Publications on Crosstalk in Digital Systems.
IEEE Trans. Comput., vol. EC-16, no. 16, December **1967 ;**
http://www.ivorcatt.co.uk/x0305.htm
“Electronics World, January/February **2011**;
http://www.ivorcatt.org/x111.pdf ; http://www.ivorcatt.org/x121.pdf
Below, “Electronics World”, February **2014**; “Electronics World”, August **2014**

EMC Concepts

IAN DARNEY PRESENTS THIS NEW SERIES OF ARTICLES ON CIRCUIT MODELLING FOR ELECTROMAGNETIC COMPATIBILITY

This series of articles will demonstrate that electromagnetic compatibility (EMC) is as amenable to the design process as any other design requirement. Key to the approach is the use of circuit models to simulate and analyse all the interference-coupling mechanisms. Such an approach results in a dramatic simplification of the mathematics.

This instalment introduces the underlying concepts, with future articles covering lumped-parameter models, transmission lines and antennae, bench testing, transients and design guidelines.

Simplifying Assumptions

The mechanisms involved in the coupling of interference are governed by the laws of physics, defined by the formulae of electromagnetic theory. These laws also control the functional behaviour of electronic systems, analysed by the much simpler mathematics of circuit theory.

Given these facts, it is reasonable to describe circuit theory as a development and simplification of electromagnetic theory. However, the simplifications inherent in the present-day usage of circuit theory that make it capable of analysing the behaviour of extremely complex electronic systems also render it ineffective in any analysis of interference coupling.

The keyword in the previous sentence is 'usage'. If the simplifying assumptions can be identified and modified, then circuit theory can also be used to analyse interference.

The most significant of these assumptions is the concept of the 'equipotential ground', which manifests itself in the use of the ubiquitous 'earth' or 'ground' symbols found scattered around present-day circuit diagrams. It is assumed that every point identified by such a symbol is held firmly at zero voltage. The simulation tool SPICE, for example, has become totally dependent on this concept.

Another assumption is that the conducting link between two nodes on a circuit diagram has zero impedance.

> *A basic assumption when using circuit theory is that action and reaction are instantaneous throughout the system. They are not!*

The Signal Link

If it is recognised that every conductor in a system possesses the properties of inductance, capacitance and resistance, then it follows that transient current in any conductor will create a voltage along that conductor. A voltage will exist between any two points designated as being at ground potential. The effect of this can be minimised by assigning a 'return' conductor to return the current delivered by the 'sending' conductor back to the voltage source.

There will be two paths between sender and receiver for the return current, as illustrated by Figure 1. Coupling between the signal loop and the ground loop is inevitable, no matter how the terminations are configured.

A circuit model which simulates the coupling of interference between these two loops is illustrated by Figure 2.

Figure 1: Basic signal link

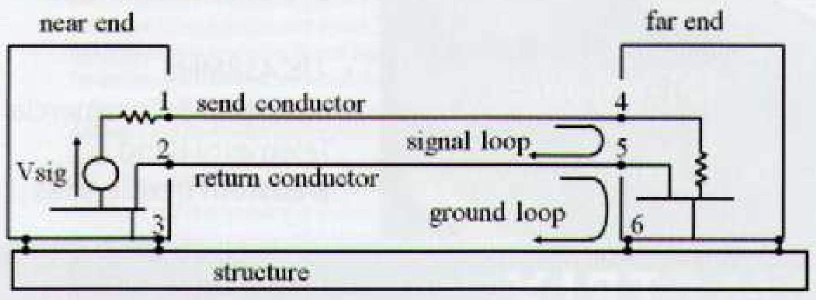
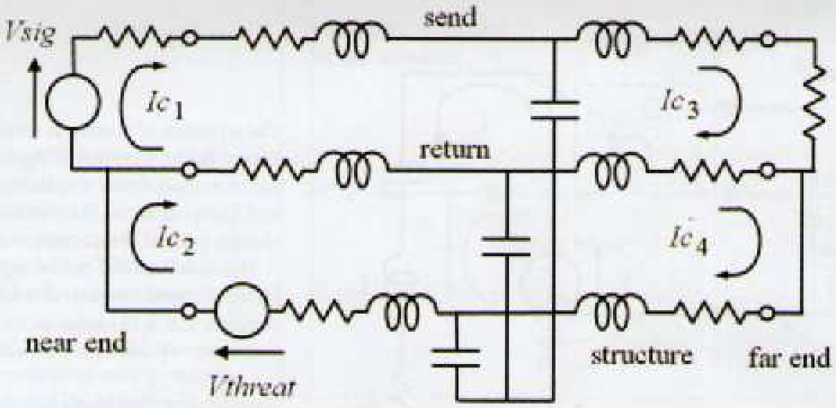


Figure 2: Circuit model of signal link



Each conductor is represented by a T-network of inductors, resistors and a single capacitor. The task of assigning numerical values to the L, C and R components of the model will be dealt with in my article on lumped parameters, later in the series.

