Apparently Simple Low Frequency Measurements: An EMC View

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***Abstract*—This paper demonstrates the need for care with some EMI problems present in even simple low-frequency (< 1 MHz) measurements. Two experiments on cable crosstalk, found in the IEEE EMC Educational Manual [1], are used. Predictions are made from field theory, and compared to results from a series of measurement setups. Although the setups appear similar, it is found that unwanted coupling between the experiment and the measurement equipment influences the results.**

***Index terms*—EMC, education**

I. Introduction

Low-frequency measurements are often made without great care. Oscilloscope probes are connected in the most physically convenient ways, and the grounding of the measurement equipment is ignored. However, even at low frequencies, unwanted magnetic and electric fields and common-mode currents in the measurement cables can couple into the measurement equipment, distorting the results. This is demonstrated using two experiments on crosstalk in cables [1]. These experiments require two loops of ordinary household flex placed next to one another. Magnetic field and resistive coupling generate the crosstalk. At the same time the magnetic field can couple into a loop formed by the measurement equipment, its grounding, and the probes, inducing a common-mode current. Several different setups are used to demonstrate this effect. Results are compared to predictions made from field theory.

II. Discussion Of The Experiments And The Theoretical Predictions

Experiments 1 and 2 are shown in Fig. 1 and Fig. 2 respectively. In both experiments the signal source is modelled as a perfect voltage source and a 50Ω resistor. This voltage source creates a current in loop 1, which is described in (1).

$$i_1 = \frac{V_S}{Z_{loop1}} \tag{1}$$

Z_{loop1} consists of the two resistors in loop 1, as well as the resistive loss in its copper lengths, and its self-

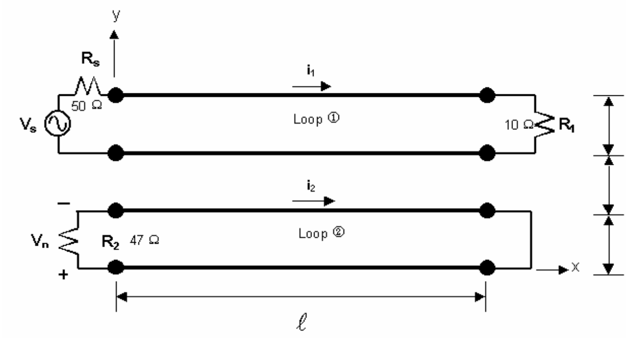

Fig. 1. Experiment 1 – Crosstalk caused by magnetic coupling.

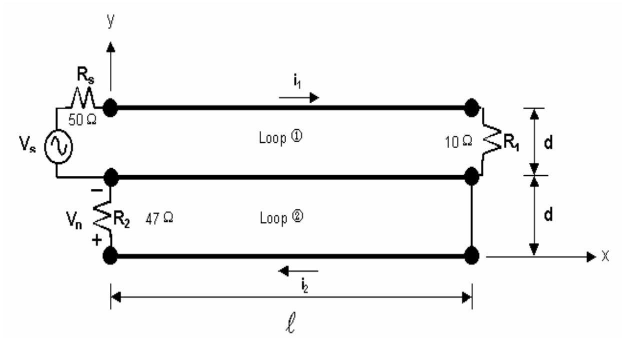

Fig. 2. Experiment 2 – Crosstalk caused by magnetic and resistive coupling.

inductance. Ignoring the skin effect, and treating the twisted strands of copper as a single solid wire, the resistance per unit length can be calculated as

$$R_\ell = \frac{1}{\sigma A} = \frac{1}{\sigma \pi \Delta^2} \tag{2}$$

where A is the cross-sectional area of the copper, Δ is the radius of the copper and σ its conductivity.

