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INTERNATIONAL ELECTROTECHNICAL COMMISSION (IEC)

INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE (CISPR)

Sub-Committee A: Radio Interference Measurements and Statistical Methods

Working Group 1: EMC Instrumentation Specifications

Subject: Current Probes for Differential Mode Conducted Emission Measurement

References:

[1] CISPR 16-1-2:2014. Coupling devices for conducted disturbance measurements.

[2] DM Lauder & RC Marshall: Measurement uncertainty and Cable Balance - with Implications for the CDNE-M and CMAD, EMC Europe 2014, September 1-4 (2014) Gothenburg.

[3] RC Marshall: Ferrite-cored transformers and their application in EMC design and test - a get it right first time guide. EMC Journal, issue 106, May 2013, pp 27-30.

Executive summary:

Some applications of the current probe described in CISPR16-1-2 Annex B (Informative) in differential mode are not well met above a few MHz because they allow or enforce EUT wiring layouts with excessive stray inductance, which disturbs the transmission-line properties of the EUT cable. In the setup shown below, taken from the work of the JTF on the CDNE, note the large loops of brown and blue wires each side of the current probe.

Within this document we describe alternative choices for the dimensions and EUT wiring interfaces which may be used within the existing design envelope. These allow for substantially improved differential mode current measurement.

Proposal

We propose introducing a physically smaller example of a current probe into Annex B, based on the guidance given in Section 3 here. Also, we propose the introduction of EUT circuit jigs (adaptors), as described in Section 4. These will ensure reduced and more repeatable leakage inductance of the EUT cable inductance and thus facilitate better measurement of CM and DM in the VHF band.

We note that the CISPR current probe is not used for DM measurement in any formal Standard, but it is used extensively in standards development. The changes proposed offer improved accuracy within the existing informative guidelines, and could usefully be incorporated without sponsorship by any other CISPR group.

We also request that an editorial error introduced in CISPR 16-1-2:2014 Section B.2 be corrected:

- The equation B.2 given for the "Mid-frequency case" should have a divisor '*L*'. This was correctly written in the previous 2004 version.

1 Introduction

The current probe described in CISPR 16-1-2 is a well-established tool for common-mode measurements on cables, but limited attention has been paid to the practicalities of making differential mode measurements as outlined in figure B.4(b) of the Standard.

This paper presents an analysis of the additional errors involved in the differential mode configuration, and shows that for good high-frequency performance the inductance of the necessary loops in the EUT cable winding becomes important.

We show that accuracy can be much improved by minimising the size of such loops, and that for use in the VHF range it is necessary to use a current probe of the smallest possible dimensions.

2 Current Practice

The customary current probe (or transformer) used for EMC work is that described by CISPR, ref [1]. This describes how Common-mode (**CM**) current flow may be measured by passing the cable concerned through the centre hole of a toroid – usually split and hinged for convenient assembly around the EUT cable. The current probe is also wound with a multi-turn secondary connected to a measuring receiver, as shown below.

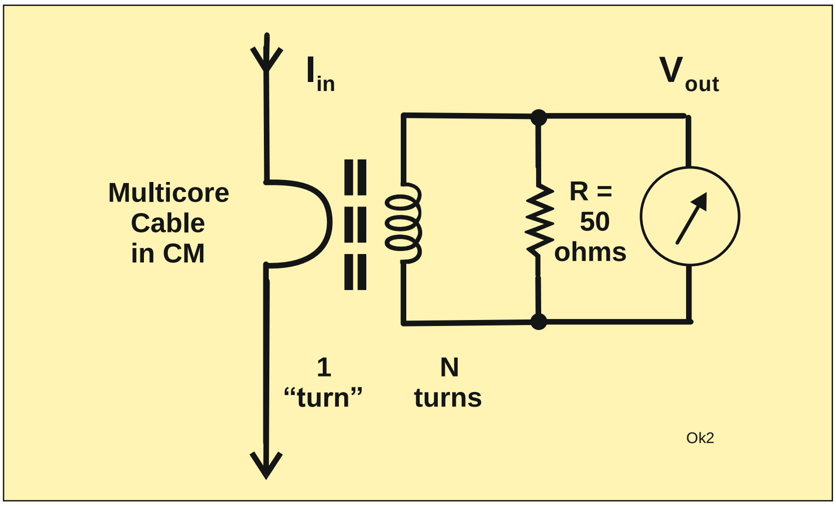

Fig. 1: The principle of the Current Probe applied to measurement of Common-mode current flow in a multicore cable.

