ISSN 0511-5728
The West Indian Journal of Engineering
Vol.42, No.2, January 2020, pp.96-104

Electrical Engineering and the New SI Definitions

Fasil Muddeen

Department of Electrical and Computer Engineering, The University of the West Indies, St. Augustine,
Trinidad and Tobago, West Indies;
Emails: Fasil.Muddeen@sta.uwi.edu; fmuddeen@gmail.com

(Received 09 July 2019; Revised 28 October 2019; Accepted 20 January 2020)

Abstract: *In 2019, the new definitions of the SI system were announced and adopted. These new definitions marked a substantial change from the previous ones and will have a considerable impact on the realisation of the various units and in particular the kilogram. Seven of these units directly relate to the units of measure used in Electrical Engineering. This paper will examine the new definitions, how the fundamental units of electrical engineering are realised from the definitions, the impact of these changes on the uncertainty of measurement of electrical units and the role of the new Volt, Ohm and Ampere in the realisation of the new kilogram.*

Keywords: *Electrical Engineering, electrical units, SI Definitions*

1. Introduction

The behaviour and relationship between magnetic fields **B** and electric fields **E** in electrical engineering are described by Maxwell's four equations (Hayt and Buck, 2006):

$$\nabla \cdot \mathbf{E} = \frac{\rho_v}{\varepsilon_0} \tag{1}$$

$$\nabla \cdot \mathbf{H} = 0 \tag{2}$$

$$\nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t} \tag{3}$$

$$\nabla \times \mathbf{H} = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E} \tag{4}$$

These four equations form the basis for many calculations in electrical engineering for example in antenna designs. In three of these equations, the constants ε_0, the permittivity of free space, and μ_0 the permeability of free space appear. The value of μ_0 was defined for many years as $4\pi \times 10^{-7}$ Hm^{-1} and the value of ε_0 was then fixed as $\approx 8.854 \times 10^{-12}$ Fm^{-1} via the fixed value of the speed of light, and the Equation $c^2 = 1/\mu_0\varepsilon_0$.

In 2019, new definitions of the *Systeme International des Unites, or the* SI system were announced and adopted (CGPM, 2018). These new definitions marked a substantial change from the existing ones and will also have a considerable impact on the realisation of the various SI units. Seven (7) of these units directly relate to the units of measure used in Electrical Engineering. The constants ε_0 and μ_0 stable for so long, and such a fundamental part of Maxwell's Equations, will change from their previously fixed values. This paper will examine the new definitions, how the fundamental units of electrical engineering are realised from the definitions and the impact of these changes on the measurement of electrical units.

2. The *Systeme International des Unites*

The name *Systeme International des Unites* or SI system, was given at the 11th Conférence Générale des Poids et Mesures, (CGPM) in 1960, and is the final attempt (so far) to have an internationally agreed set of measurement standards and units. Its history is long and interesting and well described in the 8th edition of the SI Brochure (BIPM, 2006).

Modern science and engineering measurements and results are quoted almost exclusively in SI units. In trade and manufacture, the SI system is somewhat less exclusive, especially with older plant and equipment where imperial units for example may still be encountered. In fact the existence and contemporaneous use of alternative measurement systems has almost led to tragedy, as with the Gimli Glider incident in 1983 (Witkin, 1983) or has led to the loss of expensive equipment, such as the Mars Climate Orbiter in 1999 (Hotz, 1999).

The SI system is maintained by a system of international metrology, administered by the Bureau International des Poids et Mesures (BIPM), in France. Figure 1 depicts the operational structure of the BIPM, under the authority of the Metre Convention. The BIPM and its various committees, are responsible for defining units of measurement and for publishing the *'mises en pratique',* which are the ways to create the various units. BIPM committees comprise representatives from large national measurement organisations, such as the National Institute of Science and Technology (NIST) in the United States of America (USA), the National Physical Laboratory (NPL) in the United Kingdom (UK), the

Physikalisch-Technische Bundesanstalt (PTB) in Germany, and of course, the BIPM's own laboratories. A full list of the BIPM membership, comprising 60 Members and 42 Associates, including CARICOM, is available from the BIPM's website (BIPM, 2019).

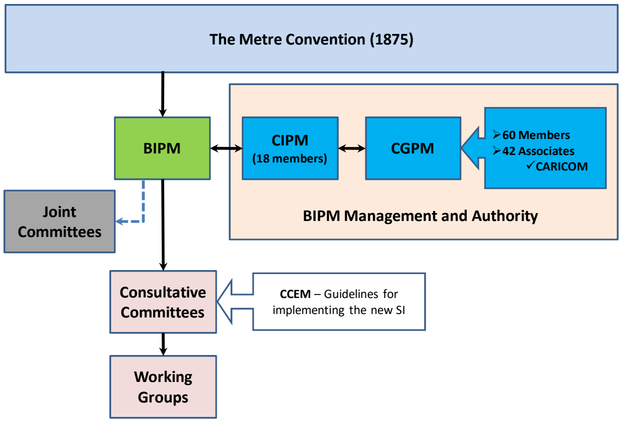

Figure 1. The Structure of the BIPM

Many of the BIPM members create and maintain their own set of measurement standards. These entities are known as Primary Standards Laboratories (PSLs), again including the previously mentioned NIST, NPL, PTB, BIPM and several others. The values of their units are inter-compared through a process organised by the consultative committees of the CIPM. The results of these 'key comparisons' as referred to by the BIPM, are published, together with the experimental uncertainty associated with the published value, in the Key Comparison Database (KCDB). Uncertainty is discussed in section 4 of this paper.