If the only path available for the return current between the two units of equipment is the structure, or the 'earth' conductors of the power supplies, then there is no point in trying to analyse EMC.

The Circuit Diagram As A Model

Before the advent of the desk computer, one method of predicting the behaviour of the servo system of a rocket launcher was to relate the currents and voltages generated by an analogue computer to the mechanical properties of the system under review. A simple illustration of this relationship is provided by Figure 3.

A simple damping system is shown in Figure 3a. If an extra mass is dropped on the weight, then the system will oscillate.

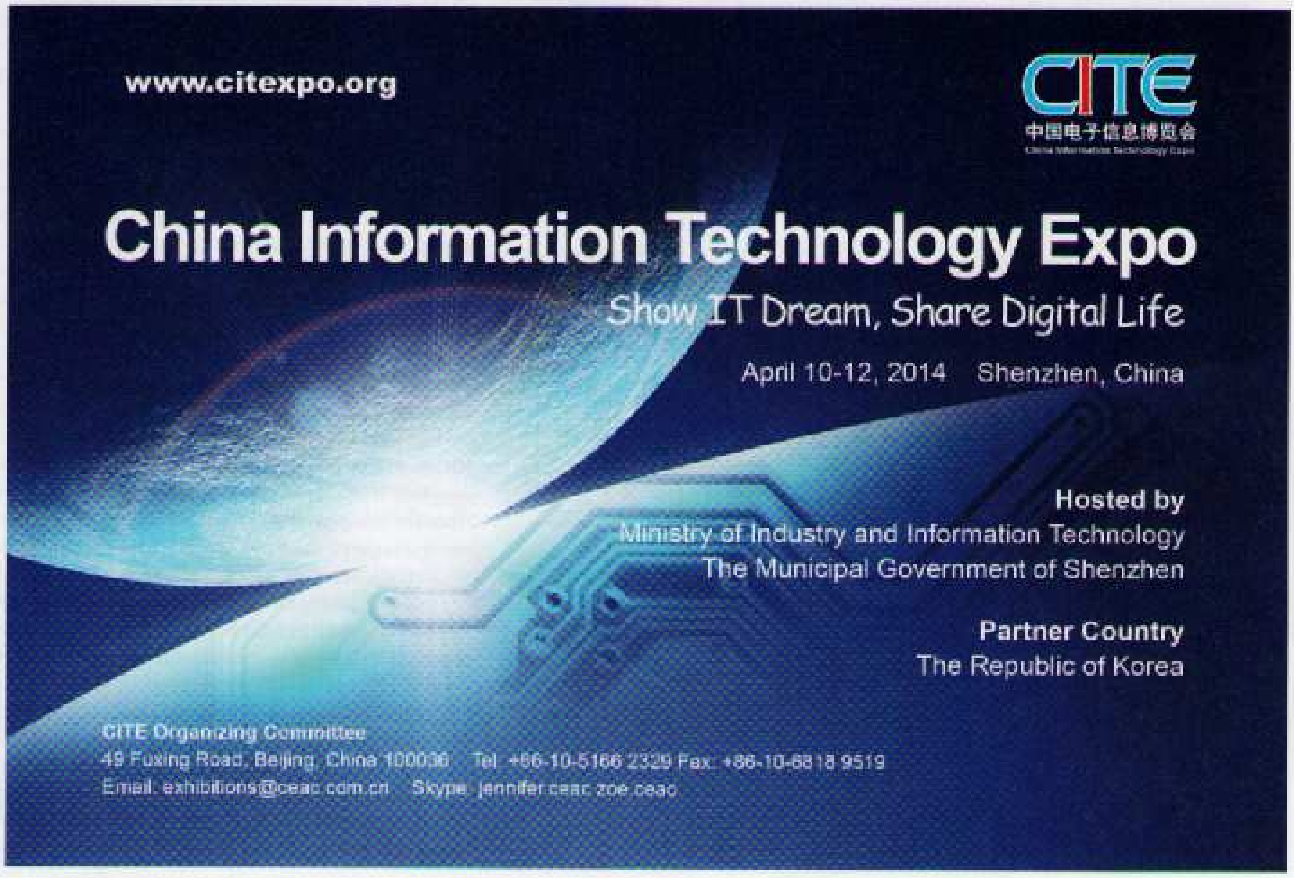


Figure 3: Use of a circuit model to simulate a mechanical system: (a) Damping system; (b) Circuit model