Only the external self-inductance of the loop is taken into account, as it is much larger than the internal self-inductance. The contributions to inductance from the ends of the loop are also ignored, as they are small. The self-inductance is calculated as

$$L_{self} = \frac{\int \overline{B} \cdot d\overline{a}}{i}$$

$$= \frac{\mu_0 \ell}{2\pi} \ln \left| \frac{(d-\Delta)^2}{\Delta^2} \right| \quad (3)$$

where μ_0 is the permeability of free space and d the distance between the conductors. The current in loop 1 generates a magnetic field that couples into loop 2. This field induces an EMF in loop 2. In Experiment 1 this is

$$EMF_{Exp1} = -jf\mu_0 i_1 l \cdot \ln\left[\frac{(d+\Delta)(3d-\Delta)}{(2d+\Delta)(2d-\Delta)}\right] \quad (4)$$

and in Experiment 2 this is

$$EMF_{Exp2} = -jf\mu_0 i_1 l \cdot \ln\left[\frac{\Delta(2d-\Delta)}{(d+\Delta)(d-\Delta)}\right] \quad (5)$$

In Experiment 1 the coupling is only magnetic, and the measured voltage across the resistor in loop 2 is given by

$$v_2 = \frac{EMF_{Exp1}}{Z_{loop2}} \cdot R_2 \quad (6)$$

where Z_{loop2} includes the self-inductance, resistor R_2 and resistive copper loss of loop 2. In Experiment 2, the coupling is magnetic and resistive, and is given by

$$v_2 = \frac{EMF_{Exp2}}{Z_{loop2}} \cdot R_2 + \frac{\ell R_\ell i_1}{\ell R_\ell + R_2 + j\omega L_{self}} R_2 \quad (7)$$

The second term in (7) is not always clearly specified by EMC practitioners, and arises from the voltage drop caused by i_1 flowing through the common line resistance.

Both experiments were performed using the following parameters:

$$V_S = 20V_{p-p}$$
$$\ell = 2m$$
$$d = 3mm$$
$$\Delta = 0.4mm$$
$$\sigma = 5 \times 10^7 S/m$$

The experiments were performed three times, with different equipment configurations. The purpose of this is to demonstrate the importance of EMC awareness in experimental practice.

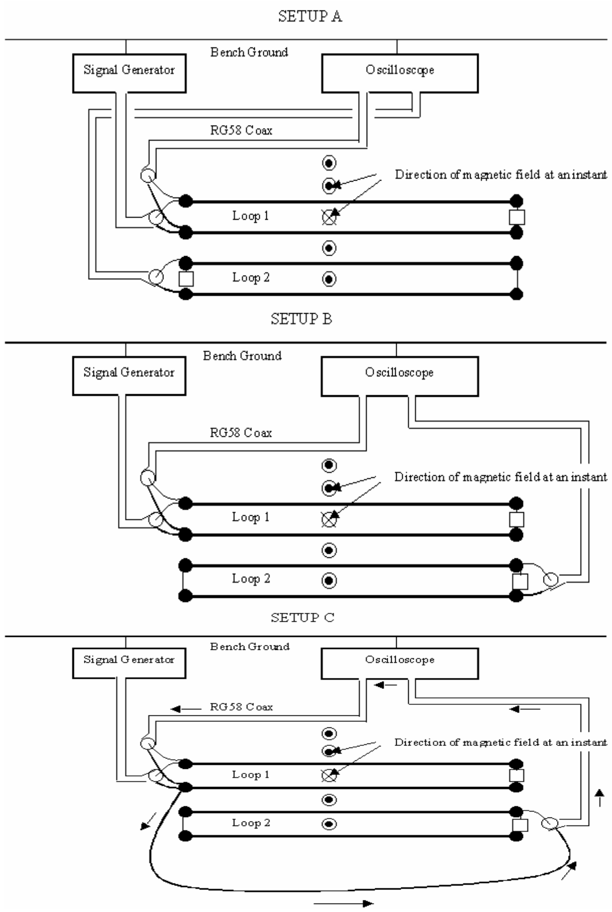

Fig. 3. Setups A, B and C for Experiment 1. The position of the measurement cables affects the results.

III. Measured Results

The three setups for Experiment 1 are shown in Fig. 3. Setup A is expected to deliver good results, as the feeding coaxial cables do not come near any of the induced magnetic fields. Setup B is also expected to deliver good results, as no closed loop including the feed cables is formed near the magnetic fields. Setup C, which attempts to enclose all of the magnetic flux in a ground loop, in principle should give good results, if a net flux cancellation occurs. However, a common-mode current path is also created, as shown with arrows. Any net flux passing through this loop will induce a common-mode current, and this current can couple into the measurement equipment through transfer impedance. The magnitude and phase measurements are compared to the field theory predictions in Fig. 4 and Fig. 5.