These comparisons form the backbone of *measurement traceability* and is the reason why, for example, a 2.5 mm^2 British Standard BS6004 electrical conductor manufactured in Trinidad and Tobago will have the same current carrying capacity as one made in Singapore.

As scientific knowledge increases, new methods are discovered to create the various units of measurement. The BIPM and the metrology community are continually seeking methods which will create units (called the realisation) with less uncertainty. When such methods are discovered, they are rigorously examined internationally over many years, compared with existing methods and the existing standards before being published by the BIPM as a new *mise en pratique* (BIPM, 2006).

Discoveries in quantum physics over the last century and vast amounts of validated experimental data, presented the BIPM with an opportunity to revise the existing SI system. The revision is not going to define any new units of measurement or remove any existing units, but rather will improve how the current units are defined (CGPM, 2018). In particular, the revision redefines four (4) of the existing base units, namely the Kilogram, the Ampere, the Kelvin and the Mole.

3. Fundamental Units of Electrical Engineering

The BIPM defines seven (7) base units quantities, namely, length, mass, time, electric current, thermodynamic temperature, amount of substance and luminous intensity (BIPM, 2019). These quantities are independent of one another. For example, the quantity of electric current does not depend on the quantity of thermodynamic temperature.

To enumerate these quantities, the BIPM defines seven (7) base units, the International System of Units Units (Liard et al., 2014), called the Metre, Kilogram, Second, Ampere, Kelvin, Mole and Candela respectively. These units are also, by definition, intended to be independent, but in reality are not so in a number of instances. For example, the pre-2019 Ampere's definition is a relationship between the Kilogram, the Second and the Metre as a dimensional analysis would show.

In addition, there are a number of derived units, which are obtained by algebraic combinations (products of powers) of base units. For example, the unit of pressure, the Pascal, can be expressed in terms of the base units as $m^{-1} \cdot kg \cdot s^{-2}$. Where there is no other multiplicative factor other than 1, the derived units are called *coherent derived* units (BIPM, 2019). There is a very large number of derived (and coherent derived) units used to express scientific quantities and the number keeps increasing as scientific knowledge expands and the need to quantify new measured phenomena arises.

Twenty-two derived units (meaning derived and coherent derived units) have been given names for ease of use, for example the previously mentioned Pascal. In addition to the Ampere, Table 1 lists the most frequently encountered coherent derived units encountered in

Table 1. Frequently Encountered Coherent Derived Units Used in Electrical Engineering

Derived Quantity	Derived Unit and Symbol	In terms of other SI units	Base Unit Relationship
Energy	Joule (J)	Nm	m^2kgs^{-2}
Power	Watt (W)	Js^{-1}	m^2kgs^{-3}
Charge	Coulomb (C)	As	As
Potential Difference	Volt (V)	WA^{1}	$m^2kgs^{-3}A^{-1}$
Capacitance	Farad (F)	CV^{-1}	$m^{-2}kg^{-1}s^4A^2$
Resistance	Ohm (Ω)	VA^{1}	$m^2kgs^{-3}A^{-2}$
Conductance	Siemens (S)	AV^{-1}	$m^{-2}kg^{-1}s^3A^2$
Magnetic Flux	Weber (Wb)	Vs	$m^2kgs^{-2}A^{-1}$
Magnetic Flux Density	Tesla (T)	Wm^{-2}	$kgs^{-2}A^{-1}$
Inductance	Henry (H)	WA^{1}	$m^2kgs^{-2}A^{-2}$

electrical engineering practice, their relationships to other SI units (their derivation) and their descriptions in terms of the base units. A more complete listing of derived units can be found in the BIPM document, the *SI Brochure* (BIPM, 2019).

4. Definitions, Realisations and Uncertainty

The previous section used the word "define" in the description of the units. Creating a unit of measurement, for example an Ampere, involves three (3) things:

1. A Definition of the unit;
2. A Realisation of the unit; and
3. A determination of the Uncertainty associated with the realisation of the unit.

The **Definition** of a unit is a written description of what the unit is in terms of scientific principles and physical constants. The Ampere, for example, prior to May 2019, was defined as:

"*The constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed one metre apart in vacuum, would produce between those conductors a force equal to* 2×10^{-7} *Newtons per metre of length.*" (BIPM, 2006)

All seven base units have such definitions. According to the BIPM (2006), the definition provides " *a sound theoretical basis upon which the most accurate and reproducible measurements can be made*."

The **Realisation** of a unit is the actual scientific method that will be used to create it while satisfying the requirements of the Definition. Physical sciences and a significant amount of engineering are required to develop a particular realisation. The BIPM publishes its recommended method to create the various units in *mises en pratique*. In addition, there generally is more than one way to realise a particular definition or the Primary Standards Laboratories will each carry out experiments according to the *mises en pratique* or of their own derivation. This creates several 'values' for each unit and this is where the third parameter, the **Uncertainty**, plays an important role.

