parameter measurement was performed to determine the series and parallel resonances. A bilateral comparison for capacitance standards is in progress with National Metrology Institute of China under APMP. Figure 10.9 shows the procedure for the evaluation of 4TP capacitance standards and S-parameter measurement of 4TP capacitance standards using vector network analyzer (VNA).
10.4 High Voltage and High Current Metrology

Nowadays, share of renewable energy and its integration with power grids are rapidly increasing. It appears that role of high-voltage direct current (HVDC) is more promising for efficient and reliable bulk power transmission over long distance [20, 21]. However, in such an application, massive breakdown failure may occur due natural or artificial events such as ice storms, thunderstorm, hurricanes or cyber-attack which requires restoration of system within a time. In this regard, maintaining stability and ensure continuous supply of electrical power at various stages such as transmission and distribution network are required to avoid such a kind of major breakdowns. A periodic calibration of instrument transformer used in such a high voltage application such as voltage transformer (VT) and current transformer (CT) are undoubtedly required and are briefly discussed in detailed.

10.4.1 DC High Voltage

The resistive dividers are the primary standard of DC high voltage. They are generally used to measure DC ratio of 100,000/10 with measurement uncertainty of 10 ppm. The traceability of DC high voltage measurement from 1 to 100 kV with an uncertainty of 20–100 μV is linked to JVS through resistive voltage dividers shown in Fig. 10.10.

The DC high voltage (100 kV) and high voltage resistance divider requires careful electrostatic shielding to minimize stray capacitance effect. The top of the divider is covered by high voltage grading ring so that the capacitance between individual
resistance units of the divider to earth is equal to the capacitance of the resistance units to the grading ring. The presence of the ring greatly reduces errors, which would be caused by capacitance leakage to earth. The guard circuit is used to reduce the leakage by corona along the whole length of the divider. The guard circuit takes the form of a resistance chain connected in parallel with the main divider having ten times its resistance. The divider is normally used in a high voltage area inside suitable screens and kept clean to keep the surface leakage to a minimum.

### 10.4.2 AC High Voltage and High Current

The calibration of instrument transformers is essential for precise measurement of bulk power. It is necessary to calibrate the CT and VT for the ratio error and phase displacement as per the IS/IEC standards [22–27]. The measurement of capacitance and \( \tan \delta \) (dissipation factor) are important for determining the deterioration and ageing effects of insulation of cables, bushings, transformers, etc. It may be noted that the increase in \( \tan \delta \) values of the insulation of electrical equipment indicates its deterioration. This may be because of ageing, chemical deterioration due to temperature and time, contamination by moisture, carbon deposits, dirt, and leakage through cracks.

The laboratory is maintaining the national standards of AC high voltage (HV) ratio measurements up to 100 kV using HV ratio measuring system (HVRMS) and AC high current (HI) ratio measurements up to 5 kA at power frequency of 50 Hz
Fig. 10.11  Schematic diagram for voltage transformer ratio measurements using HVRMS

using standard current comparator (standard CT) [28, 29]. The automatic instrument transformer test set (AITTS) is used along with these standards in voltage and current mode, respectively. The traceability of HVRMS, standard CT and AITTS is ensured through periodical calibration from PTB, Germany. The laboratory also maintains the national standards of HV capacitance and tan δ up to 200 kV using high precision C and tan δ bridge, set of standard HV and air capacitors along with standard tan δ [30]. The C and tan δ bridge are periodically calibrated from NRC, Canada. Capacitors are traceable to the primary standard of calculable cross capacitor.
10.4.2.1 AC High Voltage Ratio Measurements

The AC high voltage ratios of the VTs are measured for ratio error and phase displacement as per specified burden. The ratio error of VT can be expressed in terms of percentage as,

\[ \varepsilon = \left( \frac{K_t V_s - V_p}{V_p} \right) \times 100\% \]

where, \( k_t \) is the transformation ratio,
\( V_p \) is the actual primary voltage
\( V_s \) is the actual secondary voltage

The phase displacement of VT is the difference between the primary and secondary voltage phasors, the direction of the phasors being so chosen that the angle is zero for an ideal transformer.

The accurate and precise measurement of VT is carried out by comparison method as shown in Fig. 10.11. It consists of AC HV Source (300 kV/300 kVA), HVRMS and AITTS. The HVRMS comprises of standard HV capacitor (SF6 gas filled) of 100 pF/100 kV, standard air capacitor of 10,000 pF/1 kV and standard Electronic Voltage Divider (EVD). The same nominal ratio is selected in HVRMS for the VT ratio to be measured. The required burden is connected in parallel on the secondary of the VT. The output of EVD and VT is connected to the AITTS which is used in voltage transformer test set (VTTS) mode. The VTTS compares the difference in voltages between the HVRMS and VT, and thus determines the ratio error and phase displacement of the VT. The measurements are carried out at 80, 100 and 120% of the rated primary voltage of the selected ratio as per IS 16227 (Part 3): 2015 [26].

10.4.2.2 AC High Current Ratio Measurements

The AC high current ratios of the CTs are measured for ratio error and phase displacement at specified burden. The ratio error of CT can be expressed in terms of percentage as,

\[ \varepsilon = \left( \frac{K_t I_s - I_p}{I_p} \right) \times 100\% \]

where, \( k_t \) is the rated transformation ratio,
\( I_p \) is the actual primary current
\( I_s \) is the actual secondary current
The phase displacement of the CT is the difference in phase between the primary and the secondary current, the direction of the phasors being so chosen that the angle is zero for an ideal transformer.

The precise measurement of CT ratio is carried out by comparison method as shown in Fig. 10.12. It consists of AC HI source (5 kA/15 kVA), standard CT, AITTS, electronic programmable current burden (EPCB) and high current cables. The standard CT is having 310 standard ratios ranging from the lowest ratio of 5 A/1 A, 5 A to the highest ratio of 5 kA/1 A, 5 A. The EPCB provides the burden in the range from 1–75 VA at 0.5–1.0 Power Factor.

The standard CT and CT under test are connected in series using high current cables to a AC HI source. The AITTS is used in current transformer test set (CTTS) mode. The same nominal ratio is selected in both the CTs. The EPCB is connected in series with the secondary of the CT under test. The CTTS compares the output of the CTs and gives the ratio error and phase displacement. The measurements are carried out at 5, 20, 100 and 120% of the rated primary current of the selected ratio as per IS 16227 (Part 2): 2016 [27].
10.4.2.3 AC High Voltage Capacitance and Tan δ (Dissipation Factor) Measurements

The AC high voltage, capacitance and tan δ measurements is carried out using high precision capacitance and tan δ bridge, a set of standard HV and air capacitors along with standard tan δ. This set of capacitors consists of HV capacitors of 100 pF/200 kV and 1000 pF/30 kV, standard air capacitors of 100 pF/2 kV and 1000 pF/2 kV along with tan δ standard ranging from $5 \times 10^{-5}$ to $1 \times 10^{-3}$. The commercial $C$ and tan δ bridge used is based on double vector–meter method, which relies upon measurement of current through standard capacitor and the current through capacitor under test as shown in Fig. 10.13. The measurement of capacitors up to 2 kV is carried out using with standard air capacitors. Similarly, measurement of HV capacitors or dividers from 2 to 200 kV is carried using SF$_6$ standard HV capacitors of 30 and 200 kV.
10.4.3 Calibration and Measurement Capabilities (CMC) and Industrial Support

The measurement uncertainty of AC HV ratio error and phase displacement for voltage range up to 100 kV at 50 Hz are ± 60 μV/V and ± 70 μ rad respectively. Similarly, measurement uncertainty of AC HI ratio error and phase displacement for current range up to 5 kA at 50 Hz are ± 40 μA/A and ± 50 μ rad respectively. Whereas measurement uncertainty of high voltage (up to 100 kV) and current (up to 5 kA) are ±130 μV/V and ±120 μA/A respectively. The measurement capabilities of these quantities are approved under CIPM-MRA and are listed at BIPM key comparison database (KCDB) [4]. The measurement uncertainty and range associated with these parameters are given below in Table 10.4.

The traceability of HV and HI measurement parameter is disseminated through apex level calibration services to the power sector in general and power utilities, electrical equipment manufacturers, accredited testing and calibration laboratories in the country. In particular, it includes Current Transformers, Current Transformer Testing Sets, High Current Sources, Clamp Meters, Current Probes, CT Burdens, Voltage Transformers, Voltage Transformers Test Sets, HV Probes, Electrostatic Voltmeters (ESVM), HV Break Down Test Sets, Voltage Transformer Burdens, High
Table 10.4  CMC for AC High voltage and high current metrology

| Quantity/parameter          | Minimum value | Maximum value | Specifications | Expanded uncertainty at $k = 2$ |
|-----------------------------|---------------|---------------|----------------|---------------------------------|
| AC High voltage: source     | 10 V          | 100 kV        | 50 Hz          | ±130 μV/V                        |
| AC High voltage: meter      | 10 V          | 100 kV        | 50 Hz          | ±130 μV/V                        |
| AC High voltage ratio: ratio error | −0.02        | +0.02         | 10 V–100 kV (50 Hz) | ±60 μV/V                        |
| AC High voltage ratio: phase displacement | −20 m rad | +20 m rad | 10 V–100 kV (50 Hz) | ±70 μ rad                        |
| AC High current: source     | 1 A           | 5 kA          | 50 Hz          | ±120 μA/A                        |
| AC High current: meter      | 1 A           | 5 kA          | 50 Hz          | ±120 μA/A                        |
| AC High current ratio: ratio error | −0.02        | +0.02         | 1A–5 kA (50 Hz) | ±40 μA/A                         |
| AC High current ratio: phase displacement | −20 m rad | +20 m rad | 1A–5 kA (50 Hz) | ±50 μ rad                        |

Voltage Sources, HV Capacitors, HV Dividers, kV Meters, Capacitance and tan δ Bridges.

The traceable measurement helps the electrical manufacturing industries to develop accurate and reliable measuring equipment, which in turn translates in winning the consumer confidence in the equity of electricity trade. The traceability in HV Power measurements in support of bulk power measurements, provides a basis to the industries and utilities deeply engaged in the generation, transmission and distribution of electric power. It supports electrical power industries and utilities to be globally competitive.