For measuring Differential Mode (**DM**) the two conductors involved are passed ***in opposite directions*** through the centre aperture. This may be understood from our Fig. 2 below, which is derived from the CM circuit in ref [1], Fig. B.4(b).

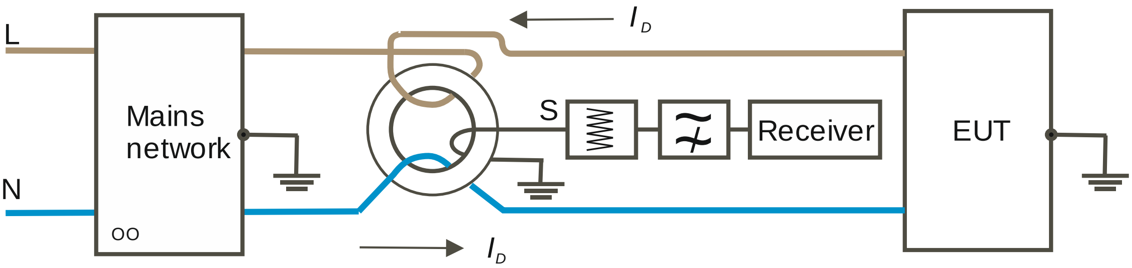

Fig.2: Schematic of Differential Mode measurement, with 'S' representing the secondary winding with N turns.

Here we comment on DM measurement using larger current probes. It can be seen that the **DM** circuit above differs from the **CM** circuit in three important respects:

- Unavoidably there are loops of the individual primary wires that may have significant inductance.
- The effective transformer ratio becomes 1:N/2, so that for a given output load the input resistance seen by the primary circuit is **quadrupled**, when compared to the equivalent CM configuration.
- The effective transformer ratio becomes 1:N/2, so that for a given input current the output voltage at the measuring receiver is **doubled**, when compared to the equivalent CM configuration.

We deal with these three factors in order, after noting that we have followed CISPR (ref [1], Table 7, Section 9) in assuming that for mains cables **CM** impedance may best be taken as 150 Ohms, and **DM** impedance 100 Ohms.

2(a) The size and effect of unwanted inductance in the primary circuit.

This may be more clearly understood from the picture below, which is representative of the casual application of a typical current probe when applied for **DM** current measurement.

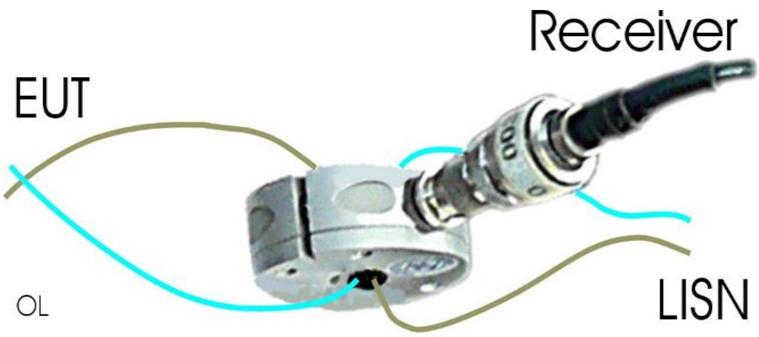

Fig.3 Configuration of casual DM measurement, showing large primary loops.