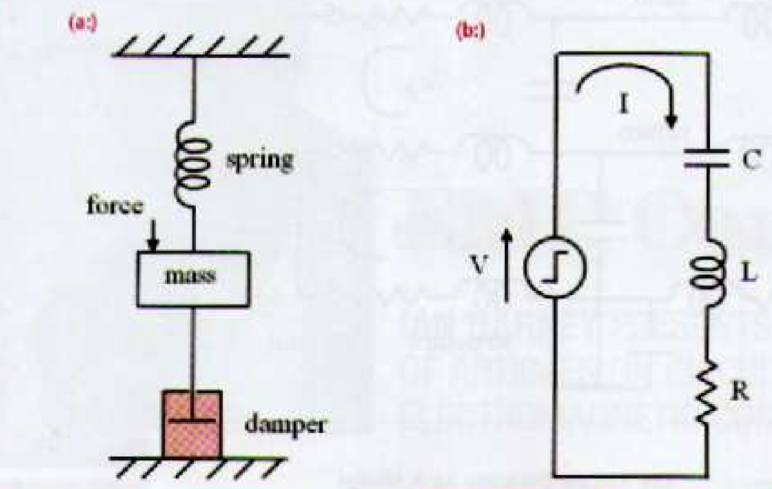


Figure 4: Distributed-parameter model of signal link conductors

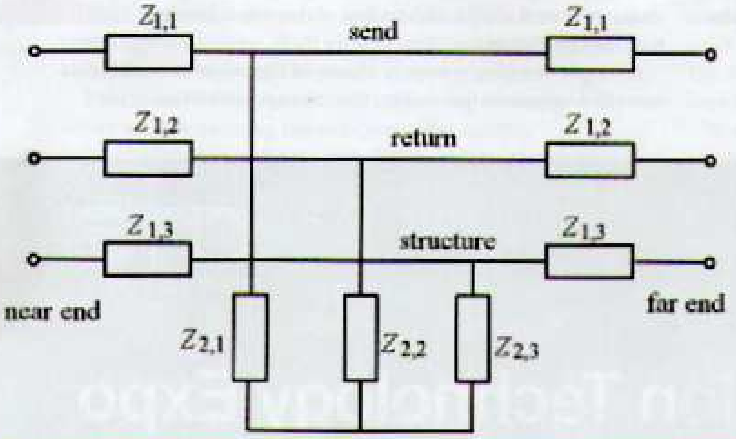
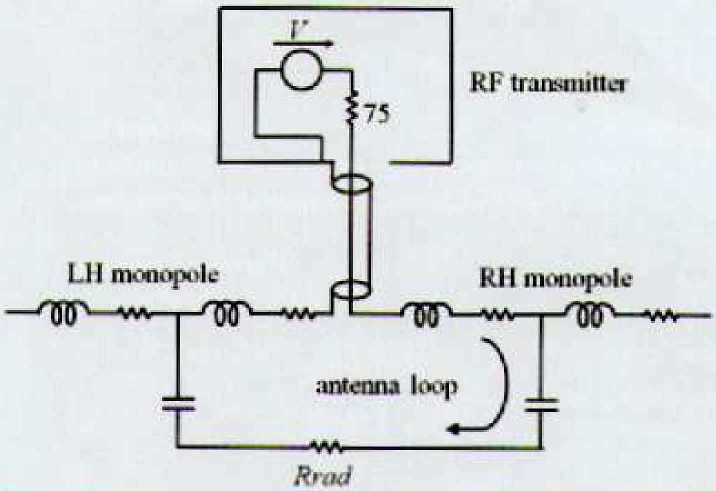


Figure 5: Lumped-parameter model of dipole antenna



The equation of motion is essentially the same as that of the LCR circuit of Figure 3b, where the parameters of force, displacement, velocity, mass and damping factor are replaced by voltage, charge, current, inductance and resistance.