10.4.4  R&D and Future Roadmap

10.4.4.1  Conventional Instrument Transformers

The voltage transformer (VT) is designed for a specified burden and its use at different burden which affects the performance. The amount and nature of the burden makes a significant influence on the ratio error and phase displacement of VTs. Burdens imposed by different instruments varies widely i.e. small for indicating instruments whereas large for recording and operating instruments. During the measurements on VT, burden equivalent to actual load in regular working conditions is connected in parallel on secondary of the VT.

To understand the effect of burden on accuracy aspect of VT, measurements have been carried out on VT of ratio 11 kV/110 V with leads burden (for laboratory grade...
and at different burdens ranging from 5 VA to 40 VA [31]. The AITTS has been used for determining the ratio error and phase displacement at 80, 100 and 120% of the rated voltage. The ratio error at 100% of rated voltage is increased to ~ 0.18% whereas, phase displacement increased to ~ 0.63 min for 40 VA burden. The results show that laboratory grade VTs should be used at rated burden. In case, such VTs are used for higher burden application, it will lead to higher errors in measurements.

Similarly, measurements were carried out on 500 A/1 A CT for ratio error for various burden values against the multi ratio standard CT having ratios up to 5 kA/1 A, 5 A ratio [32]. The burden of 2.5, 5 and 10 VA was connected in series with CT under measurement. The AITTS has been used for comparing the ratio error at 100% of the rated current. It was observed that there is substantial increase in the ratio error from leads burden to 10 VA.

10.4.4.2 Non-Conventional Instrument Transformers for High Current Measurement

In another context, non-conventional instrument transformers (NCIT), based on optical Faraday effect and Pockels Cell effect with digital readout are gaining lot of popularity in high current measurement for high voltage applications [33, 34]. NCIT’s potential are well known over conventional one for operational safety, environmental benefit, compact in size and lightweight, measurement fidelity for voltage and current [33]. However, commercially available current sensor has limitation of measurement accuracy of 0.1% for 500 kA (DC) and 63 kA rms. The traceability for non-conventional sensor based current transformer are not yet commercially available; many NMI’s are working together to achieve uncertainty below 100 μA/A for medium and high voltage application.

Future Scope: The electrical power transmission in the country is increasing towards extra HV and ultra HV. The laboratory is making continuous efforts to establish the AC HV ratio, HV capacitor and HV divider facility up to 300 kV in near future to meet the need of power industries and utilities. It also has a long-term plan to establish an ultra HV laboratory with state-of-the-art facilities for AC HV measurements up to 800 kV and AC HI ratio up to 20 kA.

10.5 AC Power and Energy Metrology

Accurate and reliable power and energy measurement has a huge economic impact, which plays crucial role in management, maintenance and distribution of electric infrastructure to protect earth’s natural resources. Looking at current scenario, the entire ecosystem and economic growth relies heavily on the power sector. These includes renewable energy sources such hydroelectric power, biomass gasifiers, urban and industrial waste power, solar energy and wind energy. The government is taking various initiatives in power sectors by launching new policies and regulations
such as program on National Smart Grid Mission (NSGM), Smart Meter National Programme (SMNP). To support government initiatives, the laboratory is trying to cater industrial needs at highest level.

10.5.1 Metrological Traceability

The traceability of Power and Energy is realised through Precision Power Calibration System (PPCS-Primary Standard) which is traceable to DC voltage (10 V), resistance (10 Ω) and frequency (10 MHz). The primary standard is based on digital sampling technique and is designed for high precision active, reactive and apparent power/energy measurements [35]. The basic idea is to utilize single clock frequency which is derived from high precision digital sampling voltmeter for sampling and synthesizing test signals. (shown in Fig. 10.14). The distortion free and highly stable test source (V_{out}, I_{out}) amplified from voltage amplifier and transconductance amplifier are fed to meter under calibration and device itself through voltage transformer and current transformer. The respective voltages V_{1_{in}} and V_{2_{in}} proportional to V_{out} and I_{out} are sampled alternately by Digital Sampling Voltmeter (DVM) using signal switch. Any cause of uncertainty arises is minimize by synchronizing sampling and switching signal. The complex amplitude (V_{1_{in}}, V_{2_{in}}) can be measured from sampled database using Discrete Fourier Transform (DFT).

Fig. 10.15 Metrological traceability for power and energy
The apparent, active and reactive power can be calculated from the ratio between test and measured signal as (Fig. 10.14)

\[
\text{Ratios, } R_1 = \frac{V_{1\text{in}}}{V_{\text{out}}} \quad \text{and} \quad R_2 = \frac{V_{2\text{in}}}{I_{\text{out}}}
\]

\[
\text{Apparent Power, } S = V_{\text{out}} I^*_{\text{out}} = \frac{V_{1\text{in}}}{R_1} \frac{V_{2\text{in}}}{R_2} = \frac{V_1}{R_1} \frac{V_2}{R_2} e^{i(\phi_1-\phi_2-\text{arg}(R_1)+\text{arg}(R_2))}
\]

\[
S = \text{Mod}\{S\} = \frac{V_1}{R_1} \frac{V_2}{R_2}
\]

\[
\text{Active Power, } P = \text{Re}\{S\} = \frac{V_1}{R_1} \frac{V_2}{R_2} \cos(\phi_1 - \phi_2 - \text{arg}(R_1) + \text{arg}(R_2))
\]

\[
\text{Reactive Power, } Q = \text{Im}\{S\} = \frac{V_1}{R_1} \frac{V_2}{R_2} \sin(\phi_1 - \phi_2 - \text{arg}(R_1) + \text{arg}(R_2))
\]

**Traceability:** The unbroken chain of power/energy measurements traceability maintained at the laboratory. The traceability of power/energy standard is ensured by calibrating it against reference power/energy standards as shown in Fig. 10.15.

### 10.5.2 Measurement Capability and Metrological Services

#### 10.5.2.1 Calibration and Measurement Capabilities (CMC)

The mandate of the laboratory is to maintain and disseminate the unit’s related to power and energy and associated measurements from frequency 40 to 400 Hz
Table 10.5  Calibration and measurement capabilities for AC power and energy

| Parameter       | Range                  | Expanded uncertainty \((k = 2)\) | Single phase                                                                 | Three phase                                                                 |
|-----------------|------------------------|-----------------------------------|-------------------------------------------------------------------------------|------------------------------------------------------------------------------|
|                 |                        |                                   | 50–70 μW/VA \((40–70 \text{ Hz})\) 70–300 μW/VA \((70–400 \text{ Hz})\) | 65–150 μW/VA \((40–70 \text{ Hz})\)                                          |
| Active power    | 10–576 V              |                                   | 50–70 μW/VA \((40–70 \text{ Hz})\) 70–300 μW/VA \((70–400 \text{ Hz})\) | 65–150 μW/VA \((40–70 \text{ Hz})\)                                          |
|                 | 10 mA–120 A           |                                   | 50–70 μW/VA \((40–70 \text{ Hz})\) 70–300 μW/VA \((70–400 \text{ Hz})\) | 65–150 μW/VA \((40–70 \text{ Hz})\)                                          |
|                 | PF: 0.01 (lag/lead) to 1.0 |                                   |                                                                               |                                                                               |
| Apparent power  | 10–576 V              |                                   | 80–150 μW/VA \((40–70 \text{ Hz})\) | 80–150 μVA/VA \((40–70 \text{ Hz})\)                                        |
|                 | 10 mA–120 A           |                                   | 80–150 μW/VA \((40–70 \text{ Hz})\) | 80–150 μVA/VA \((40–70 \text{ Hz})\)                                        |
|                 | 40–70 Hz              |                                   | 80–150 μW/VA \((40–70 \text{ Hz})\) | 80–150 μVA/VA \((40–70 \text{ Hz})\)                                        |
|                 | PF: 0.01 (lag/lead) to 1.0 |                                   |                                                                               |                                                                               |
| Reactive power  | 10–576 V              |                                   | 90–150 μW/VA \((40–70 \text{ Hz})\) | 90–150 μV/VA \((40–70 \text{ Hz})\)                                         |
|                 | 10 mA–120 A           |                                   | 90–150 μW/VA \((40–70 \text{ Hz})\) | 90–150 μV/VA \((40–70 \text{ Hz})\)                                         |
|                 | 40–70 Hz              |                                   | 90–150 μW/VA \((40–70 \text{ Hz})\) | 90–150 μV/VA \((40–70 \text{ Hz})\)                                         |
|                 | PF: 0.01 (lag/lead) to 1.0 |                                   |                                                                               |                                                                               |
| Active energy   | 30–576 V              |                                   | 50–70 μW/VA \((40–70 \text{ Hz})\) 70–300 μW/VA \((70–400 \text{ Hz})\) | 65–150 μWs/VA \((40–70 \text{ Hz})\)                                         |
|                 | 10 mA–120 A           |                                   | 50–70 μW/VA \((40–70 \text{ Hz})\) 70–300 μW/VA \((70–400 \text{ Hz})\) | 65–150 μWs/VA \((40–70 \text{ Hz})\)                                         |
|                 | 40–70 Hz              |                                   | 50–70 μW/VA \((40–70 \text{ Hz})\) 70–300 μW/VA \((70–400 \text{ Hz})\) | 65–150 μWs/VA \((40–70 \text{ Hz})\)                                         |
|                 | PF: 0.25 (lag/lead) to 1.0 |                                   |                                                                               |                                                                               |
| Apparent energy | 30–576 V              |                                   | 80–150 μW/VA \((40–70 \text{ Hz})\) | 80–150 μVAs/VA \((40–70 \text{ Hz})\)                                       |
|                 | 10 mA–120 A           |                                   | 80–150 μW/VA \((40–70 \text{ Hz})\) | 80–150 μVAs/VA \((40–70 \text{ Hz})\)                                       |
|                 | 40–70 Hz              |                                   | 80–150 μW/VA \((40–70 \text{ Hz})\) | 80–150 μVAs/VA \((40–70 \text{ Hz})\)                                       |
|                 | PF: 0.25 (lag/lead) to 1.0 |                                   |                                                                               |                                                                               |
| Reactive energy | 30–576 V              |                                   | 90–150 μW/VA \((40–70 \text{ Hz})\) | 90–150 μV/VA \((40–70 \text{ Hz})\)                                         |
|                 | 10 mA–120 A           |                                   | 90–150 μW/VA \((40–70 \text{ Hz})\) | 90–150 μV/VA \((40–70 \text{ Hz})\)                                         |
|                 | 40–70 Hz              |                                   | 90–150 μW/VA \((40–70 \text{ Hz})\) | 90–150 μV/VA \((40–70 \text{ Hz})\)                                         |
|                 | PF: 0.25 (lag/lead) to 1.0 |                                   |                                                                               |                                                                               |

For Voltage range 10–576 V, Current range 10 mA–120 A and Power Factor 0.01 (lag/lead) to 1.0. The measurement capabilities of these quantities are approved under CIPM–MRA and listed at BIPM key comparison database (KCDB) [4]. The uncertainty associated with these parameters are given below in Table 10.5.