The results from the first two setups show a voltage magnitude difference of approximately 2 dB and a phase difference of 45 degrees to the field theory. Setup C has a voltage difference of 12 dB and the phase measurement does not follow the field theory well at the low frequencies.

The setups for Experiment 2 are shown in Fig. 6. Set-up A is expected to give good results, as the feed cables avoid the magnetic fields. Set-up B should give poorer results, as some of the magnetic flux is trapped in a

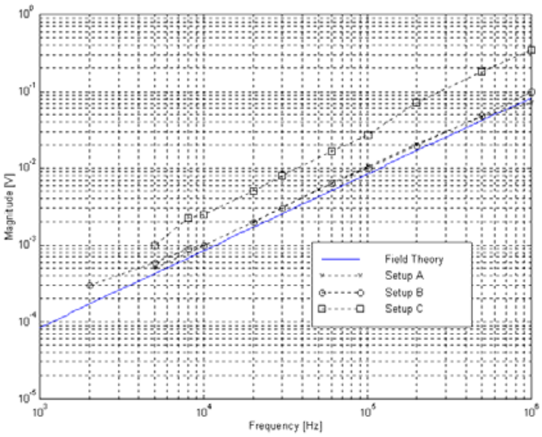

Fig. 4. The measured voltages for the different setups of Experiment 1.

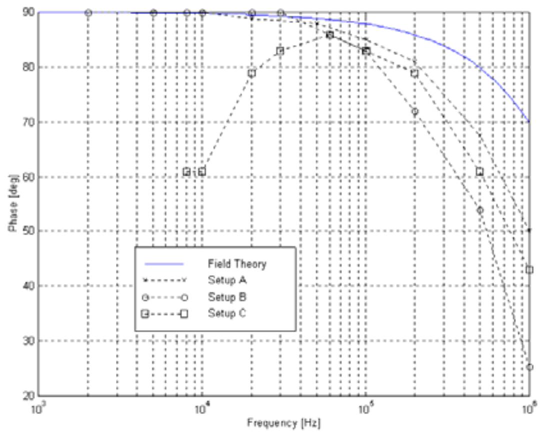

Fig. 5. The measured phases for the various setups of Experiment 1.

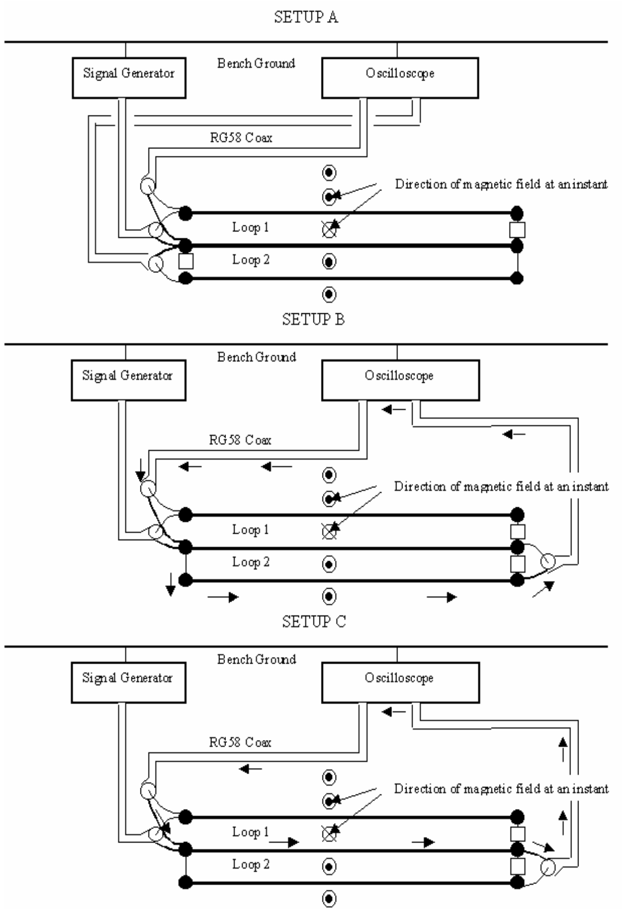

Fig. 6. Setups A, B and C for Experiment 2. The positions of the measurement cables affects the results.