The circuit model can be regarded as a pictorial representation of a set of equations. In concept, this is the same as treating it as the unknown variable in mathematical problems.

Developing the Model

A basic assumption when using circuit theory is that action and reaction are instantaneous throughout the system. They are not! The velocity of propagation of current and voltage is finite. Transmission line theory allows for this by deriving a pair of hybrid equations that relate current and voltage at the sending end to current and voltage at the receiving end of the line. This derivation can be developed further to define a pair of loop equations that can be manipulated using the rules of circuit theory.

The lumped-parameter model of Figure 2 can be replaced by the distributed-parameter model of Figure 4. These two figures are so named because the first assumes that inductance, capacitance and resistance are discrete components, whilst the second allows for the fact that these three parameters are distributed along the length of the cable. The transformation formulae are discussed in the article on transmission lines and antennae later in the series.

The Radiation Resistor

The theory of the dipole antenna identifies the concept of the radiation resistance. This parameter is probably new to circuit designers, but is well understood by students of electromagnetic theory. It is not a component in the sense that it can be purchased from a supplier. It is a mathematical constant derived from the analysis of the power density of the electromagnetic field over a spherical surface enclosing a transmitting antenna. When a dipole is providing maximum radiated power output, the load presented to the transmitter is purely resistive. This leads to the resistance *Rrad* in the model of Figure 5.

The reactive components act as a series tuned circuit. At resonance the only components limiting the current delivered to the environment are the resistors. Although the model is defined in terms of lumped parameters, it is analysed in terms of distributed parameters.

The Virtual Conductor

Since the model of Figure 5 represents each monopole as a T-network, it is a simple step in the reasoning to speculate that if a twin-conductor cable was to replace one of the monopoles, with the structure acting as the other, the result would be the model shown in Figure 6.

Since the assembly of components representing the environment of each monopole is shown as a T-network and since every conductor of the signal link is also configured as a T-network, it is natural to identify this assembly as a virtual conductor. Again, the lumped parameters are changed into distributed parameters during the analysis.

For susceptibility analysis, the threat voltage *Vthreat* can be calculated by relating it to the electric field of the threat environment.

To analyse emission, it is assumed that the threat voltage is zero. A voltage source *Vsig* at the near end of the signal link will generate a current *Irad* in the antenna loop. The maximum field strength H at a radius r due to *Irad* can then be calculated.

Bench Testing

Having established a method of modelling any signal link, the way is open for correlation to be established between the performance of the actual hardware and the simulation provided by the model.

Figure 7 illustrates a bench test setup that can be used to measure susceptibility. The clamp-on transformer injects a common-mode voltage into the cable; channel 1 of the oscilloscope monitors this voltage. Simultaneously, channel 2 monitors the effect of this voltage on the function of EUT1.

Figure 8 illustrates a setup used to measure conducted emission. In this test, the voltage delivered to the sending end of the signal link is derived from the signal generator and monitored by channel 1; channel 2 monitors the amplitude of the common-mode current.

In both tests, the designer can monitor the input and output simultaneously. With formal testing, engineers at the test house do not have that option.

The ability to carry out bench tests and create a circuit model of the interference coupling parameters means it is possible to predict the outcome of formal EMC testing and implement corrective measures before submitting the manufactured equipment to the test house. ●