**10.5.2.2 Metrological Services**

**Calibration Service:** The laboratory provides apex level calibration services for power and energy measurements for those who needs the best accurate and reliable measurement. Generally accredited laboratory, power utility, energy meter manufactures require such a highest class of the reference power/energy traceability for stable, accurate and reliable measurements. Single (three) phase power (energy) comparators, power converters, power quality and energy analyzer and meter test equipment are calibrated at the laboratory. The methods and procedure used in the high precision measurements are internationally recognized at par with other leading NMIs. The laboratory also periodically validates its own capabilities by participating in various international key comparison.
Testing Services: The performance of energy meters are tested at par international/national standards such as IEC: 62053-21, IEC: 62053-22, IS: 13779, IS-14697, IS: 13010 and CBIP-88 [36–41]. Various tests are performed on energy meters before rolling out into actual field such as

- Test of accuracy requirements
- Test of electrical requirements
- Test for electromagnetic compatibility
- Test for climatic influence
- Test for mechanical requirements
- Test of influence quantities: Influence of voltage variation, frequency variation, phase sequence, Third harmonics and Fifth harmonics, voltage unbalance should not affect accuracy class of meter as per standard specifications.
- Test of influence of AC/DC magnetic inductions
  
  i  Test of influence of AC magnetic inductions
  
  AC abnormal magnetic induction of 10 milli Tesla ±5%
  
  AC abnormal magnetic induction of 0.2 T ±5%
  
  ii  Test of influence of dc magnetic inductions
  
  DC stray magnetic induction of 67 milli Tesla ± 5%
  
  DC abnormal magnetic induction of 0.27 T ±5%
  
  DC abnormal magnetic induction of 0.5 T ±5%

- Tamper and fraud protection Tests: Single Phase Energy Meter
  
  i  Interchange of phase and neutral wires
  
  ii  Reversal of line and load terminals
  
  iii  Reversal of line and load terminals with phase and neutral exchange
  
  iv  Load Earthing: The meter should keep on registering energy even when the load is not terminated back to the meter and instead current is drawn partially or fully through earth.
  
  v  Earth load (Forward): The supply to the meter is connected as normal but the load is returned to earth.
  
  vi  Earth load (Forward) with phase neutral exchanged
  
  vii  Earth load (Reverse): The line and load terminals are reversed, and load is returned to earth.
  
  viii  Earth load (Reverse) with phase neutral exchanged
  
  ix  Earth load with neutral disconnection
  
  x  Any other tamper feature is also checked/tested as per customer’s requirement.

- Tamper and fraud protection Tests: Single Phase Energy Meter: Three Phase Energy Meters
  
  i  Interchange of Phase and neutral
  
  ii  Missing Potentials
  
  iii  CT Polarity Reversal
iv Phase sequence Reversal
v The working of the energy meter is checked in unbalanced condition
vi The detection of CT short/open condition
vii Tampering against magnetic field
viii The meter functioning for accuracy on all phases individually
ix All single-phase meter tampering conditions applied

However, tampering condition are unknown to all, nevertheless tamper events can be tested and verified as per customer’s requirement.

Consultancy Services: The technology which is being adopted for energy meter design and specification are varying in many different ways, resulting difference in their functionality, operation and performance. From Metrological aspect, the performance of energy meter must withstand under influence of electrical and environmental condition; accordingly, it is necessary to optimize each component for accurate measurement and tariff billing. Furthermore, at distribution side, power loss arises due to Transmission and Distribution can be considerable but power theft, the non-technical losses, is a common concern and serious offence. Replacement of electronic meter over electro-mechanical one, technically reduces some sort of meter tampering condition, but in practice, there are numerous ways to tamper electronic meter. In turn, the distribution companies suffer enormous amount of economic problem at power management side. Utility, distribution boards and consumers require technical assurance for quality of product. Being the NMI of the country, the laboratory provide technically assistance to metering industries, power utilities, distribution boards and consumers for parametric optimization for advance design and measurements. The laboratory also supports Bureau of Standards (BIS) technically for policy implementation as when requires standardization in Metering Industry.

10.5.3 R&D and Future Roadmap

10.5.3.1 International Key Comparison

The laboratory also participates in various key comparison, one such a comparison organized by EURAMET under project no. 687 for measurement of power at low frequency is discussed here. [42] total of 12 NMIs, UME Turkey, PTB Germany, NCM Bulgaria, SMU Slovakia, OMH Hungary, INM Romania, DMDM Serbia, MIKES Finland, VSL Netherlands, CSIR-NPL India, LNE France and UMTS Ukraine were participated. HEG C1-2 Power Converter was used as a traveling standard for measurement of power proportional DC voltage (10 V at full range). The measurement taken at 120 V, 5 A, Power Factor \(1/0.5i/c/0i/c\) (\(i\): inductive, \(c\): capacitive) and 53 Hz of frequency. Since the PTB Germany was pilot laboratory, the measurement results of PTB Germany considered as a reference to link each other
participant. The measurement uncertainty DC output voltage proportion to 120 V, 5 A, UPF @ 53 Hz power at a coverage factor $k = 2$ shown in Fig. 10.16.

The laboratory is also developing new calibration and testing method for precise measurement power and energy. Laboratory has upgraded measurement capability of power/energy from voltage 0.1 to 640 V; from current 5 mA to 160 A; from power factor: 0.01(lag/lead) to 1.0; from frequency 40 to 70 and 400 Hz with measurement uncertainty $\pm 10$ to $\pm 30$ ppm. Furthermore, laboratory is involved in improving power/energy measurement capabilities beyond 400 Hz to cater industrial needs.

Besides, there are two critical issues which are of concern in metering industries that cannot be forsaken; first influence of electromagnetic field in energy data storage; second load analysis, load forecasting and load management.

Fig. 10.17 The top panel shows the actual device on TO8 holder with contacts and contact schematic (right). Typical specifications of the GaAs/AlGaAs based QHE devices used at CSIR-NPL are as follows: GaAs-Al$_x$Ga$_{1-x}$As ($x = 0.3$), GaAs (1.5 eV) is lightly p-doped, AlGaAs (2.2 eV) is n-doped, $\sim$10–20 T$^{-1}$, $n \sim 3–6 \times 10^{15}$ m$^{-2}$, $B (i = 2) \sim 7–9$ T. The graph in the lower panel depicts longitudinal ($R_{xx}$) and transverse ($R_{xy}$ or the Hall) resistance of a GaAs-Al$_x$Ga$_{1-x}$As ($x = 0.3$) device measured at 1.3 K.
10.5.3.2 Influence of Electromagnetic Field on Energy Meters

The performance of energy meter under influence of conducted electromagnetic influence cannot be neglected, as reported in early publications [43, 44]. The feeders, active infeed converters (AIC) or active front ends (AFE), are widely used to transmit energy to the grid for ensuring better power quality. However, lack of the electromagnetic interference (EMI standards), between 2 and 150 kHz, possibly increase interference level between feeders and grid can cause error in energy measurement [43]. The performance of energy meter has to be tested for conducted emission, radiated emission, immunity to electromagnetic HF field, fast transient burst test, test of electrostatic discharge, surge immunity test, voltage dips and short interruptions and, flicker and harmonics measurements at par IEC 62052-11, CISPR 22, IS 16444 (Part 1) and IS 6842 for IS 16444 (Part 2) guidelines [45–47]. Considering effect of EMI, the laboratory is engaged in establishment of electromagnetic interference and compatibility measurements capability up to 40 GHz for compliance testing on energy meter.

10.5.3.3 Smart Energy Metering

A real time energy monitoring and digitalization of substation are really required to accomplish goals of smart grid infrastructure. During past decade, smart meters (SM), an energy monitoring unit, with bi-directional communication capability were introduced. The number of parameters associated with it such as load analysis, load forecasting and load management cannot be underestimate. Numerous extensive researches have been put forward for handling data set of energy consumption, but yet it is not up to the mark for big data analysis. In fact, real time analysis of big data is essential for load forecasting and load management. Also handling these data involves potential security risk from metering to head end system. There is substantial need of development in privacy challenges, privacy laws, policies, regulations, standards and privacy-enhancing technologies. Number of protocols have been used for liable data exchange with inter-operability such as ZigBee, Modbus, M-Bus, DLMS/IEC62056, IEC61107 and ANSI C.12.18. DLMS/IEC62056 [48–52] accepted in India due its efficiency; considering the above facts the laboratory is engaged in strengthening testing capability for smart metering to address above issues.

10.6 Quantum Metrology

10.6.1 Quantum Hall Resistance Metrology

The measurement of electrical resistance is very fundamental to electrical/electronic metrology. Quantum Hall Resistance Standard (QHRS) provides an invariant
quantum standard of resistance in terms of the fundamental constants. The Quantum Hall Effect (QHE) is a characteristic of a perfectly quantized 2-dimensional electron gas (2DEG) system realized in Si-MOSFETs, GaAs/AlGaAs quantum wells, Graphene, etc. at low temperatures and intermediate to high magnetic field. The QHE was discovered by K von Klitzing, provides an invariant reference for resistance linked to fundamental constants “e” and “h” \((R_H = h/e^2)\) and is being used as the primary standard of resistance and its comparison since 1990. In order to facilitate international comparisons and conservation of the ohm, a conventional true value \(R_{K-90}\) of \(R_K\) was fixed by the CIPM on 1st January 1990. Numerically, \(R_{K-90}\) equals exactly to 25,812.807 \(\Omega\). The QHE (at 1.3 K) and a magnetic field of 5–14 \(T\) supplies a quantum Hall resistance standard (QHRS) of value \(R_{K/i}\) \((i = 2 \text{ or } 4)\), with a relative reproducibility better than \(10^{-10}\). The bridge used for comparison of resistance standards is based on a cryogenic current comparator (CCC) or room temperature direct current comparator (DCC); the former having much better accuracy (uncertainty \(\sim 10^{-9}\) in terms of \(R_{K-90}\)). The most popular QHE device currently used in metrology is the GaAs/AlGaAs 2DEG quantum well where a 2DEG system is composed of modulation doping in a heterostructure, in which the barrier provides the carriers in the quantum well or hetero-interface of semiconductor multilayer. The quantized Hall resistance is given by \(R_H = h/e^2 = R_{K-90}/i\), where ‘\(h\)’ is the Planck constant, ‘\(e\)’ is the electron charge, and ‘\(i\)’ is an integer. The voltage \(V_J\) obtained from the Josephson Effect and the resistances \(R_H\) obtained from the QHE are directly linked to two phenomenological constants, the Josephson constant \(K_J\) assumed to correspond to the ratio \(2/e/h\), and the von Klitzing constant \(R_{K-90}\) taken to be the quantum resistance \(h/e^2\).