The **Uncertainty** of the particular realisation is a carefully determined expression of the accuracy (closeness to the definition) and precision (repeatability) of the method used. A scientific result should always be presented together with its uncertainty. For example, according to CODATA (2014), the agreed value of Planck's constant was

$h = 6.626\,0693(11) \times 10^{-34}\text{Js}\ [1.7 \times 10^{-7}]$

The uncertainty of this value of h, depends on the last two significant figures shown in parentheses and is given by number in square brackets. That is 0.17 parts per million.

The determination of measurement uncertainty is a complex process and generally requires large quantities of historical data to enable the essential statistical analyses to be done. For measurements, the BIPM document - *Guide to the expression of uncertainty in measurement* (BIPM, 2008) is the internationally accepted standard for determining and describing measurement uncertainty.

Therefore, a realisation that can produce a unit with an uncertainty of 1 part per billion (10^{-9}), would be better than one with an uncertainty of 1 part per million (10^{-6}). The current state of the art in realising some of derived units that is able to achieve a lower degree of uncertainty than the base units from which they emanate (Mills et al., 2006). The Farad, for example, can be realised using a Thompson-Lampard Calculable Capacitor with lower uncertainty that can be achieved in the realisation of the Ampere. This will be described in Section 6 of this paper.

5. The Rationale for Changes to the SI system

The main problems that lead to the revision of the SI system can be identified by a careful examination of the definition of one of the base units as a typical illustrative example, the Ampere, repeated here for convenience:

"*The constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed one metre apart in vacuum, would produce between those conductors a force equal to* 2×10^{-7} *Newtons per metre of length.*" (BIPM, 2006)

This definition can be translated into an equation according to electromagnetic theory. The force per unit length developed between two parallel current carrying conductors spaced d metres apart, carrying steady currents of I_1 and I_2, respectively, is given by:

$$\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi d} \qquad (5)$$

If both currents are exactly equal to 1 Ampere and the separation distance d, is exactly 1 m, then the force per unit length is exactly 2×10^{-7} N/m .

The definition requires a number of conditions to be inherently satisfied, namely, that:

i) The wires must be infinitely long;
ii) Their diameters must be negligibly small compared to d;
iii) The currents must be exactly 1 Ampere, identical and constant;
iv) The experiment has to take place in a vacuum;
v) That the separation distance, d, is exactly 1m;
vi) The constant μ_0 in Equation (5) is exactly $4\pi \times 10^{-7}$ N/m; and
vii) There are instruments available to measure the distances, current and force to the required levels of accuracy and uncertainty.

In practice, conditions (i) and (ii) can be engineered to be very close to these requirements by making the length and separation distance considerably greater than the wire diameter, using for example, coils of very fine wire. Conditions (iii) and (v) depend on the instrumentation (i.e., Condition (vii)). Condition (iv) can be obtained but at great expense. Condition (v) requires precise measurement of the distance, which in turn depends on specialised instrumentation to achieve this. Condition (vi) is addressed by defining μ_0 to be *exactly* $4\pi\times10^{-7}$ N/m. In this way knowledge of π to some number of significant digits is avoided. Condition (vii) includes reference to the part of the definition which requires a force measurement, and therefore a relationship to the SI unit *kilogram*. This leads to the first problem with the last SI system.

Problem #1: The kilogram was the only SI base unit which depended on a physical artefact. The actual SI value of the kilogram has been the value of the international prototype kilogram (IPK), a cylinder made of a 90%/10% platinum iridium alloy kept in a vault at the BIPM in France. Its value has changed minutely over time due to handling and micro-deposits of contaminants on the surface of the metal so that it isn't really a standard in the true sense of the word.

The realisation of the Ampere is typical of the realisation of all SI units. The engineering and scientific complexity required to realise any of them is daunting and presents several problems which have to be overcome. In the case of the Ampere, the *quantity* of current is not dependent on any other quantity, however the *unit* of current, that is the realisation of the Ampere, depends on the Kilogram and as we will see, the Volt, the Watt and the Ohm (Chyla, 2012).

There are two (2) accepted ways to realise the Ampere (Mills et al., 2006). The first method uses an apparatus called a Kibble Balance to compare an electrical watt with a mechanical watt. The second method uses realisations of the Volt (V) and Ohm (Ω) and the relationship of Ohms Law, $V = IR$, to calculate a value of the Ampere.

At present, the best realisations of the Ampere use the second method and achieve a better uncertainty than the Kibble Balance method. This is the second problem with the SI system.

Problem #2: The current state of the art in realising some of derived units achieves a better uncertainty than the base units from which they emanate. For example, despite the fact that the Ampere is an SI base unit it is possible to realise other derived units, namely the Volt and the Ampere, with better uncertainties. These realisations are described in the next section.

6. Realisations of the Electrical Units pre-May 2019

6.1 The Volt

Figure 2 shows the Josephson's Junction Schematic. When certain materials are cooled below a very low temperature called the transition temperature, electrons are able to travel throughout the material without resistance, a behaviour called superconductivity. A particular superconductor can accommodate a maximum flow of electrons, called the critical current, before the flow begins to exhibit resistance. Brian Josephson discovered that when a junction, comprising two (2) thin layers of superconductor material separated by a very thin layer of insulator, was cooled below the transition temperature of the superconductor, a current flowed across the insulator (Wikipedia, 2019).