Figure 6: General circuit model of exposed cable and structure

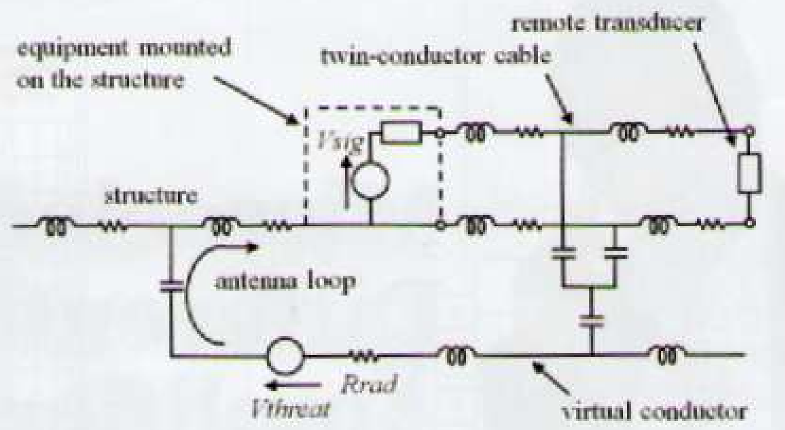


Figure 7: Bench test of conducted susceptibility

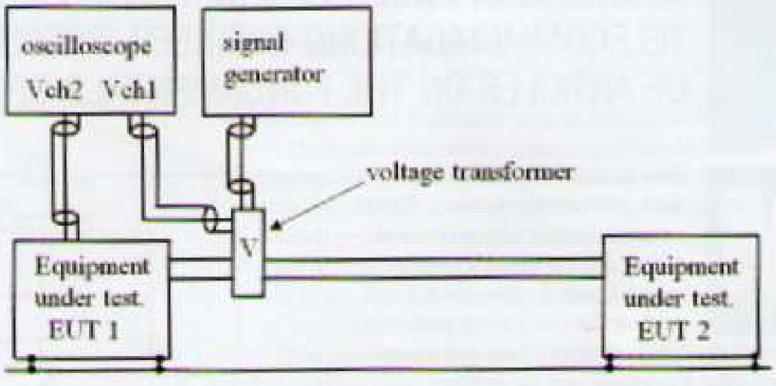
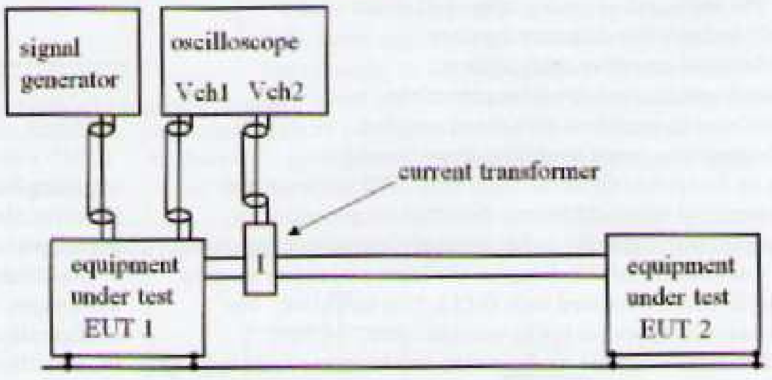


Figure 8: Bench test of conducted emission



THEORETICAL AND EXPERIMENTAL STUDY
OF CAPACITIVE AND INDUCTIVE CROSSTALK

BY **OTHMAN B.K. HASNAOUI** AND **AKRAM GHARBI** FROM ENSIT (SCHOOL OF ENGINEERING) IN TUNISIA

One of the prevalent industrial concerns is electromagnetic compatibility (EMC) – the electromagnetic noise emitted by electrical systems has important consequences, since each system can be affected by it or affect another. So, EMC is the ability of an electronic or electric system to operate properly in its intended electromagnetic environment and, also, not be a source of pollution.

We have made an experimental setup for testing conducted emissions due to capacitive and inductive crosstalk (see Figure 1). We use the Tektronix TPS 2012B oscilloscope to display voltage noise generated by the connections, and the software "Open Choice Desktop" for the acquisition and recording of curves on a computer. We also use a low-frequency generator "GWINSTEK (GFG-8015G)" as a noise source.

Evidence Of Capacitive Crosstalk

In the case of capacitive coupling there is an interfering voltage capable of producing voltage noise; there is even capacitive coupling between the source conductor and the 'victim'. The workbench presented in Figures 1 and 2 shows this kind of coupling.

With the following equation, we can calculate the parasitic capacitance C_p:

$$C_p = \frac{\pi.\varepsilon_0}{\log\left(\frac{2.D}{d}\right)} \tag{1}$$

where:

ε_0 is vacuum permittivity $= \frac{1}{36.\pi.10^9} = 8{,}85.\,10^{-12}$

D is the distance between electrical wires = 4×10^{-3}m

d is diameter of the conductors = 1.5×10^{-3}m

$C_{p,1}$ is the parasitic capacitance between the first wire (source of disturbances) and second wire (victim) as shown in the figures:

$$C_{P,1} = \frac{\pi.8{,}85.10^{-12}}{\log\left(\frac{2\times4.10^{-3}}{1.5.10^{-3}}\right)} = 0.03824nF/m \tag{2}$$