### 10.6.1.1 SI Traceability and Measurement Capabilities

The primary standard of resistance in terms of the QHE is maintained at laboratory and has been peer reviewed in 2005 and 2010 by international technical experts. The \(i = 2\) plateau with 129,06.4035 \(\Omega\) is taken as the primary standard and a 1000 \(\Omega\) resistor maintain in constant temperature enclosure is compared with it. For a 1000 \(\Omega\) standard measured against the QHRS using a direct current comparator (DCC) bridge, the combined expanded uncertainty at coverage factor \(k = 2\) is \(U_c (k = 2) = 80 \text{ ppb}\). DCC bridge is capable of measuring resistance ratios (1:1, 10:1 and 13:1) in the range 100 m\(\Omega\)–100 k\(\Omega\). The CMC of 1000 \(\Omega\) resistor at fixed temperature with a combined expanded uncertainty of \(U_c = 80 \text{ ppb}\) is listed at the BIPM website [4] (Figs. 10.17, 10.18).

### 10.6.1.2 R&D in Quantum Hall Resistance Metrology

Typically, GaAs/AlGaAs devices based on QHE operated at 1.3 K, 8–10 T magnetic fields and breakdown current of \(\sim 10–40 \mu \text{A}\) [53–59]. Operation at lower magnetic
Fig. 10.18 Results of the comparison of a 1000 Ω standard resistor with $R_{K-90} \ (i = 2) = 129,06.4035 \ Ω$ using a high precision DCC bridge. Each measurement was done at fixed temperature in temperature ascending as well as descending cycle. The left panel of the figure shows the measured value while the right panel gives the deviation from the nominal value.

Fig. 10.19 Indigenously developed system for growth of epitaxial graphene on SiC.

fields, higher temperatures with larger breakdown current may result in ease of realization and economically cheaper QHRS. It is also desirable to test the universality and material independence of QHRS. Considering these aspects, there has been ongoing efforts to realize QHRS in other system than GaAs/AlGaAs. Among all the new two dimensional electron gas (2DEG) systems, graphene has stolen all the lime light ever since its discovery in 2004 [60]. The origin of the exceptional physical attributes of graphene properties lies in the intriguing crystal structure, nature of chemical bonding and special electronic band structure of graphene [61]. Consequent to the discovery of integer QHE (IQHE) in graphene [62], global R&D efforts have
been focused on the realization of the resistance standards under relaxed conditions. Realization of reliable QHRS based on graphene critically depends on the quality and behavior graphene device. There are three most popular synthesis methods to obtain graphene, namely, exfoliation of graphite, chemical vapor deposition (CVD) on metallic foils, and sublimation of SiC. Even though QHE has been observed at room temperature in the device made using exfoliated monolayer graphene, it could not qualify for reliable QHRS due to the limitation of quantization accuracy arising due to small flake size and charge impurities related very low breakdown current. Generally, graphene grown on Cu foil using CVD method is cheaper and easier. However, structural defects due to polycrystalline nature and transfer to Si/SiO2 substrate hinder the observation of dissipation less QHE, a prerequisite to QHRS. Therefore, it is important to have single crystalline graphene with minimum structural defects and homogeneous monolayer thickness over large area, ideally in millimeter scale. Although, epitaxial graphene grown on SiC is much more costly and technically challenging; it can be grown in millimeter scale with highest structural quality. Availability of large area single crystalline epitaxial graphene allows easier fabrication of QHE devices exhibiting much higher breakdown current and thus, better signal to noise ratio. After the first demonstration of QHE in Graphene, NPL-UK took the lead and made the first demonstration of the quantum Hall effect in Graphene in quantum resistance metrology. The recent reports (NPL-UK, LNE-France, PTB-Germany and NIST-USA) in this direction clearly establish the fact that devices based on epitaxial Graphene grown on SiC are the most suitable for quantum resistance metrology. The agreement between quantized Hall resistance in Graphene and GaAs/AlGaAs with an ultimate relative uncertainty of $8.2 \times 10^{-11}$ is also very encouraging. It should also be noted that epitaxial graphene based QHRS can operate at much relaxed conditions compared to conventional GaAs/AlGaAs QHE devices i.e. at higher temperatures, lower magnetic field and with larger breakdown current, and it has resulted in the possibility of realizing QHRS in a table-top cryogen free system.

Since it is becoming clearer now that epitaxial graphene based QHRS may replace the conventional GaAs/AlGaAs based QHE devices due to its better performance, it becomes imperative on the part of the laboratory to have a focused program on the development of the quantum resistance metrology devices and measurement techniques based on epitaxial graphene. We envision developing indigenous technology/devices for the realization of graphene based QHRS through concerted, committed and continuous research focused on indigenous development of 2DEG systems to achieve leadership and global visibility. It will be part of national capacity building in the field of quantum metrology. Looking at ourselves as a self-reliant nation, it is essential to focus on advanced quantum material system like graphene so that desired goals are achieved in the area of quantum electrical metrology. Graphene growth is being performed in custom built growth system. This indigenous customized epitaxial graphene growth system Fig. 10.19 has been designed and fabricated and commissioned at the laboratory. Base pressure of growth system is 1
× 10⁻⁷ mbar and it can reach to ultra high vacuum (2 × 10⁻⁸ mbar) after overnight pumping and without baking.

Growth system is equipped with turbo molecular based pumping system and two gas lines equipped with mass flow controllers and various valves for attaining controlled gas atmosphere. Specially designed graphite enclosure containing 4H-SiC piece (2 × 4 to 7 × 7 mm) is heated using RF-induction heating to attain temperatures ~ 2273 K. In situ C-type thermocouple measures the temperature which are cross-checked by a suitable optical pyrometer. Near equilibrium growth is achieved by confining the sublimating Si vapor in a tight enclosure and let it to escape in controlled manner. Atomically smooth SiC is heated to 1673–2273 K in high vacuum as well as Ar atmosphere using RF induction heating to produce highly homogeneous, single crystalline (area near 1–4 mm²) monolayer graphene. Exhaustive growth parameter (growth temperature, gas pressure, and heating rate and Si vapor escape rate from the close confined graphite enclosure) tuning is being done to achieve best quality monolayer graphene suitable for QHRS applications. Figure 10.20 shows the performance of the growth system in terms of achieved temperature of graphite enclosure and corresponding heating power.

AFM images of monolayer epitaxial graphene grown on 4H-SiC (1000) are shown in Fig. 10.21. It is evident from Fig. 10.21a that graphene covers underneath SiC surface like a carpet and height profile exhibited in Fig. 10.21c shows clearly that unit cell height (1 nm) of 4G-SiC is intact even after the growth. Phase contrast image shown in Fig. 10.21b demonstrates the uniformity of grown graphene.

Raman spectroscopy is a very reliable tool to ascertain the presence of graphene and to determine its layer thickness. Figure 10.22 exhibits the Raman spectra of graphene grown in Ar gas environment, vacuum conditions (~5 × 10⁻⁶ mbar) nearly 1773 K. There are two important features to look for graphene in Raman spectrum, $G$ (1580–1590 cm⁻¹) peak associated with in-plane vibration mode of graphitic carbon and 2D (~2701–2770 cm⁻¹) peak associated with double phonon scattering. $G$ peak
Fig. 10.21  AFM image (3 × 3 μm), a topography image and b phase contrast image of epitaxial graphene grown on 4H-SiC (1000) at 1773 K, 1030 mbar Ar gas pressure along with c height profile across dashed line shown in a

Fig. 10.22  Raman spectra of epitaxial graphene grown at Ar gas and high vacuum environment

is not very sensitive to the layer thickness of graphene. However, position and full width at half maximum (FWHM) of 2D peak are very sensitive to doping and layer thickness, respectively of graphene. In Fig. 10.22, we can observe both G and 2D peaks for both the samples along with multitude of features at lower wavelength range (1000–2000 cm⁻¹) originating from underlying SiC substrate. For graphene grown at vacuum environment, G and 2D peaks are diminished compared to growth at Ar gas environment. It shows growth at Ar gas environment is favourable to better quality graphene.

2D peak of graphene grown at Ar gas environment can be fitted with single Lorentzian component as shown in Fig. 10.22, whereas more than one component (not shown here) is required to fit 2D peak for graphene grown at vacuum condition,
indicating larger layer thickness. Peak position and FWHM of 2D peak of graphene grown at Ar gas environment turns out to be 2715 ± 6 cm\(^{-1}\) and 50 ± 0.45 cm\(^{-1}\), respectively and these numbers support the monolayer thickness of grown graphene.

Further optimization of growth parameters and more characterization is going on to achieve reproducible, highest quality epitaxial graphene over a large area, preferably 4 \(\times\) 4 mm\(^2\). Later on, metal contact will be optimized with aim to have sub-ohmic contact resistance and 6/8 contact Hall bar QHE devices will be fabricated to realize graphene based QHRS.