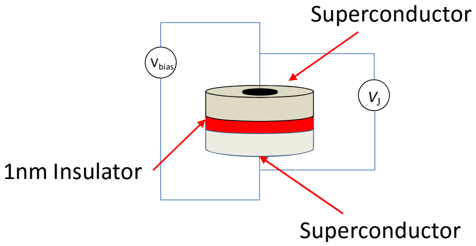

Figure 2. Josephson's Junction Schematic

If the junction was deliberately biased with a dc voltage V_{bias}, as shown in Figure 2, such that a supercurrent greater than the critical current flows across the junction, a very high frequency signal appeared across the junction. This is known as the Josephson's effect (Warburton, 2011), and the frequency of the signal is developed, as given by:

$$f_J = \frac{1}{2\pi}\left(\frac{2e}{h}\right)V \qquad (6)$$

In Equation (6), h is Planck's Constant and e is the fundamental charge on an electron. The ratio $2e/h$ is known as the Josephson Constant K_J. Until the redefinition of the SI in 2019, the value, agreed to in 1990 and denoted as $K_{J\text{-}90}$, was 483 597.9 GHzV^{-1}.

More interesting from an electrical engineering point of view though is that if the junction is irradiated with a magnetic field at harmonic multiples of f_J, then the voltage across the junction develops in precise, highly stable and predictable integer multiples of K_J and is given by:

$$V_J = n\left(\frac{2\pi f_J}{K_J}\right) \qquad (7)$$

The voltage V_J, is called the Quantized Josephson's Voltage, n is an integer, f_J is the frequency of the magnetic field radiation. A single junction develops a very small voltage, on the order of a few mV, so that in order to make a practical voltage source, several hundred junctions contained in a cryogenic chamber together with complex instrumentation are required.

6.2 The Ohm

The Lorentz force, $d\mathbf{F}$, exerted on an element of charge, dQ, moving through a magnetic field, $\mathbf{B}$, with drift velocity $\mathbf{v}$, is given by:

$$d\mathbf{F} = dQ\mathbf{v}\times\mathbf{B} \qquad (8)$$

If a slab of current carrying semiconductor material, is exposed to a magnetic field, the force described by Equation (8), results in displacement of electrons in a direction perpendicular to both the magnetic field and the direction of motion of the charges, indicated by the cross product. This displacement produces a voltage across the semiconductor and is known as the Hall effect.

If the semiconductor is cooled below its critical temperature and the magnetic field is on the order of 10T, the resistance across the current carrying channel in the direction of the developed Hall effect voltage, assumes very stable, discrete values according to the following Equation (9):

$$R_{\mathrm{H}} = n\left(\frac{V_H}{I_{channel}}\right) = n\left(\frac{h}{e^2}\right) \tag{9}$$

This is known as the Quantum Hall effect and leads to the realisation of a very accurate unit of resistance (Taylor and Witt, 1989). The ratio (h/e^2) in Equation (9) is known as the Von Klitzing Constant, R_K. The current agreed value of the Von Klitzing Constant, denoted as $R_{\mathrm{K\text{-}90}}$ is 25 812.807 Ohm.

Like the Josephson voltage standard, the apparatus to produce this effect in measurable levels is very complex. Besides, like the Josephson voltage standard, the Quantum Hall devices can be used to independently determine accurate values of h and e. These can then be cross compared with those obtained by other methods after which an agreed value of h and e is published (Stock, 2012).

6.3 The Amp

The Ampere can be realised indirectly by a device called a Kibble Balance (or Watt balance in older usage). The device relates electrical power to mechanical power in order to determine Planck's constant, h, in terms of a mass traceable to the international prototype kilogram. From this determination and a primary realisation of the Ohm for example, a very accurate value of the Ampere can be calculated.

A diagram indicating the principles of the Kibble Balance is shown in Figure 3. In essence, the Kibble balance, after Bryan Kibble (Robinson and Schlamminger, 2016) is a mechanical balance with a current carrying coil suspended in a strong magnetic field on one arm and a conventional mass pan on the other.

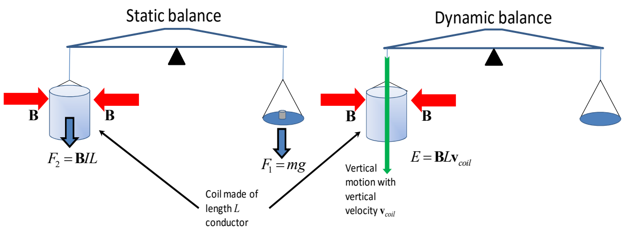

Figure 3. Kibble Balance schematic

The balancing of the arm occurs in two parts: (i) a static balance; and (ii) a dynamic balance. The final relationships do not require the knowledge of the field strength or the length of the coil.