The worrying feature of this set-up is the wire layout. The Line (brown) and Neutral (blue) conductors form loops each side of the current probe that are similar to the size of the probe itself. Each one often approximates to a circular loop of 75mm diameter. The Inductance of such a loop, formed of 0.5mm diameter wire, is estimated in ref [2] as 0.24 micro-henries, i.e. an impedance of 45 Ohms at 30MHz and 450 Ohms at 300MHz. **DM** current flow through the probe as pictured above faces the obstacle of two such loops in series totalling 900 Ohms (this estimate assumes no direct inductive coupling between the two loops). Since the characteristic **DM** impedance of a two-core cable is about 100 Ohms these loops form a serious impediment to **DM** current flow. There would have been some benefit to be gained by using thicker wire for this section of the EUT cable; quadrupling the wire diameter would have reduced the loop inductance by some 25%.

These estimates are simplistic, but they have been confirmed by measurements as below. All the measurements in this paper have been made using a kit of parts built around representative “wires” each of which is actually made from coaxial cable, with an outer shield diameter of 2mm, furnished with SMB connectors, and with the inner and outer conductors wired in parallel. Twisted pair cables made from these "wires" have a measured characteristic impedance of 84 Ohms. The test configuration is shown in Fig. 4 below.

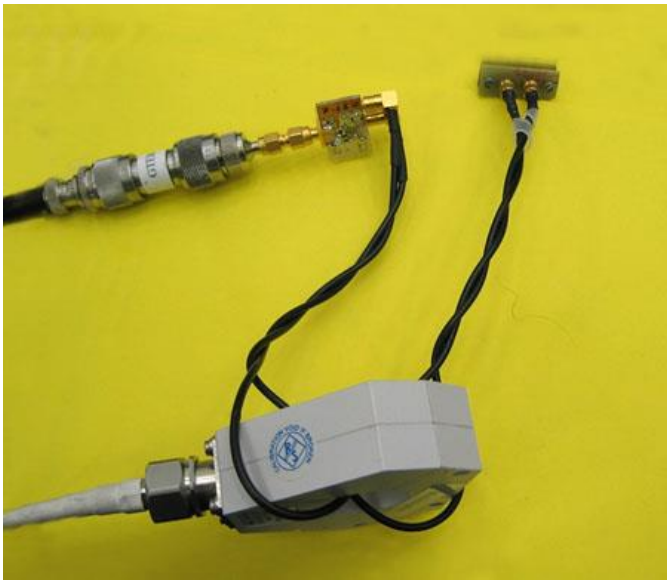

Fig. 4: Test configuration showing DM current measurement.

The Port 1 input from the VNA is at the top left, and this is connected via a minimum-loss pad (MLP) to the black "wires". The MLP is implemented on the PCB at top centre; to change the characteristic impedance from 50 Ohms to 100 Ohms. The twisted "wires" are 450mm long and threaded through the current probe in the necessary figure of eight arrangement, and then on to a 100 Ohm terminating resistor at top right (output load).

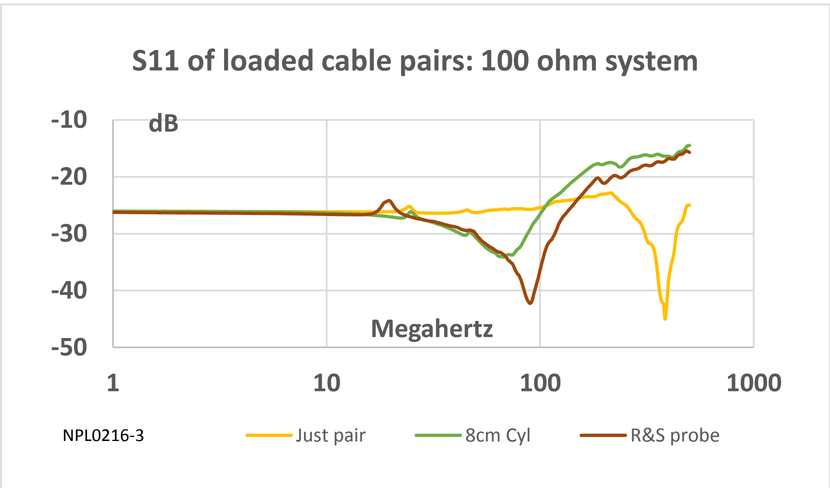

Fig. 5: Measured S11 from Port 1 of the VNA, with 3 configurations: just the twisted pair, an 8cm cylinder forming a loop in the wires, and the DM setup with a correctly terminated R&S probe type EZ-17.