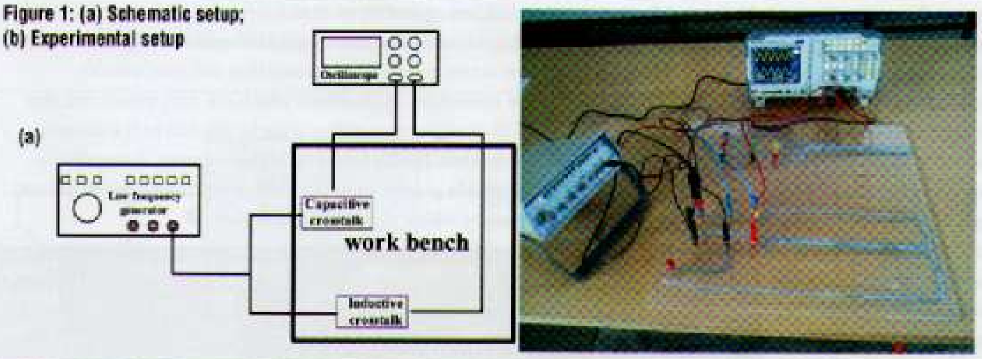
$C_{p,2}$ is the parasitic capacitance between the interfering source and the third wire (see Figure 2):

$$C_{P,2} = \frac{\pi.8{,}85.10^{-12}}{\log\left(\frac{2\times8.10^{-3}}{1.5.10^{-3}}\right)} = 0.02704nF/m \tag{3}$$

Figure 3 shows the parasitic voltage displayed on the oscilloscope, confirming the results of the equations.

Using a frequency generator, a 2MHz sinusoidal voltage is applied on the 'aggressor' wire. Clearly, the value of the parasitic capacitance decreases the further apart the wires are.

Figure 1: (a) Schematic setup; (b) Experimental setup



	Aggressor wire	'Victim' wire with screen	'Attacked' wire without screen	Percentage
Voltage level V(cc)	12.5	0.52	0.992	52.4%

Table 1: Shielding effect on capacitive coupling

Shielding Effect On Capacitive Crosstalk

We see the voltage noise caused by the source wire with the use of an oscilloscope, as shown in Figure 4. We find that the use of screened wire reduces the parasitic effects from 0.992V to 0.52V peak-to-peak (see Table 1).

If we increase the signal frequency applied to the source wire, the parasitic current that flows between the source and the victim increases (see Figure 5).
The interfering current is:

$$I_p = \frac{U}{R} \qquad (4)$$

where U is the voltage (peak) between terminals of the resistor R = 10kΩ.

For F = 1kHz, there is no induced voltage; for F = 10kHz, $I_p = \frac{75.10^{-3}}{10.10^3} = 7.5\mu A$; for F = 100kHz, $I_p = \frac{244.10^{-3}}{10.10^3} = 24.4\mu A$; and for F = 1MHz, $I_p = \frac{780.10^{-3}}{10.10^3} = 78\mu A$.

We conclude that with increased frequency, the capacitive interference intensifies.

Evidence Of Inductive Crosstalk

In the case of inductive coupling, there is a current in the 'offending' circuit likely to produce a current near the victim circuit. To illustrate this phenomenon we have developed an appropriate test-board (see Figure 7), which consists of two circuits: S_1, source of disturbance, and S_2, the victim loop. Inductance L which characterizes the current flow generated by the aggressor in the victim circuit is calculated with Equation 5:

$$\Phi = \iint B.dS = L.I_1 \qquad (5)$$

When a part of flux Φ crosses the second circuit S_2, this flux Φ_{12} is characterized by the mutual inductance M_{12}:

$$M_{12} = \frac{\Phi_{12}}{I_1} \qquad (6)$$

The voltage induced in the loop area S_2 is embraced by a magnetic field B. This phenomenon is expressed by the equation that results from Faraday's law:

$$\underline{V_i} = -\frac{d\Phi}{dt} = -\frac{d(\int \vec{B}.\vec{n}.dS)}{dt} \qquad (7)$$