For the static balance, a current is passed through the coil. A Lorentz force is developed on the coil which is carefully counterbalanced by known masses on the other pan. Previously, it was stated that the Lorentz force, $d\mathbf{F}$, exerted on an element of charge, dQ, moving through a magnetic field, $\mathbf{B}$, with drift velocity $\mathbf{v}$, is given by Equation (8). Therefore, the total static force $\mathbf{F}$, on the current carrying coil due to the movement of the charges in it is found by integrating (8) over the length of the coil.

$$\mathbf{F} = \oint dQ\mathbf{v} \times \mathbf{B} \tag{10}$$

Since it can be shown for a current carrying conductor that (Hayt and Buck 2006):

$$dQ\mathbf{v} = Id\mathbf{L} \tag{11}$$

then, substituting into (15)

$$\mathbf{F} = \oint Id\mathbf{L} \times \mathbf{B} \tag{12}$$

For the long conductor in the coil arrangement, it can be shown that (12) reduces to:

$$\mathbf{F} = I\mathbf{L} \times \mathbf{B} \tag{13a}$$

$$\text{and } |\mathrm{F}| = \mathrm{BIL}\sin\theta \tag{14b}$$

In Equation (13b), θ refers to the angle between the field and the coil. At static balance and with $\theta = 90°$,

$$mg = \mathbf{B}IL \tag{15}$$

For the dynamic measurement, the coil is made to move through the magnetic field with a constant velocity, $\mathbf{v}_{coil}$. Because of this, a voltage E, is induced in the coil given by:

$$E = L\mathbf{B}\mathbf{v}_{coil} \tag{16}$$

Since the coil is the same for both experiments, $\mathbf{B}L$ can be eliminated from Equations (15) and (12).

$$L\mathbf{B} = \frac{mg}{I} \tag{17}$$

The final equation for I is then:

$$I = \left(\frac{mg}{E}\right)\mathbf{v}_{coil} \tag{18}$$

The value of E is measured with by a very accurately calibrated voltmeter traceable to a Josephson junction voltage standard. The mass m, is traceable to the international prototype kilogram, g is measured by accurate gravimetry experiments, for example by the National Research Council (Liard et al., 2014), and $\mathbf{v}_{coil}$ by laser interferometers. The Kibble Balance measurements are very complicated and have to include corrections for gravitational variations due to tidal, earth motion and atmospheric effects. They typically run over several weeks (Liard et al., 2014).

Interestingly, the Kibble balance can also be used to realise a mass standard in terms of Planck's constant as follows (Robinson and Schlamminger 2016). In Equation

(17), the current I can be measured by passing it through a known resistance R, and measuring the voltage drop E_1 across it. Thus, Equation (17) can be re-arranged as follows:

$$m = \left(\frac{IE}{g\mathbf{v}_{coil}}\right) = \left(\frac{\left(\frac{E_1}{R}\right)E}{g\mathbf{v}_{coil}}\right) \qquad (19)$$

Both E and E_1 are measured by calibrated voltmeters traceable to the same Josephson junction voltage standard voltage, while R is calibrated to a reference traceable to a Quantum Hall device resistance standard. The mass to Planck's constant relationship is then derived as follows. Since E and E_1 are both traceable to Equation (7) and R is traceable to Equation (9), the factor (E_1/R) E in Equation (18) turns out to be traceable only to integer multiples of h as shown below.

$$\left(\frac{E_1}{R}\right)E = \left(\frac{n_1 h}{e}\right)\left(\frac{n_2 e^2}{h}\right)\left(\frac{n_3 h}{e}\right) = nh \qquad (20)$$

where $n = n_1 n_2 n_3$ is an integer.

Therefore, from Equation (18), m in kilograms, will be calculated in terms of Planck's Constant, h, which has an agreed value, the metre and the second, which are both SI base units. Note that the value of h, can itself be independently determined from the realisations of the Volt and the Ohm as described before.

The realisations of the Volt, Ohm and Ampere, at this point in time ultimately depend on having accurate values of h and/or e. This inter-relationship is depicted in Figure 4. The bi-directional arrows indicate that h and/or e can either be used in the realisations of the units, or can themselves be determined from the accepted current values of the units. Whichever of the three (3) units is realisable with the lowest uncertainty can be used to calculate the other two. Also to be noted is the presence of the *Kilogram* in Figure 4.

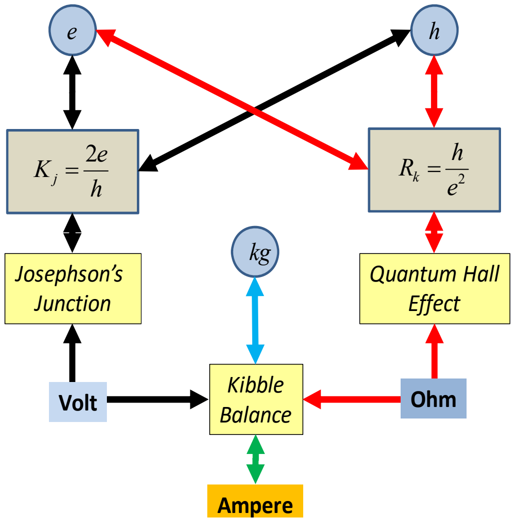

Figure 4. Present Volt-Ohm-Ampere Inter-relationships

6.4 The Farad

Interestingly, the SI electrical unit which offers the lowest realised uncertainty at this time, is the Farad (Mills et al., 2006). This uncertainty is achieved through a device called the Calculable (Thompson-Lampard) Capacitor (Clothier, 1965) and is based on a theorem in electrostatics proposed by Lampard (1957). The theorem proved that it was possible to create a capacitor whose value was directly proportional to the length of the electrodes. In the specific case of a cylindrical capacitor, the theorem states that the capacitance per unit length, C, was given by:

$$C = \frac{\log_e 2}{4\pi^2} \text{ Farads/metre} \qquad (21)$$

Equation (20) means that if the electrode length can be accurately measured using equipment traceable to the SI unit of length, then the calculated value of C, will be known to the same degree of uncertainty as the metre, 1 x 10^{-8}

This low uncertainty has led to the calculable capacitor being used as the most accurate method to realise the Ohm using a technique proposed by Thomson (Thompson, 1968). As discussed before, whichever of the three (3) electrical units is realisable with the lowest uncertainty will be used to calculate the other two (BIPM, 2019).