This set-up was used to study the reflections from the black twisted pair back towards the "EUT" source. These reflections result from the various discontinuities along the wires. The situation with the current probe in place as shown in the photograph of Fig. 4 is the brown plot of Fig, 5. This is not much different from that produced by an 8cm plastic cylinder and shown in the green plot. In both cases disturbance is evident at about 40MHz. It is perhaps for this reason that CISPR [1] suggests that DM measurements may not be possible above 20MHz.

These plots illustrate that **DM** measurements are seriously disturbed by wiring inductance, and if higher frequency operation is desired then one must minimise loop areas. However, such efforts are limited by the bulk of the current probe itself, making a strong case for the introduction of physically-smaller current probes.

2(b) Input resistance seen by the primary circuit is quadrupled, for a given output load.

The input resistance has to be a small fraction of the characteristic impedance of the circuit concerned. Current probes are designed in accordance with the CISPR requirement (Section 5.1, ref [1]) for an insertion impedance of less than 1 Ohm, which creates minimal disturbance to calibration in the 50 Ohm **CM** test fixture. It can be seen from our Fig. 1 above that if the number of secondary turns ($N = 8$ for example), and the transformer is loaded by a 50 Ohm receiver, the insertion impedance is $50/N^2 = 0.78$ Ohms. However, if such a probe is used in **DM** mode, the insertion impedance rises to 3.125 Ohms which is outside the specification limit! Since practical **DM** circuit impedances are typically 100 ohms, the situation is not too serious although the resulting error ought to be allowed for in the error budget. Fortunately, consideration of the third issue below offers a better solution to this problem.

2(c) For a given input current the output voltage is doubled.

Ref [1] notes that a 6dB attenuator may be inserted before the measuring receiver in order to compensate for the doubling of current sensitivity in **DM** mode. It is on this basis that the measurements in this paper have been conducted, but it is notable that if a 50 Ohm through termination (i.e. a single shunt 50 ohm resistor) is substituted, the required attenuation is provided because of the current-to-voltage conversion, but in a manner such that the effective load impedance on the transformer secondary is halved. Thus the primary insertion impedance is also halved. Taken in conjunction with the example in the previous paragraph, the insertion impedance is then only 1.56 Ohms. Furthermore, the lowered impedance broadens the mid-frequency region of constant calibration factor.

Accordingly: we recommend the use of a 50 ohm through termination to correct for the increased sensitivity of DM measurement in all circumstances.

Note that the choice of $N = 8$ in these two paragraphs is by way of example only. The underlying argument does not rely on any particular choice.

3) A Broad-band Current Transformer Design

We propose the following guidance to improve the VHF performance of current probes, particularly with respect to DM measurements.

a) A nominal 10mm aperture is necessary to meet the majority of EMC applications though this does not fall within the present specification [1] in Section 5.1.3, so perhaps some allowance is needed in the specification here.

b) To be useful for **DM** measurement the device must be made as small as possible. Small overall dimensions are just as important as a small centre hole. There needs to be a method to ensure a consistent primary winding layout that results in minimum disturbance of the EUT cable RF circuit impedance.

c) The core material must be chosen for appropriate bandwidth. See [3]

d) For **DM** use the nominal 50 ohm measuring receiver load impedance must be preserved by incorporating an appropriate attenuator in the receiver cable **close to the probe**.

e) The nominal 50 ohm load impedance must be preserved by tightly coupling the secondary winding to the core and minimising the winding's self-capacitance.

f) Leakage into the measuring receiver of current from any **CM** voltage on the EUT cable must be minimised by electrostatic shielding between the cable and the probe winding, and by providing a ferrite sleeve choke on the receiver cable. However, capacitance between the EUT cable and the probe must also be minimised to avoid disturbing any **CM** measurement by the added shunt capacitance.