### 10.6.2 Quantum Current Metrology

In the absence of direct quantum current standard, the practical realization of the ampere using the established quantum standards of volt based on Josephson effect and...
ohm from quantum Hall effect via Ohm’s law has become almost universally accepted [71]. However, being the only base unit in the electrical metrology, the ampere has to be established by direct realization of quantum current standard with sufficient accuracy so that the interrelation with other derived units via fundamental laws of physics can be verified. For example, one of the important and unresolved issues related to the quantum electrical metrology is the quantum metrological triangle (QMT) experiment which can be made with the quantum standards of voltage, resistance and current [72, 73]. The closure of the QMT is one of the important tasks in quantum metrology. From the QMT, not only one can inter-relate the three SI units \(V, I\) and \(R\) but also the validity of Ohm’s law at the quantum limit can be verified [74]. Currently, the QMT needs to have a better accuracy for the current standard so that the other two established quantum standards, namely, the voltage standard based on Josephson Effects (JE) and the quantum resistance standard based on the Quantum Hall Effect (QHE), can be placed with the quantum current standard and their inter relation through Ohm’s law can be verified without deviating the accuracy [73].

In the revised SI units effective from May 20, 2019, a new way of defining the base units has been adopted by using a set of seven defining constants that range from the fundamental constants of physics and other constants of nature [1]. In the new definition, the aforesaid defining constants are assigned to fixed numerical values leading to lower uncertainty with better accuracy. For example, by definition, electric current is the transportation of electrical charge per unit time and as per the new definition in revised SI, the unit of current ‘ampere’ is defined by fixing the value of the fundamental constant, the elementary charge ‘\(e\)’. The new definition follows as: “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 \(1.602\ 176\ 634\ \times\ 10^{-19}\ C\) when expressed in the unit \(C\), which is equal to \(As\), where the second is defined in terms of \(\Delta \nu_{Cs}\), the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be \(9\ 192\ 631\ 770\) when expressed in the unit Hz, which is equal to \(s^{-1}\)” [1]. Therefore, from the new definition, one ampere is a measure of the electric current in which \([1/(1.602\ 176\ 634\ \times\ 10^{-19})]\) (or \(6.2415\ \times\ 10^{18}\)) elementary charges (e) move across a given point in one second. So, by controlling one electron at a time and by defining the charge on the electron as a fixed number, we can create a current which is precisely known and self-calibrated.

However, as the discoveries associated with quantum phenomena have brought revolutionary changes in the world of metrology, the quantum electrical metrology comes into play with enhanced measurement capability by exploiting quantum strategies for improved sensitivity and accuracy of measurements. There are two most popular quantum phenomena, viz. (i) single electron tunnelling (SET) effect and (ii) quantum phase slip (QPS) effect, by which the current can be defined in terms of the fundamental unit of electronic charge, ‘\(e\)’. Direct measurement of ampere is possible by counting the number of moving electronic charges over a period of time using SET devices. Here, one has to make sure that the counting is error free so that all the tunnelled electrons should be collected at the receiver end with no backward tunnelling. Further, in order to have a reasonable amount of current, the
transit of electrons should be very fast, i.e. the frequency of pumping out of individual electrons from a device should be very high. Here come the experimental and measurement challenges that are being addressed by national metrological institutes and other high-end laboratories in the world. Meanwhile, researchers are looking into another exciting quantum phenomenon, quantum phase slip (QPS), which occurs in one-dimensional superconducting nanowires. The QPS is exact dual to the Josephson Effect (JE) which leads to the quantum standard of voltage. Quantized current steps are predicted to appear when a QPS junction is excited with microwave radiation and these steps, known as Shapiro steps, may lead to the realization of quantum current standard. For QPS based devices, the quantized steps do not deal with counting of individual electrons and the amplitude of current can be higher by tuning the frequency of the microwave excitation. However, there are enormous experimental challenges to execute and implement it successfully up to the level of quantum current standard.

10.6.2.1 Single Electron Tunneling (SET)

To realize this new definition of ampere, a standard transistor electron pump is being used to transport and electron across a device, which is based on the principle of SET phenomenon. This phenomenon states that “a quantum mechanical particle has a finite probability of crossing a barrier even if its energy is less than the barrier”. It consists of three electrodes; source, drain and gate connected with an island. Source and drain electrodes are coupled resistively to the island and gate electrode are coupled capacitively. Island has finite number of electrons and charges on the island are quantized. Tunnelling of an electron with charge e, or rather a known number N of electrons Ne in each operation of a single-electron pump that is cyclically repeated at frequency f, generates an output DC current, ideally, equal to Ne \times f. The first single-electron transistor was reported theoretically by Likharev and D.V. Averin [75] and further experimentally demonstrated by Fulton and Dolan [76]. After that Geerlings did the experiment on the linear array of small tunnel junctions with rf signal, which opened the way for higher frequency current standards [77]. Later, H. Pothier demonstrated the reversible turnstile operation under which the electron transfer path is determined by the phase of gate voltage [78].

SET as an Electron Pump: The needs of precision metrology generally state that this operation has to be performed at a relative error level not larger than 10^{-8} and at the same time the current level needs to be several hundreds of pico amperes. The precision of the single electron pump was first measured numerically and analytically by Dalsgaard et al. [77]. In which they demonstrated that cotunneling, thermal activation, and operating system at very high frequency limits the accuracy. Co-tunnelling can be suppressed by increasing both the resistance of the tunnelling island and the number of tunnel junctions. Keller et al. [79] reported single-electron pumping using seven tunnel junctions arranged in series in 1996. This experiment used a 5 MHz signal and yielded an error rate of 15 parts in 10^9. A four junction SET traps was made by Fulton and Gammel and Dunkleberger et al. had maximum trapping time of
Dresselhaus et al. used seven junction trap of Al/AlOx/Al tunnel junctions to store electron for 2 h. Nine junction traps were also made by Krupenin et al. [81] and they have trapped electron for more than 8 h. For having the control on the electrons Ono et al. fabricated a device which is the combination of MOSFET and SET, this structure shows good long term stability, but the frequency is limited by RC time constant [82] at that time it is difficult but now with the advancement of fabrication technology it’s possible. Wright et al. [83] and Giblin et al. [84] found the effect of the magnetic field on the pumping accuracy, Giblin showed the uncertainty of 1.2 ppm for 150 pA at 14 T. Seo et al. showed that the shape of the potential barrier also helps to improve pumping, they found the uncertainty of 0.1 ppm for 80 pA [85]. At laboratory, we are currently fabricating silicon nanowire based SET devices for electron pumping and counting.

In the low current range uncertainty increases due to the lack of sensitivity of the measurement techniques. Brun-Picard et al. reported a programmable quantum current generator, which used a highly accurate cryogenic amplifier [71] which gives the uncertainty of $10^{-8}$ however its current range is limited to 10 mA to 1 μA. Recently at PTB Germany ultra stable low-noise current amplifier has been developed which gives ppm gain at 100 pA [86]. Material wise Graphene and carbon nanotubes could be good candidates for single-electron pumping, in terms of maximizing the frequency.

One more important thing to discuss is the noise, if in the environment there is thermal noise or any other kind of noise we would not able to see our device performance accurately even though it is doing good. So for this, it’s important to have appropriate filtering, for covering wide frequency range we can combine the RC, LCR, LC filter with powder filters [87].

### 10.6.2.2 Quantum Phase Slip (QPS)

So far in the world scenario, the efforts have been focused in realization of quantum current standard (QCS) mainly by single electron tunnelling (SET) through Coulomb blockade effects in a single electron pump which relates the electrical current with the elementary charge and the pumping frequency. However, to perform the quantum metrological triangle (QMT) experiment the QCS should be able to deliver the current at least in the nano-ampere range and hence the pumping frequency of the SET device should be much faster than that achieved so far or there should be alternate strategy to combine many such SET pumps in parallel so that final output current is in the desired range. Obviously, the electronic circuitry and fabrication of parallel SET pumps become much more complex and the issues of reduced uncertainty and low reproducibility limit the realization of practically relevant QCS.

An alternative approach, known as quantum phase slip (QPS) phenomenon in one-dimensional superconducting nanowires, has been taken up as the challenge for the realization of QCS by many leading groups worldwide [88, 89]. In 1D limit, a small region of superconducting nanowires can block the flow of supercurrent momentarily and hence switches to the normal state due to constant quantum fluctuations of
the order parameter and this allows the phase of the order parameter to slip by $2\pi$. This phenomenon is known as quantum phase slip (QPS). With appropriate coupling to the microwave excitation, equally spaced quantized current steps, $I = 2nf$, are expected from a voltage biased QPS junction. Here, $f$ is the microwave frequency and $n$ is an integer. Similar to the measurement of Shapiro steps observed for the Josephson junction (JJ) based voltage standard, under microwave irradiation the quantized current steps from a voltage biased QPS could in principle lead to the QCS with accuracy limited by the accuracy of the measurement of frequency [90].

Theoretically it has been predicted that quantum phase slip (QPS) process in superconducting nanowires is dual to the Josephson Effect (JE) leading to quantum standard of voltage which is now used and established in world metrology for measuring voltage [91]. Similarly, there are now unprecedented attentions around the globe towards exploration of QPS in superconducting nanowires for the establishment of quantum current standard. The simplicity in the concept with better performance for the QPS based current standard than the existing routes makes it a novel and attractive candidate for the realization of QCS. However, there are several challenges which should be addressed in order to have successful experimental realization of the QPS based QCS.

As mentioned, the various crucial steps in the journey from fabrication of superconducting nanowire based QPS junction to reach to the QCS are technically very much challenging and very rich in quantum physics. For example, the demonstration of dual nature of QPS to the JE itself is very much complicated. Further, the microwave coupling to a voltage-biased QPS junction needs high level of instrumentation and engineering. Fundamental physics behind QPS, its dependence on external parameters like temperature, magnetic field, electrical biasing are the backbones of the realization of QCS by using QPS. However, in the present scenario, establishing a quantum standard of current, capable of delivering at least nano-ampere range current with uncertainty better than one part in 100 million, by using QPS junction is the utmost requirement. In order to achieve that, first and foremost priority is to demonstrate QPS effect experimentally which and is a challenging task by itself. There are major challenges mainly related to

(i) Fabrication of long 1D superconducting nanowires with dimensions: $\sqrt{\sigma} \sim \xi$; $\sigma = \text{cross section}$ and $\xi = \text{coherence length}$,

(ii) On-chip designing of inductive and resistive circuitry in series with the QPS junction (QPSJ) to provide the necessary damping and the high impedance environment favourable for the QPS events to occur,

(iii) Determination and tuning of the characteristic voltage ($V_C$) for the QPS junction in order to obtain the QPS energy $E_{\text{QPS}}$,

(iv) Fabrication of on-chip low-loss microwave coupler circuit to the QPS junction for obtaining the quantized constant current steps desired for the establishment of QCS,

(v) Retrieving ultralow current signals from the proposed QPS device using sophisticated current meter or using ultra-low noise current amplifiers.
A process flow chart for QPS based QCS is shown in Fig. 10.23. The first step is to grow ultrathin homogeneously disordered superconducting thin films with thickness of the order of the coherence length ($\xi$) or less. Some of the promising superconducting (SC) materials as reported in the literature are TiN, InO$_x$, Nb, NbGd, NbSi, Nb$_2$N, NbN, W etc. [92–101].