7. The New Definitions

The solution declared by the BIPM to the problems identified in Section 5 of this paper and other historical issues, is to redefine the SI definitions in terms of declared fixed values of some universal constants (BIPM, 2019). The most significant consequence of the new definitions is to remove any future dependence on the physical kilogram artefact.

The following constants are now exactly defined to the respective stated values. These are:

1. the ground state hyperfine splitting frequency of the caesium 133 atom $\Delta\nu(^{133}\text{Cs})_{\text{hfs}}$ is exactly 9 192 631 770 Hertz (unchanged),
2. the speed of light in vacuum, c, is exactly 299 792 458 metre per second (unchanged),
3. the Planck constant, h, is exactly 6.626 060 701 5 $\times 10^{-34}$ Joule second (new),
4. the elementary charge, e, is exactly 1.602 176 634 $\times 10^{-19}$ Coulomb (new),
5. the Boltzmann constant, k_B, is exactly 1.380 649 × 10^{-23} Joule per Kelvin (new),
6. the Avogadro constant, N_A, is exactly 6.022 140 76 x10^{23} reciprocal mole (new), and
7. the luminous efficacy, K_{cd}, of monochromatic radiation of frequency 540 $\times 10^{12}$ Hz is exactly 683 Lumen per Watt (unchanged).

Note that these values are exact and therefore have no uncertainty. The seven (7) SI base units remain the same, but because of the above definitions, it will be possible to realise all of them without having to resort to using the physical kilogram. Hence, of specific interest to the electrical engineering profession are the declaration of the elementary charge and Planck's constant as constants. These will now have the effect of defining a fixed value for the Volt, Ohm and in particular, the Ampere as described next.

7.1 The Volt 2019

The Volt, V, will once again be realised using the Josephson effect and the new fixed value of the Josephson constant: K_J = 483 587.848 416 984 GHzV^{-1}, calculated to 15 significant digits according to Equation (1) in the *Mise en pratique* for the definition of the Ampere and other electric units in the SI (BIPM, 2019, Appendix 2). This level of accuracy has been achieved following many years of deriving the values of *e* and *h*, for example at NIST (Haddad et al., 2017) and the NRC (Wood, 2017). The 'new' Volt is smaller than the $K_{J\text{-}90}$ version by 108.665×10^{-9} (BIPM, 2019, Appendix 2) because of the difference between K_J and $K_{J\text{-}90}$.

7.2 The Ohm 2019

Similar to the Volt, the ohm Ω will be realised using a Quantum Hall device and the following value of the von Klitzing constant R_K = 25 812.807 459 3045 Ω. Like the value of K_J, this value has been calculated to 15 significant digits according to Equation (2) in the *Mise en pratique* for the definition of the Ampere and other electric units in the SI (BIPM, 2019, Appendix 2). The 'new' Ohm is smaller than the $R_{K\text{-}90}$ version by 17.793×10^{-9} (BIPM, 2019, Appendix 2).

7.3 The Ampere 2019

According to BIPM (2019), the new definition of the Ampere is, "*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* 1.602 176 634×10^{-19} *when expressed in the unit C, which is equal to As, where the second is defined in terms of* $\Delta\nu_{Cs}$."

This definition will be realised in one of three (3) methods, as follows:

1) Via Ohm's Law and the realisations of the 'new' Volt and Ohm;
2) Using the relationship $A = C/s$, the fixed value of *e* and the SI base unit of time, the second; or
3) Using the relationships $I = C{\cdot}dV/dt$, $A = F{\cdot}V/s$, the 'new' Volt, the Farad and the SI base unit of time, the second.

A consequence of this definition is that primary standards labs, for example, NIST (Robinson and Schlamminger, 2016), can now use the Kibble Balance to create a practical realisation of the kilogram.

8. Implications of the Changes for Electrical Engineering

The BIPM clearly indicated that the new SI definitions "*will be so chosen that at the moment of change the magnitudes of the new units will be indistinguishable from those of the old units*." (CGPM, 2018)

There should be no discernable impact to normal electrical engineering calculations after the redefinitions are implemented, but there will be change. For example, as discussed in the previous section, the new SI definitions make it possible to have values for the Ampere, Volt and Ohm, calculated to 15 significant figures because of these units' relationships to *e* and *h*, which are now exactly defined and fixed. Of significance is that for the first time since it was originally defined, the Ampere is not dependent on the kilogram (BIPM 2019).

From an Electrical Engineering viewpoint, the constants μ_0, the permeability of free space and ε_0, the permittivity of free space, will change from their current, fixed values to new experimentally determined ones. Because *e*, *h* and *c* will be fixed, the following equations will be used to derive μ_0 and ε_0, respectively:

$$\mu_0 = \frac{2h\alpha}{ce^2} \quad \text{NA}^{-2} \tag{22}$$

and

$$\varepsilon_0 = \frac{1}{\mu_0 c^2} \quad \text{Fm}^{-1} \tag{23}$$

In Equation (21), the symbol α refers to the fine structure constant, which is a quantum level, dimensionless number, derived from the electromagnetic interaction between elementary charged particles such as the electron and the proton. According to CODATA 2014 values, α has the experimentally determined value of 7.297352566417×10^{-3}.