These constraints have implemented in a 2-part assembly comprising a basic probe that can be incorporated in a variety of primary circuit setups. However, the development of improved configurations remains as an opportunity for test equipment designers.

The basic probe is shown below together with an exploded isometric view of its construction

Fig. 6: Design of a basic probe which meets the new constraints.

Note the inner electrostatic shield with gap – and the absence of any outer shield which together with the integral ferrite sleeve avoids excessive bypass for **CM** current flow. The secondary winding comprises 5 turns of thin tinned copper tape. 5 turns is the minimum that allows conformance to the specification [1] whilst offering enhanced VHF performance. The use of tape rather than wire allows the use of a ferrite toroid with smaller diameter hole, whilst still leaving room for double insulation of the primary circuit if required.

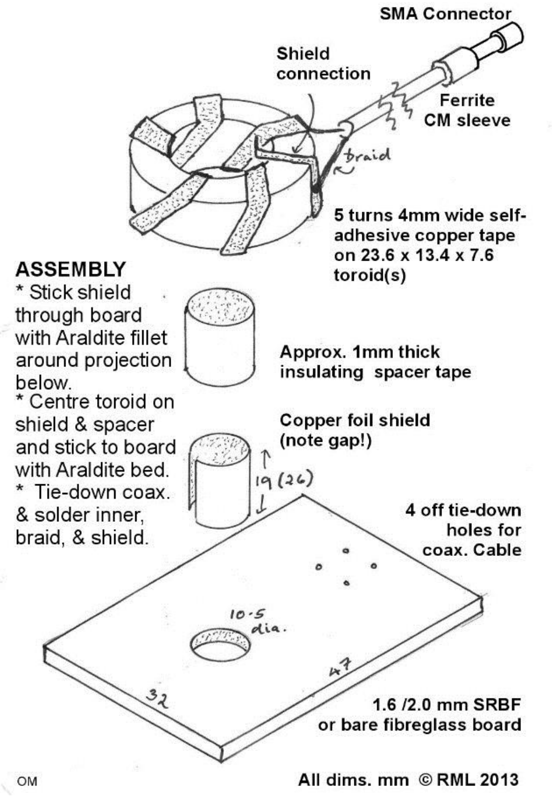

Fig.7: Exploded diagram of the improved design

The fact that the ring is not split for easy assembly round the wire(s) concerned is not a serious disadvantage. Indeed the resulting possibility for tight control over the primary “winding” is very beneficial.

Calibration of this probe may be done using a Vector Network Analyser to make measurements of S21. Calibration of the **DM** mode is physically different than that for **CM** usage since the coaxial structure shown in Figure B.9 of reference [1] is no longer appropriate.