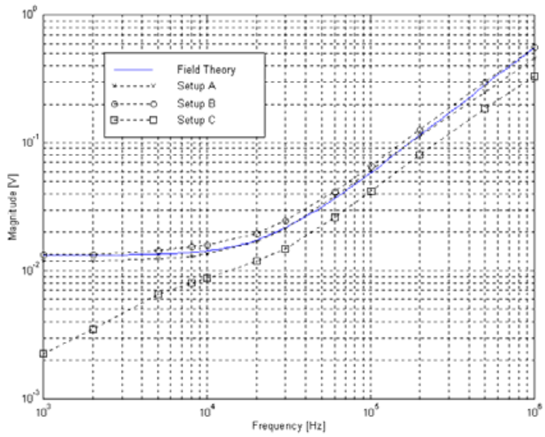

Fig. 7. The measured voltages for the various setups of Experiment 2.

ground loop, shown with arrows. However, there is partial cancellation (as some of the flux is pointing up and other parts are pointing down). Setup C is expected to give the worst results for two reasons: the magnetic flux is partially enclosed, inducing common mode currents in the cables (as shown by the arrows), and cable leads to the probes add a new connection in parallel with the centre conductor. Current that would only have flown along the centre conductor now can also flow over the oscilloscope. The magnitude and phase results are show in Fig. 7 and Fig. 8, where they are compared to field theory.

Setup A delivers the best correlation to the field theory, with less than 2 dB magnitude difference, and less than 25 degrees phase error. Setup B shows good magnitude correlation, with a fairly constant 2 dB error, but a phase difference of 40 degrees at the highest frequencies. Setup C does not follow the field theory well, in both voltage magnitude (5 dB difference at best) and phase (up to 45 degrees).

In Experiments 1 and 2, the measurement errors in setup A can be attributed to non-ideal voltage sources, inaccuracies making readings from the oscilloscope and uncertainties regarding the flex. Setup B in Experiment 2 shows some of the effects caused by the induced currents.

However, the large errors in both experiment's Setup C are associated with induced common-mode currents.

IV. Conclusion

The measurement results show that when making measurements that involve field coupling, great care must be taken to avoid inducing common-mode currents in the measurement equipment. The measurements that avoided common-mode currents produced the results closest to the field theory, and to one another. As most low frequency equipment is constructed without much precaution against common-mode currents, the common-mode currents easily couple into the measurement equipment and are seen as noise voltages. The grounding of the probes, oscilloscope and the signal generator in these experiments can create pickup loops. Even at low frequencies the effect of the equipment grounding is marked. The poor repeatability of such measurements may be as a result of unwanted coupling. Although not shown in this paper, the ground loop formed by the signal generator and its leads forms another pickup loop.

V. Acknowledgements

Marc Rütschlin is thanked for thoughts on the ground loop problem. Louis Becker and Johan Maree are thanked for developing the basic coupling practicals from the IEEE EMC Manual for an EMC short course [4], Charl Coetzee is thanked for critical evaluation of some of the material, and Prof. Johannes H Cloete for continued debate in this field.

VI. References

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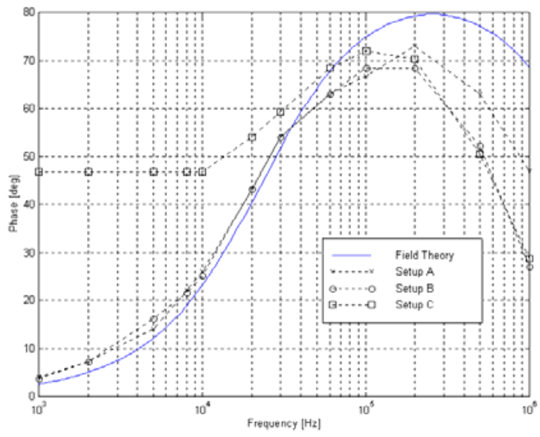

Fig. 8. The measured phases for the various setups of Experiment 2.