Using the proposed values of *e*, *h* and *c*, μ_0 can be calculated using Equation (21). The existing value of μ_0 is 1.2566370614×10^{-6}NA^{-2} (CODATA 2014). This value differs from the new calculated value of 1.256637062×10^{-6}NA^{-2} by |1.809×10^{-9}|NA^{-2}. This supports the BIPM guiding principle that there should not be any drastic change in the defined values of the universal constants. We have shown that the calculated value of μ_0 is not going to be significantly different from the current value as to have a noticeable effect in electrical engineering calculations.

One electrical engineering sector which could certainly feel the most impact is the calibration industry - the manufacturers of standards and calibrators of electrical and electronic equipment. For example, Fluke, a manufacturer of high end calibrators, had to make drastic adjustments to the performance specification of one of their devices, with respect to the newly redefined Volt and Ohm.

According to Gust (2011), the effect of the 1990 volt change was approximately 100% of the one year specification for DC voltage. While the BIPM have gone to great lengths to avoid as drastic a change in going to the 2019 SI revision, there is going to be an impact at the cutting edge of electrical metrology and other areas.

9. The Kilogram 2019

Perhaps the most dramatic and significant change with the new version of the SI is the removal of the artefact kilogram as the standard of mass. This standard mass, in its various forms, has existed since 1889 and remained the only unit still based on a physical object. According to (BIPM, 2019), the 'new' kilogram is defined as follows:

"*The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be* $6.626\,060\,701\,5 \times 10^{-34}$ *when expressed in the unit J s, which is equal to kg* m^2 s^{-1} *, where the metre and the second are defined in terms of c and* $\Delta\mathbf{v}_{Cs}$."

The most likely practical realisation of this definition will be via the Kibble Balance and the declared values for *e* and *h* and the relationship developed in Equation (18). In fact, in 2012 the BIPM published a possible method for doing exactly this and described in a paper by Stock (2012). Another possibility is through Avogadro's Constant, also declared as fixed in the new SI (Stenger and Göbel, 2012) and (Bartl et al. 2017). The possible techniques which have the required level of uncertainty and repeatability to realise the kilogram are described by the *Mise en pratique* for the definition of the kilogram in the SI, in Appendix 2 of the 9th edition of the SI brochure (BIPM, 2019), but the front runner remains the Kibble Balance realisation.

Figure 5 depicts the New Volt-Ohm-Ampere inter-relationships. There are two major changes from the previous relationship (as illustrated in Figure 4). The first is the one-way arrows following from the now constant declared values for *e* and *h*, straight through to the Ampere. The second is that the kilogram is now defined (the most likely at this time) from the electrical units Volt, Ohm and Ampere via the Kibble balance.

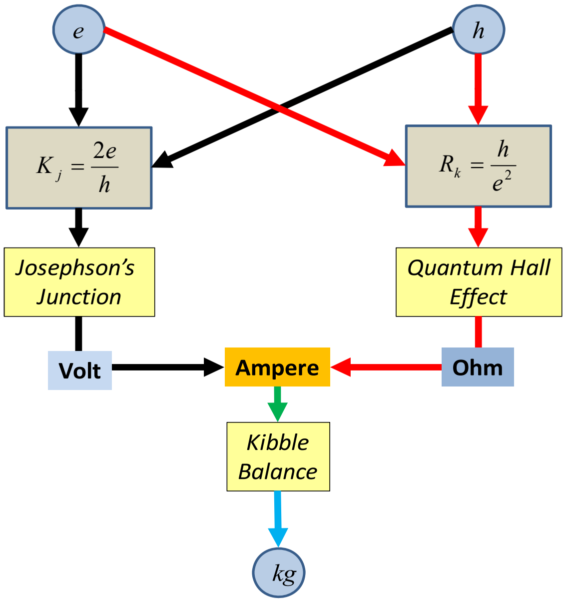

Figure 5. New Volt-Ohm-Ampere Inter-relationships

According to the note 5, Appendix 2 of the SI Brochure - 9th edition (BIPM, 2019), the value of the new kilogram will be the currently agreed reference value in order to preserve the international equivalence of calibration certificates.

10. Conclusion

The new SI definitions, which came into effect on May 20th 2019, have the electrical base unit Ampere and the derived units Volt and Ohm, now fixed by declared universal constants and therefore inherently stable. The electrical units themselves have now assumed new importance in that they will be used in at least one method to derive the first non artefact kilogram in 130 years. The BIPM took a deliberate decision to minimise the effects of the redefinitions and for the most part they will succeed. There may be an impact on high end calibration equipment manufacturers.

This paper gave an overview of the previous and new SI system from the perspective of electrical engineering units and in so doing described how units are created, how traceability works, international electrical metrology, measurement uncertainty and the level of scientific and engineering effort required to maintain a system for the units of measurement.