Here, selection of materials is very important as the phase slip rate depends strongly on the material properties like the normal state resistivity ($\rho_N$), [102] superconducting critical temperature ($T_c$) etc. The immediate next step after the thin film growth is to fabricate long uniform one-dimensional (1D) nanowire which acts as the QPS junction (QPSJ). This is one of the most important and crucial steps as it needs state of the art facilities and skilled expertise. Two main facilities, viz., electron-beam lithography (EBL) and reactive ion etching (RIE) systems are must to achieve 1D superconducting nanowire based QPSJs.

Further, recent studies demonstrated the use of focused ion beam (FIB) for the fabrication of nanowires [103]. FIB is also used to fabricate tungsten nanowires with a superconducting transition temperature $\sim$ 5.2 K which is also a promising candidate for QPS study [101]. However, FIB may not offer the most desired dimensions and purity levels (Ga contamination) of the fabricated nanowires suitable for the QPS study.

In addition to the conventional 1D nanowires, superconducting meander lines are also used to study QPS [101, 104, 105] as meandering offers much longer nanowire in small space and eventually with increased normal state resistivity ($\rho_N$) [104]. The representative two types of structures, viz. nanowire and meander lines, from FIB-fabricated superconducting W are shown in Fig. 10.24.

These nanostructures are patterned by using the FIB facility. The length can contribute to the kinetic inductance which provides the inductive energy of the QPSJ. For QPS study the normal state resistance ($\rho_N$) should be higher or of the order of quantum resistance [89] and by using long nanowire with diameter of the order of the
superconducting coherence length one can achieve higher ($\rho_N$). In addition, on-chip fabrication of resistive and inductive circuitry, in series with the superconducting nanowire based QPSJ, is needed to provide high impedance environment leading to an overdamping of circuit and hence suppression of charge fluctuation which is highly desirable for QCS [88, 97].

Figure 10.25 represents schematically the device geometry along with the microwave coupling scheme via an rf antenna, its equivalent circuit diagram and quantization of current under microwave irradiation with frequency $f$. As Cooper pair tunnelling in JJ is equivalent to phase fluctuation/slip in QPS junction, analogously to a resistively and capacitively shunted JJ, an equivalent QPS junction can also be described by a resistively and inductively series coupled junction (RLSJ) as shown in Fig. 10.25a and b. The essential components of QPSJ include a voltage source, a nonlinear serial shunt resistor that has different values of resistance in different phases of operation including normal to superconducting transition as a function of the voltage across the device, an inductor that represents the inductance of the nanowire and the ideal QPSJ device in series. The time dependent voltage across the QPSJ can be obtained through [88, 89, 91],

$$V(t) = V_C \sin \left(\frac{2\pi q}{2e}\right) + L \frac{d^2q}{dt^2} + R \frac{dq}{dt}$$

Here, $V_C$ is the critical voltage of the QPSJ and it is related to QPS energy $E_{QPS}$ as, $V_C = \left(2\pi E_{QPS}\right)/(2e)$, $q$ is the charge of the device at that instant, $L$ is the inductance of the device, $R$ represents the non-linear resistance of the device describing different resistance regions of the QPSJ before, during and after superconducting transitions which is a function of the voltage, $V(t)$ is the voltage across the junction as a function of time.
Fig. 10.26 Demonstration of phase slip events in NbGd thin film with Gd concentration varying in the range between 0 and 1 at.

of time. In the above equation the Cooper pair current, \( I = dq/dt \), is different from zero for only time dependent \( q \). For a QPSJ, \( q \), the charge, is a good quantum variable and further improvement is obtained by employing the overdamped junction so that the charge fluctuation is minimized.

Importantly, the equation for \( E_{\text{QPS}} \) given below is valid when it is larger than the inductance energy \( E_L \), \( E_L = \phi_0^2 / 2L \), with \( \phi_0 \) and \( L \) are the flux quantum and the inductance, respectively. Further [106],

\[
E_{\text{QPS}} \sim \left( -a \frac{\sigma T_c^{1/2}}{\rho_N} \right)
\]

where, \( \sigma \) is the cross-sectional area of the QPS nanowire, \( 'a' \) is a dimension-dependent parameter, \( e \) is the electronic charge, \( \rho_N \) is the normal state resistivity and \( T_c \) is the superconducting critical temperature. A large value of \( V_C \) corresponds to large QPS energy (\( E_{\text{QPS}} \)) which is favourable for the QPS to be observed experimentally.

Under microwave excitation with suitable range of frequency, QPSJ is expected to exhibit quantized current steps as, \( I = 2enf \), known as dual Shapiro steps. Here, \( f \) is the microwave frequency, \( 2e \) is the charge on Cooper pair and \( n \) is an integer representing the quantization number. Figure 10.25c represents the quantized current...
steps expected to appear in the current voltage characteristics (CVCs) of a voltage biased QPSJ coupled with microwave. With large $E_{\text{QPS}}$, Bloch-type oscillations are expected with a frequency $f_B = \frac{I}{2e}$ for QPS junctions and when these oscillations are synchronized with external microwave drive with frequency $f$, quantized current steps appear due to resonance at matching current. Therefore, Bloch-type oscillations and resonance at plasma frequency, which is related to the QPS energy, are the favourable conditions for the observation of quantized current steps or the Shapiro steps [91]. The range of excitation frequency can be determined from the junction characteristics of the QPSJ. For example, the characteristic voltage, $V_C$ can be obtained from measured CVCs as shown in Fig. 10.25. Further, as explained previously, $V_C$ relates to the QPS energy $E_{\text{QPS}}$ which relates to the frequency as $E_{\text{QPS}}/\hbar$ with ‘$\hbar$’ being the Plank’s constant. Therefore, every circuit element in the QPSJ should be controlled very efficiently so that experimental observation of quantized current can be achieved.

10.6.2.3 Current Status and Developments

Being the national metrological institute (NMI), the has the mandate to maintain and establish the metrological standards. laboratory have started working on the realization of quantum current standard (QCS) by quantum phase slip (QPS) phenomenon. In the previous section, we have discussed about how to establish QCS by using QPS effect in superconducting nanowires. Here, we discuss about the on-going work towards the establishment of QCS including the achievements till date and the future plans.

In this direction, we have tried doping of a conventional superconductor like Nb with magnetic material in very dilute concentration limit of about 1 at.% or less. By magnetic doping with Gd of $\leq 1$ at.% into superconducting Nb, phase slip events are shown to be triggered and the composite NbGd material can be a promising candidate for the QPS study. The experimental demonstration of phase slip process in NbGd thin film is summarized in Fig. 10.26 which represents the temperature dependent resistance $R(T)$ measurements for few selective samples with variations in Gd concentration and current voltage characteristics (CVCs) measured at low temperature. Figure 10.26a highlights a strong dependence of metal-superconductor (NM–SC) phase transition on the Gd concentration. The (NM-SC) transition curve shifts towards lower temperature with wider transition region for increasing Gd concentration. Figure 10.26a and b present the CVCs for two different samples varying in Gd concentration. The phase slip lines are evident for both the samples by the appearance of the intermediate resistive states. Finally, in Fig. 10.26d, the phase diagram, based on the temperature dependent critical current for the sample shown in Fig. 10.26c, is displayed. Various dynamical regions are illustrated in the phase diagram including the specific phase slip regions as PSLs. The related research and the results are very promising towards the application of these composite materials for phase slip studies, Josephson effects, proximity effects etc. and are highly significant towards their application in the field of NanoSQUID, quantum computations, single photon detection, quantum current standards etc. [95, 96].
Fig. 10.27 Observation of phase slip events in Nb$_2$N thin films. a Normalized resistance ($R/R_N$) with respect to reduced temperature ($T/T_{c0}$) for three representative Nb$_2$N samples differing in thickness. Here $T_{c0}$ is the superconducting critical temperature corresponding to zero-resistance. The isothermal CVCs for those three samples are displayed in b, c and d, respectively. Inset in a represents the device geometry.

Recently, we have demonstrated a novel nitridation technique to transform transition metal Nb to one of its stable phases, Nb$_2$N, which has been further explored by studying its exciting superconducting properties. We simply deposit Nb thin films on Si$_3$N$_4$/Si substrate at high temperature and continue heating the substrate for a couple of hours and finally we end up having Nb$_2$N from the deposited Nb. Here, the Si$_3$N$_4$/Si substrate acts as the only source of nitrogen which is available when Si$_3$N$_4$ decomposes into Si and N atoms by high temperature annealing. Among the members of niobium-nitrogen family, cubic NbN has been explored extensively in the field of superconductivity, however, Nb$_2$N is mainly known for its hardness and other mechanical properties. Superconductivity is not been explored in that extent for this phase of niobium nitride. By performing low temperature transport measurements down to mK temperature range, we show here that indeed Nb$_2$N possesses interesting superconducting properties and more specifically it may be considered as a potential candidate to study phase slip related quantum phenomena and the related
applications. Further, we show that this material can serve as a model macroscopic system to study the phase slip phenomenon beyond 1D limit.

In Fig. 10.27, we have presented few selected low temperature transport measurement data that actually exemplify the superconducting properties as well as the material’s suitability for phase slip study. Three different samples, varying in thickness, have been presented here and the metal-superconductor transition has been observed for all of them in their $R(T)$ measurements presented in Fig. 10.27a. The CVCs are enriched with phase slip lines and the evolutions of phase slip lines with temperature and with sample thickness have been illustrated in Fig. 10.27b, c and d, respectively, in a order of reduced thickness. With very broad transition width, transition at mK temperature as presented in $R(T)$ measurements along with the phase slip lines in the CVCs, the material indeed can be a very promising candidate for future studies on QPS and other superconductivity related applications [98].