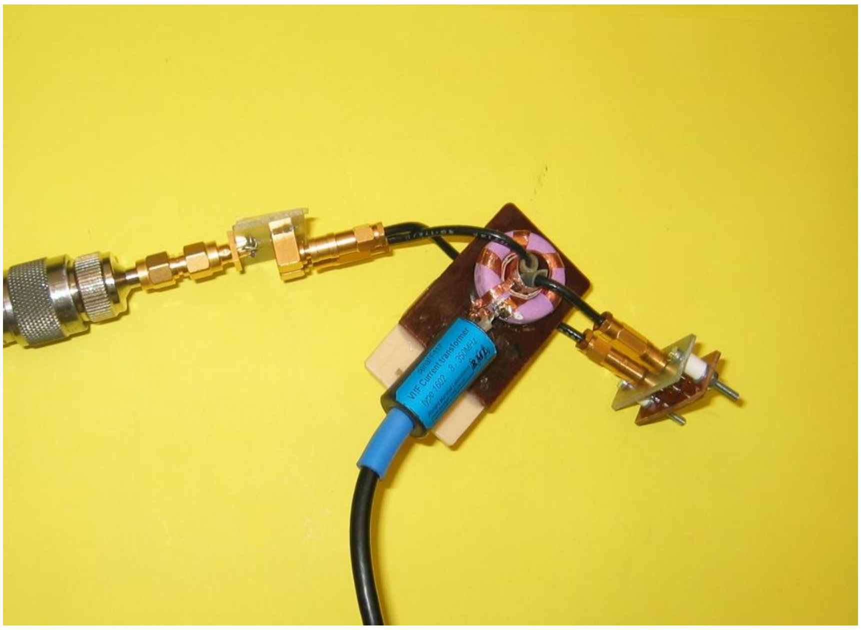

Fig.8: Calibration of improved DM current probe

Since 100 Ohms is the preferred **DM** circuit impedance, we have adopted the measuring setup shown in our Fig. 8. The S parameter test set port 1 is connected to a minimum loss attenuator on the left-hand side of the picture. This provides conversion from 50 ohms to 100 ohms at the cost of 7.66 dB loss which is accounted for in the analysis. The wires are terminated with 100 Ohms on the right.

The wire figure of eight primary appears to be adequate at this stage: It is for a test equipment designer to further improve electrical balance, characteristic impedance, and mechanical integrity. However, the calibration curve of the design in Fig.7, tested as in Fig.8, and shown in Fig.9 is very satisfactory.

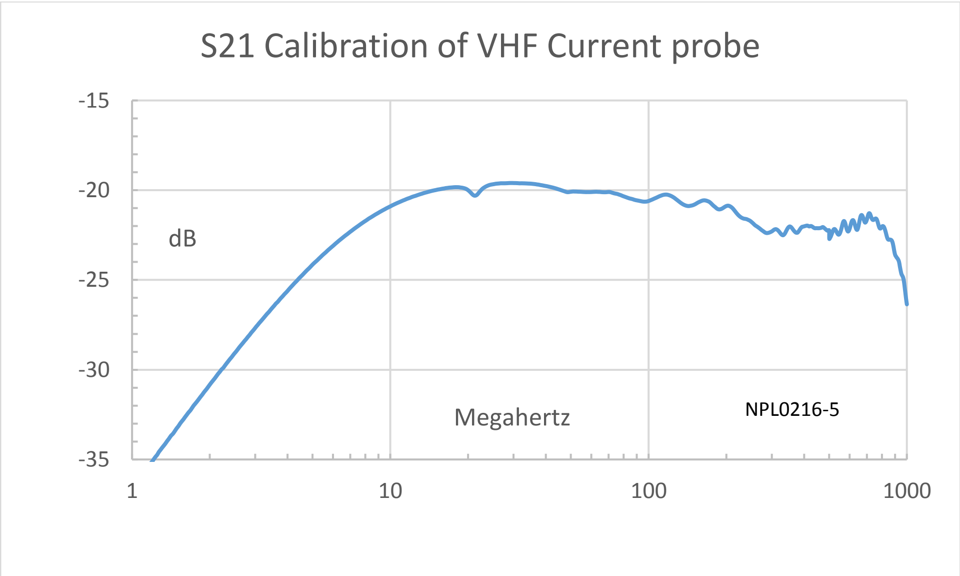

Fig.9: Calibration result for improved DM current probe

The low-frequency roll-off is expected, since the core chosen was specified to provide 87nH for a single turn. The winding had 5 turns that would give $5^2=25$ times the inductance, i.e. 2.18uH. This inductance, in parallel with the 50 Ohm measuring receiver input, should result in 3dB loss at 3.66MHz, which it does approximately.

The vertical scale of the above calibration chart is that customary for S21 measurement, and shows a mid-band power loss of 19.5dB for the total set-up: that is the current probe plus the 100 Ohm test jig. However, the current probe itself takes a current input and develops a voltage across the 50 Ohm load of the measuring receiver, so its transfer impedance is the most fundamental specification.