References:

Bartl, G., Becker, P., Beckhoff, B., Bettin, H., Beyer, E., Borys, M., Busch, I., Cibik, L., D'Agostino, G., Darlatt, E., Di Luzio, M., Fujii, K., Fujimoto, H., Fujita, K., Kolbe, M., Krumrey, M., Kuramoto, N., Massa, E., Mecke, M., Mizushima, S., Müller, M., Narukawa, T., Nicolaus, A., Pramann, A., Rauch, D., Rienitz, O., Sasso, C.P., Stopic, A., Stosch, R., Waseda, A., Wundrack, S., Zhang, L., and Zhang, X.W. (2017), "A new 28 Si single crystal: counting the atoms for the new kilogram definition", *Metrologia*, Vol.54, No.5, pp.693.

BIPM (2006), *SI Brochure: The International System of Units (SI)*, 8th edition, Bureau international des poids et mesures (The International Bureau of Weights and Measures), France (accessed December 2018).

BIPM (2008), *Guide to the Expression of Uncertainty in Measurement*, Bureau international des poids et mesures, France.

BIPM (2019), *SI Brochure: The International System of Units (SI)* 9th edition, Bureau international des poids et mesures, France (accessed 30 June 2019).

CGPM (2018), *The 26th General Conference on Weights and Measures*, Palais des Congrés, Versailles, France, November 13-16 2018.

Christof, G., Bernd, F., Norbert, H., Axel, K., Bettina, T-K., Thorsten, Z., Joachim, F., Otto, J., and Wladimir, S. (2017), "Final determination of the Boltzmann constant by dielectric-constant gas thermometry", *Metrologia*, Vol. 54, No.3, pp.280.

Chyla, W.T. (2012), "On the structure of the new SI definitions of base units", *Metrologia*, Vol.49, No.4, pp.L17-L19.

Clothier, W.K. (1965), "A calculable standard of capacitance", *Metrologia*, Vol.1, No.2, pp.36-55.

CODATA (2014), *Recommended Values of the Fundamental Physical Constants*, Committee on Data of the International Council for Science, International Council for Science (ICSU), Paris, France.

Gust, J. (2011), "The impact of the new SI on industry", In: NCSL (2011)(ed), *NCSL International Workshop and Symposium*, National Conference of Standards Laboratories.

Haddad, D., Seifert, F., Chao, L.S., Possolo, A., Newell, D.B., Pratt, J.R., Williams, C.J., and Schlamminger, S. (2017), "Measurement of the Planck constant at the National Institute of Standards and Technology from 2015 to 2017", *Metrologia*, Vol.54, No.5, pp.633.

Hayt, W.H., and Buck, J.A (2006), *Engineering Electromagnetics*. 7th edition, McGraw-Hill

Hotz, R.L. (1999), "Mars probe lost due to simple math error", Los *Angeles Times*, October 1, Retrieved from http://articles.latimes.com/1999/oct/01/news/mn-17288

Lampard, D.G. (1957), *A New Theorem in Electrostatics with Applications to Calculable Standards of Capacitance*, IEEE Monograph.

Liard, J.O., Sanchez, C.A., Wood, B.M., Inglis, A.D. and Silliker, R.J. (2014), "Gravimetry for watt balance measurements", *Metrologia*, Vol.51, No.2, pp.S32-S41.

Mills, I.M., Mohr, P.J., Quinn, T.J., Taylor, B.N., and Williams, E.R. (2006), "Redefinition of the kilogram, ampere, kelvin and mole: a proposed approach to implementing CIPM recommendation 1 (CI-2005)", *Metrologia*, Vol.43, No.3, pp.227-246.

Robinson, I.A., and Schlamminger, S. (2016), "The watt or Kibble balance: a technique for implementing the new SI definition of the unit of mass", *Metrologia*, Vol.53, No.5, pp.A46-A74.

Stenger, J., and Göbel, E.O. (2012), "The silicon route to a primary realisation of the new kilogram", *Metrologia*, Vol.49, No.6, pp.L25-L27.

Stock, M. (2012), "Watt balance experiments for the determination of the Planck constant and the redefinition of the kilogram", *Metrologia*, Vol.50, No.1, pp.R1-R16.

Taylor, B.N., and Witt, T.J. (1989), "New International Electrical Reference Standards based on the Josephson and Quantum Hall Effects", *Metrologia*, Vol.26, No.1, pp.47-62.

Warburton, P.A. (2011), "The Josephson Effect: 50 years of science and technology", *Physics Education*, Vol.46, No.6, pp.669-675.

Wikipedia (2019), *Josephson Effect*, October 1, Retrieved from https://en.wikipedia.org/wiki/Josephson_effect

Witkin, R. (1983), "Jet's fuel ran out after metric conversion errors", *New York Times*, July, https://www.nytimes.com/1983/07/30/us/jet-s-fuel-ran-out-after-metric-conversion-errors.html.

Authors' Biographical Notes:

Fasil Muddeen *is a Lecturer in the Department of Electrical and Computer Engineering at The University of the West Indies. His areas of research include the acoustics of the steelpan, digital signal processing, electronics, measurement and instrumentation. Dr. Muddeen is a registered engineer with the Board of Engineering of Trinidad and Tobago, a Fellow of the Association of Professional Engineers of Trinidad and Tobago, a Member of the IEEE and a former Chairman of the IEEE Trinidad and Tobago Section.*

■