So far, we have been discussing mainly on superconducting thin films for the use in QPS study. As the next step obviously is to move towards 1D nanowires, here we discuss about our ongoing work on nanowires and meander type of structures specifically based on FIB-deposited W in dirty limit.

We have established a protocol for preparation of nanowires and meander structures of W deposited by focused ion beam (FIB) induced techniques. The $T_c$ of the material is $\sim$5 K, and the nanowires exhibited phase slip behaviour. The transport measurements data for three selective W-meanders are presented in Fig. 10.28.

![Transport measurements on FIB-deposited W-meanders with varying dimensions.](image)

**Fig. 10.28** Transport measurements on FIB-deposited W-meanders with varying dimensions. a–c Temperature dependent resistance [$R(T)$] data for three different samples. The dimensions are shown in the insets. d Magnetic field dependent resistance [$R(B)/MR$], measurements for sample W1. Inset: crossing of MR isotherms at single critical field $B_x$ indicates the onset of field induced superconductor-insulator transition (SIT)
The $R(T)$ curves, displayed in Fig. 10.28a–c, show the changes with the dimension. However, the $T_c$ remains in the range of 4–4.5 K and with reduced width—the transition gets wider with residual resistance tailing at temperature below the transition temperature. This indicates the dominance of phase slip events for the reduced width. In Fig. 10.28d, we have shown magnetic field dependent resistance (MR) data for sample W1 and interestingly, the MR isotherms cross at a particular field, $B_x$, at which the MR becomes independent of temperature. The crossing of MR at a single point indicates the onset of superconductor-insulator transition (SIT) which is another criterion for the observation of QPS. Therefore, we believe that the W-based meanders and nanowires could be very important material for the future QPS related studies [101].

Finally, in accordance with revised SI, the primary standard for the only base unit in electrical metrology, the ampere, needs to be established by using the laws of physics dealing with elemental charge, $e$, as the ampere relates to the flow of elementary charges per unit time [71]. Conventionally, two different quantum phenomena have been adopted by the scientific community for the realization of quantum current standard. Single electron tunnelling (SET) is the one which deals with direct transport of electrons by using a pump probe technique. However, the amplitude of current and the uncertainty need to be improved and there have been continuous efforts worldwide to resolve the issues so that QMT experiment can also be performed. The other quantum phenomenon, which is totally different from its principle than that of SET, relates to continuous phase fluctuation in 1D superconducting nanowire and it’s known as quantum phase slip (QPS) process. As phase and charge are canonically conjugate quantum variables, they are dual to each other. And correspondingly, a QPS junction is shown as the analogue or dual to a Josephson junction which leads to the quantum standard of voltage. Therefore, a QPS junction with the correct combination of inductive and resistive circuitry can be developed as the future quantum standard of current in a suitable electromagnetic environment. Further, QPS junctions are capable
of transporting larger currents with higher accuracy than that with SET pumps [107]. However, high level of instrumentation and interfacing between many sophisticated low-noise electronic instruments are must to achieve the demonstration of QPS based quantization of current steps to be used for the quantum current metrology.

As the modern era heavily depends on electrical accessories and appliances requiring a wide range of driving current for their functioning, the accurate and precise measurement of electric current is not only a mandatory requirement but it has an enormous influence on the nation’s economic growth and infrastructure. The realization and establishment of quantum current standard is thus a very important step towards the growth of the country and its self-reliance.

### 10.6.3 Quantum Nano Photonics Metrology

#### 10.6.3.1 Superconducting Nanowire Single Photon Detector (SNSPD)

The fantasy of capturing and analysing any matter that exists in this world leads to an opening of a new era in the field of physical science and related technology. One such era has evolved from capturing a source of light in early days to now grabbing a few photons. Detecting a single photon from millions of photons that exists in a ray of light is now not only limited to a research topic but is slowly finding applications in almost every field. This includes medical care, space communication, cyber security, metrology, quantum cryptography, quantum computing, quantum key distribution etc. [108, 109]. Photo multiplier tube (PMT)-a photon detector and its better counterpart Avalanche photo diode (APD) possesses some limitations at telecom wavelength. Efficiency of InGaAs based photo detector is better at infrared wavelength range but it suffers from high dark count rate, large time jitter, after-pulsing effect etc. To overcome these limitations, new materials and technology are explored. Superconducting nanowire-based detectors is turning to be a good solution for such problem. It’s been proved and demonstrated that the superconducting nanowire single photon detector (SNSPD) has low dark count rate, high spectral response over a large wavelength range, less timing jitter etc. [110]. SNSPD operation is based on the concept of hotspot formation [111] whereby, a meander shaped superconducting nanowire is biased below or close to the critical current. After photon absorption, superconductivity is lost and we get a voltage pulse that corresponds to a photon count. After a short interval superconductivity reappears and detector is ready for the detection of next photon. Besides single photon, there are many such exciting research areas involving physical quantities and are being developed or enhanced for futuristic applications. For most of the physical quantities, the laboratory have basic and derived SI units that help us to achieve standardization. The SI units had undergone a change and now are mostly being realized in terms of fundamental constants [112]. This had paved the way to realize quantum standards for each of the existing non-quantum standards particularly for SI units. Working on these aspects, the laboratory is developing photon-based quantum standards for optical radiation.
10.6.3.2 Fabrication

Single photon detection requires a nanoscale size chip and patterning. The laboratory have dedicated multi chamber sputtering facility and a PLD (Pulsed Laser Deposition) chamber for depositing superconducting thin films, ultra-thin films and devices. Superconducting thin films of different materials such as NbN, NbTiN, VN, YBCO etc. had been deposited using DC magnetron sputtering and PLD system under different growth conditions. They exhibit superconducting behaviour and are further being investigated for their application as single photon detector.

10.6.3.3 Measurements and System Integration

To characterize deposited thin films was done using a stable low temperature cryostat with the maximum drift of ~4 mK for electrical insert and ~7 mK for optical insert [113]. The individual characterization of the thin films gives us an idea about its initial performance in terms of diffusivity, coherence length, critical magnetic field etc. that are crucial for fabricating photon detectors. These parameters affect detection efficiency, timing jitter, dark counts etc. that marks the performance of a single photon detector. Once the fabrication concludes, the time is to test its real performance i.e. the photon count. The testing of single photon detector by shining the light requires a precise and accurate instrumentation setup. Some of the complex process in instrumentation includes light beam alignment, reading of the pulse, noise elimination etc. We are into the process of developing a setup that caters to all these issues. Figure 10.29 shows one such setup using a photo diode at visible and infrared wavelength.

10.6.3.4 Traceability Chain

Cryogenic radiometer will serve as the primary standard and will be at the top of the traceability chain for single photon detection measurements.

For visible wavelength, Si trap detector will serve as the transfer standard whereas for infrared wavelength, thermopile detector will be a transfer standard.

Finally, working standard will be optical power meter that will be used to calibrate single photon detectors efficiency.

With the advent of single photon detectors and related devices, the need arises of having a traceability chain for them, to ensure that the measurements made using detectors are accurate and are traceable to some SI standard. We propose a traceability setup based on single photon detector [114] as shown in Fig. 10.30.
**Fig. 10.30** Traceability chain for single photon detector [PTB Germany]

**Fig. 10.31** Electricity consumption (TWh). *Source [117]*
10.7 Electrical and Electronics Metrology for Quality Infrastructure in India

10.7.1 Training and Human Resource Development

Electrical and Electronics Metrology is associated with the design and development of electrical networks, electronic circuits, communication equipments, monitoring devices, navigational equipments, data interface with computers. Human resources often are to be built in the fields of calibration and testing, product-quality evaluation and equipment maintenance and repair. With the advent of Industry 4.0, expertise in electrical and electronic automation processes are also on demand. A generalized system for automatic current and voltage measurements consisting of a set of programmable instruments interfaced with proper software has been on high-end metrology research. If such attempts are integrated with portable solutions, calibration and testing activities can be performed on on-site bulk equipments. Hence, the future for electrical and electronics metrology demand in for various specialization related to power generation, energy storage, control and distribution of electrical energy. It is also noted that materials science also would play a vital role. Materials for long distance transmission cables (superconducting wires), and oxide materials and graphene for realization of Quantum Hall Effects at or near room temperature are active fields of research.

Having understood that electrical and electronic metrology plays an important role in daily lives, CSIR-NPL has integrated in its AcSIR affiliated diploma programmes, the following modules—Introduction to AC power and energy measurements, testing and calibration of AC power and energy measuring instruments, transformers, bulk energy metering and allied equipments, kA meters, high voltage capacitors and others.

A survey over different job advertisement websites, shows more than 3000 job offers in the field of electrical and electronic metrology. These are associated with calibration technician and engineers. In common, the job responsibilities include calibration and testing of electrical equipments at customer site. The desired qualification includes experience of 2–3 years, with a prior diploma or degree from any university or All India Council for Technical Education (AICTE) approved institutes. Besides, familiarity with computerized systems, various plant and laboratory equipments, and experience in process control are also emphasized. Experience in National Accreditation Board for Testing and Calibration Laboratories (NABL) accredited calibration laboratories are at times considered as an additional advantage in the job selection process.

Given the job scenario, as above, India lack the appropriate skill sets due to the under-developed laboratory access to the trainees. Such human resource training centers fail to realize the practical side of the metrology aspects associated with the electrical and electronic measurement traceability. A possible solution to the gap is to have CSIR-NPL scientists and technicians as consultants and trainers to the
industries, where practical knowledge can be imparted to the industry recruits based on their needs and requirement.

10.7.2 National Mission and Programs

10.7.2.1 Smart Grid and Smart Meter National Programme

For better energy efficiency and energy management, Advanced Metering Infrastructure (AMI) can be integrated with current grid infrastructure. The installation of smart energy meters, part of AMI, can convey complete information of energy usage almost in a real time. This information can be utilized to monitor, analyse, and control the substation for resolving energy peak demand problem. Thus, the installation of smart meters will resolve problem like billing efficiency and reduction in commercial and aggregate technical losses. The integration of smart energy meters not only help in boosting per capita income, but also will lead to accurate billing through real time monitoring usage. In effect, consumer get better knowledge on management of power usages because of reliable measurement and transparency in reading. It can provide complete solution to energy disputes problems, power wastage and indirect reduce in carbon emission. Following Energy Efficiency Services Limited (EESL), has taken up the charge to replace 250 million conventional meters with smart energy meters [115] in phases and by 2027 under SMNP, Integrated Power Development Scheme, Ujwal DISCOM Assurance Yojana (UDAY) scheme. Until now, more than 12 lakhs smart energy meters have been installed including 9.84 lakhs in Uttar Pradesh, 1.23 lakhs in Haryana, 0.57 lakhs in NDMC New Delhi and about 0.28 lakhs in Bihar.