To convert S21 into a transfer impedance it is necessary to convert the input power from the VNA into probe primary current, and also to recover the voltage presented to the measuring receiver from the output power measured by the VNA. For the 100 Ohm test jig used here, the first factor can be shown to be +70dBuA per dBm, and the second factor -107 dBm per dBuV. Accordingly the mid-band transfer impedance is -19.5 -70 +107 dB(Ohms), that is 17.5 dB(Ohms) or 7.5 Ohms. This compares adequately with the theoretical loss-less value of receiver input resistance / turns ratio = 50/5 = 10 Ohms that may be understood from our first figure.

If the above design of transformer is connected to the 50 ohm measuring receiver via a 50 ohm through termination as recommended earlier, the nominal insertion impedance becomes 1 Ohm, and the transfer impedance 5 Ohms, which will conform to the mandatory requirements of [1] para. 5.1.3. However, these mandatory requirements might usefully be relaxed to accommodate the basic usage described in our previous paragraph.

4) Primary circuit jigs

For measurements of the emission from products a suite of packaged VHF current probes arranged to measure **DM** and the two possible **CM** configurations has been constructed. In order to manage the exact wiring layout of these **CM** and **DM** probes, assemblies of the devices were wired between pairs of IEC C13/C14 mains connectors. These are illustrated in the figures below.

Note that in all cases the current probe is assembled so as to allow use as close as reasonably possible to the EUT. This is desirable to obtain reproducible results at higher frequencies, but does not prevent exploration at greater distances if extension cables are used.

The 55cm cable to the measuring receiver is decoupled from the probe by a ferrite sleeve integral with the probe, and terminated in a BNC connector.

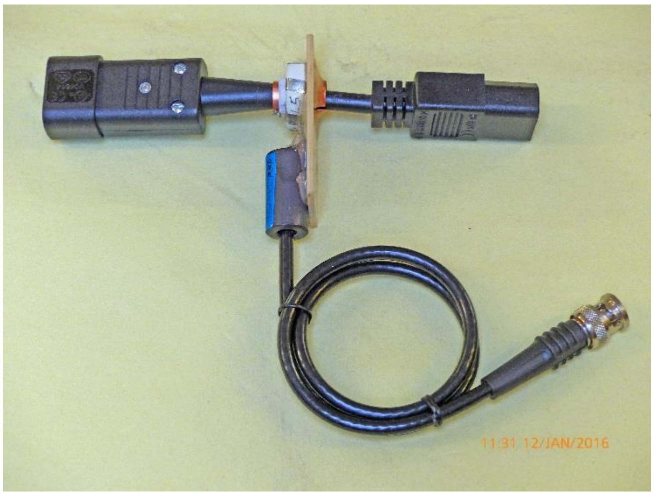

Fig.10:

The VHF **Common Mode** probe. It conforms to the general understanding of response to the algebraic sum of the current flow in the three wires – or just two if no ground wire is present in the connected cable. The outer jacket of the EUT cable provides the double insulation necessary for safety.

Fig.11

The **Differential Mode** probe senses the difference between the current flow in the Line and Neutral conductors as may be seen by the different directions of the brown and blue wires. The green/yellow ground wire bypasses the current probe, which may be used with either 2-wire or 3-wire cables. An additional insulating sleeve is provided inside the core aperture as a safety precaution.

Fig.12:
This **CM of Line and Neutral with local ground return** probe is of considerable interest for Standards development in cases of small EUTs with only a single cabled port that includes a ground connection. It allows measurement of the circulating current between the Line and Neutral conductors treated as one conductor, and the associated ground return.

5) Conclusions

Whilst the principle of using current probes in Differential Mode is well-covered in EMC standards, there needs to be more detail, particularly to support VHF use.

6) Acknowledgments
The authors acknowledge the support of their respective organizations and of the UK National EMC committee GEL210/11. The RS EZ-17 current probe was loaned by Mr. J Rayner of Samsung UK.