Related but in another context, the transformation of electrical grid into digital one requires special attention on development of energy management using supervisory control and data acquisition systems (SCADA) with energy management systems (EMS) and distribution management systems (DMS), reduction in AT&C losses, automatic metering infrastructure, monitoring and automation of substation. In this regard, numerous programs were launch by Indian government such as national smart grid mission (NSGM, renewable generation program, national mission on electric mobility, restructured-accelerated power development and reforms program (R-APDRP). Number of regulatory, standardization, administrative, the private, and the wide range of bodies working together to achieve the objectives of the 24 × 7 Power for All.

The natural resources for power generation are limited and unevenly distributed in different regions, the optimum utilization of the power is necessary by transferring power from the resource centric to load centric regions. Moreover, with the introduction of renewable energy sources, the HV transmission grids are crucial for transportation of the electricity generated by large-scale renewable set-ups. Thus, synchronization of all regional grids is very important, which in turn facilitates the electricity trade across regions. The traceable measurements play a vital role in
the synchronization of all regional grids in achieving One Nation-One Grid-One Frequency.

In support of national bodies, CSIR-NPL, keeps on targeting to improve and develop new measurement capability to ensure traceability chain for Electrical Power and Energy measurements.

### 10.7.3 Electric Vehicle (EV): The Next Generation Transport

EV is going to be next generation transport, which is needed to be adopted in mass scale in coming future. The benefit of EV is the reduction of fossil fuel dependency on large scale and thereby by reducing the CO₂ emission levels. Government of India (GoI) has adopted several schemes like FAME (Faster Adoption and Manufacturing of (Hybrid) and Electric Vehicles), which incentivises the manufacturing and implementation of the industries associated with the EV adoption. In general, EV runs on the chemical energy available from Li-ion battery. The battery needs to charge before they get completely drained off. So, the successful adoption of EVs also depends on the implementation of mass charging stations across the country. Under the Fame-II scheme, GoI aims for implementation of more than 3000 charging stations. To augment the developments of EV ecosystem, CSIR-NPL is planning to implement standardisation schemes for charging stations and EV battery testing facility: specifically, for Li-ion battery (the battery chemistry of Li-ion technology is completely different from other battery technologies). The developments in this direction are at a very infancy stage, needs an amalgamation of EV industries, MSMEs and GoI at large. CSIR-NPL is already providing support for adoption of EV standards in India through the ETD-51 technical committee on EV standards.

### 10.7.4 Quantum Technologies for Enhancing the Metrological Capabilities

The top priority for CSIR-NPL is to pursue fundamental R&D in quantum phenomena which will enable realisation of SI units linking to the constants of nature. This will also lead to development of quantum technologies which are beneficial for societal and economic developments and will lay the foundations for futuristic quantum technologies. The key benefit of incorporation of quantum technologies in metrology is the unprecedented accuracy and very low noise levels, that the classical counterpart cannot produce. Some of the quantum technologies relevant to metrology are realisation of the unit of resistance by the quantum hall effect, voltage through Josephson effect, current through the single electron tunnelling etc. The Josephson effect has also led to the development of superconducting quantum interference device (SQUID),
through which the unit of magnetic flux quanta is realised. Now there is considerable evidence suggesting the use of proximity Josephson junctions and SQUIDs as quantum bits (qubits) which will lead to the realisation of quantum computation. Josephson effect is also linked to the development of quantum noise thermometry for measurement of the Planck’s constant $k$ and for defining the unit of temperature. R&D on SNSPD can change the way of counting/detection and even manipulation of photons. A large body of evidence is coming out for the use of SNSPD technique for experiments related to quantum teleportation and quantum computation. Finally, when voltage, current and ampere are realised using quantum technologies, the test of constancy of Ohm’s law at the quantum limit is desirable, which gives the direct proof of consistency of the constants of nature. The future of quantum technologies demand much more than that of the realisation of fundamental units and determination of the constants of nature. For example, determination of physical quantities related to single atoms or molecules (spin, charge and flux etc.) demand cross disciplinary technologies. Thus, the use of quantum technology in metrology has led to the new definition of units such as volt, current and resistance. The unit of impedance also can be replaced through AC quantum Hall effect. Thus, the whole spectrum of electrical units in near future will be replaced by their quantum counter parts.

10.7.5 Economic and Social Impacts

10.7.5.1 Environmental Concern

During the past 20 years, the India economy has grown very rapidly [116] as a result of government’s strong emphasis on industrial development. However, today’s dependency on electrical energy consumption [117], carbon emission [118] of environmental concerns are posing serious economic and social impact which exert negative impression on environment (Figs. 10.31, 10.32, 10.33). In fact, the data shown in Fig. 10.34 are of great concern; which represents rising energy demand in near future. The data is estimated by Partial End User Method (PEUS) shows unprecedented rise in demand for energy. A detailed survey on long term analysis of electricity demand forecasting has already conducted by Central Electricity Authority (CEA), Ministry of Power and reported in a 19th Electric Power Survey (EPS) Report [119].

Improving energy efficiency and reducing energy demands are the two dominants factors considered as the most promising, fastest, cheapest and safest ways to reduce climate change [121]. Until now numerous efforts have been explored in understanding relation between electricity use and economic activity [122]. However, putting limits on reduction of energy demand is not a good sign considering economic consequences. The only remain challenge is to identify and improvise energy efficiency limitation [123]. Once it is known then remain is to develop new technology, implement policy and market framework.
Fig. 10.32 CO₂ Emission from electricity and heat (Mt of CO₂). Source [118]

% Share of Fuel of installed capacity (371,054 MW) till date 30.06.2020

Fig. 10.33 % Share of fuel of installed capacity (371,054 MW) till date 30.06.2020. Source [120]

CSIR-NPL has a significant role to play in above said areas by bringing technologies and measurements traceable to SI units as well as by incorporating new measurements and methods for assessment of real-time consumption, dynamic load response and estimation of losses. There are several technologies with direct dependence on CSIR-NPL such as smart grid, smart metering for real-time energy monitoring, electric vehicle grid integration, technologies for distributed energy generation, electrification of the transport sector, implementation of zero energy infrastructures, high voltage DC transmission, transformer loss measurement. Metrological tools are
10.7.5.2 Health Care Concern

The health care industry at present and that which evolves for future applications undoubtedly depend on metrological parameters such as voltage and current. The role of CSIR-NPL to health care industry is not only to provide measurements traceable to SI units but also to provide better measurement techniques and diagnostic methods for betterment of human health and diagnosis in certain specific areas of diseases. Certain specific areas of direct involvement in health care industry are providing measurement traceability of voltage from 1 to 5 mV for Electrocardiogram (ECG) system, radiation dosimetry standards (low ionisation current as result of high energy ionising radiations etc.), electro-surgery analyzer, electrical safety analyzer. Also, there are a host of imaging and measurement techniques (MRI, CT Scan, tissue engineering, cancer diagnostic tools, targeted drug delivery to name a few) which directly and indirectly are dependent on EEM in many ways starting from traceable measurement standards, artifacts etc. and to develop and innovative measurement techniques [124–126]. One of aspects in the coming age (fighting against COVID-19 pandemic) is that the requirement of real time diagnosis and greater use of non-invasive measurement tools and diagnostic procedures that avoids/minimises physical contact with patient [127–129]. The IoT (Internet of Things) techniques and instrumentation can greatly help for such real time diagnosis and investigation tools. In addition, risk
associated with safety of medical devices is a primary concern. Some of medical electrical hazards are power source, voltage, current leakage, insulation, earthing and grounding, separation of parts, and electromagnetic compatibility (EMC) [130]. The major concern is to provide measurement traceability for medical electrical equipment at various stages of safety requirements [131–134]. CSIR-NPL provides and interface between traceable measurements and for development of measurement procedures. Thus, the role of CSIR-NPL in health care sector is to provide quality assurance, traceable measurements, competitiveness with cutting edge technologies to support design and manufacturing at uniform across the globe.

10.8 Conclusion

The Electrical and Electronics Metrology (EEM) at CSIR-NPL maintains the national standards for electrical and electronics parameters traceable to SI units at par with leading NMIs. The EEM involves impedance, voltage and current, power and energy and quantum hall resistance metrology. The EEM continuously maintains and upgrades its facilities towards improved CMCs, new CMCs and range extension to meet the needs of the growing industries. The traceability of these parameters are disseminated through apex level calibration and testing services to power utilities, electrical and electronic equipment manufacturers, MSMEs, PSUs, strategic sector, STQC labs, NABL accredited calibration and testing laboratories, etc. The accurate and precise measurements support Indian Industries and business to innovate and improve their product to be globally competitive. This supports the government of India’s missions such as Make in India, Smart Cities, Shashakt Bharat, Smart Grid, etc. as for “Aatmanirbhar Bharat”.

The EEM is working towards establishment of compliant measurement facility for EMI/EMC up to 40 GHz, National facility creation for smart energy meters, national facility creation for 300 kV AC High voltage and 20 kA high current measurements, traceability of impedance standards using ac-dc calculable resistance standard traceable to QHR, automated IVD calibration procedure based on virtual instrumentation for enhancement of measurement capability promoting governmental missions and policies.

Further, as the NMI of the country, the EEM of CSIR-NPL is also involved in fundamental research at forefront concerning various electrical parameters such as JVS and QHR for quantum standards of voltage and resistance. Current emphasis is mainly on graphene for QHR and superconductor materials for QPS. The focus is on to realize quantum current standard (QCS) through SET, QPS. We also envisage single photon detection/counting through SNSPD based detectors.

As a leading NMI, the CSIR-NPL is focused on developing and enhancing its metrological capabilities for better service to the industries with the aim of achieving over all development of the country for becoming self reliant. This in turn helps the Indian industries to enhance their manufacturing/export and other services, thus contributing to the GDP of the Nation.
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