In our case the magnetic field is sinusoidal, so (7) becomes:

$$\underline{V_i} = jw.B.S.\cos(\theta) \qquad (8)$$

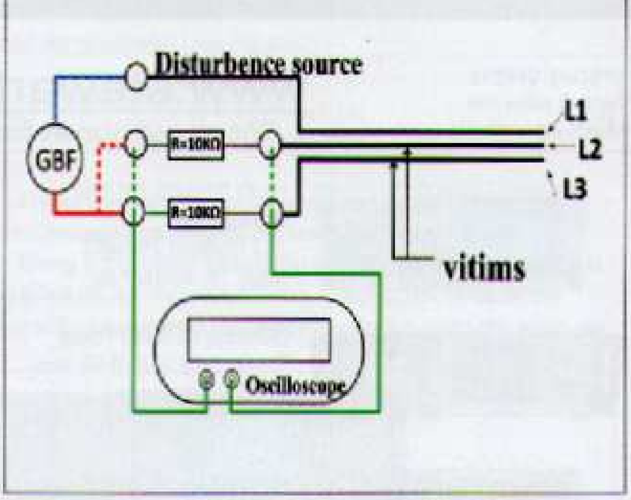
where θ is the angle between the normal $\vec{n}$ of the circuit and the magnetic field.

To the first circuit we apply an input voltage of 12.6V peak-to-peak; the noise voltage across the second circuit is 472mV peak-to-peak, as shown in Figure 8.

Inductive Crosstalk Tests

When we want to reduce the induced voltage V_i generated by the magnetic field B, generated in turn by the first circuit, we must take several factors into consideration.

Figure 2: Capacitive coupling test-board



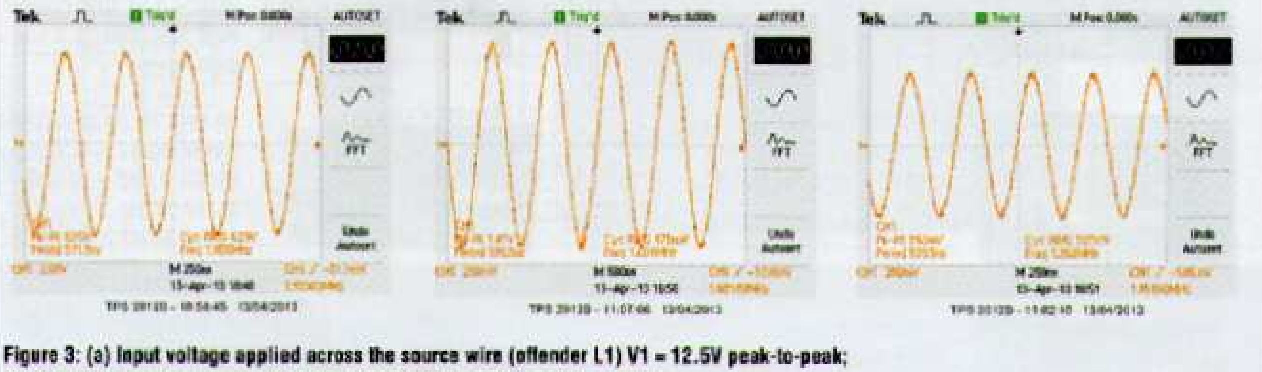


Figure 3: (a) Input voltage applied across the source wire (offender L1) V1 = 12.5V peak-to-peak;
(b) Voltage generated across the victim wire L2 (V2 = 1.56V peak-to-peak);
(c) Voltage generated across the victim wire L3 (V3 = 992mV peak-to-peak)

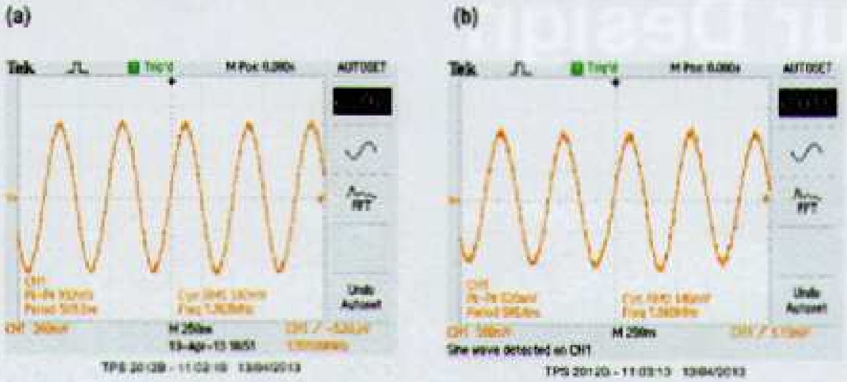


Figure 4: (a) Voltage generated by interference of the wire to the terminals of the victim L3 without screening; (b) Voltage generated by disturbances displayed to the terminals of wire L3 with screening

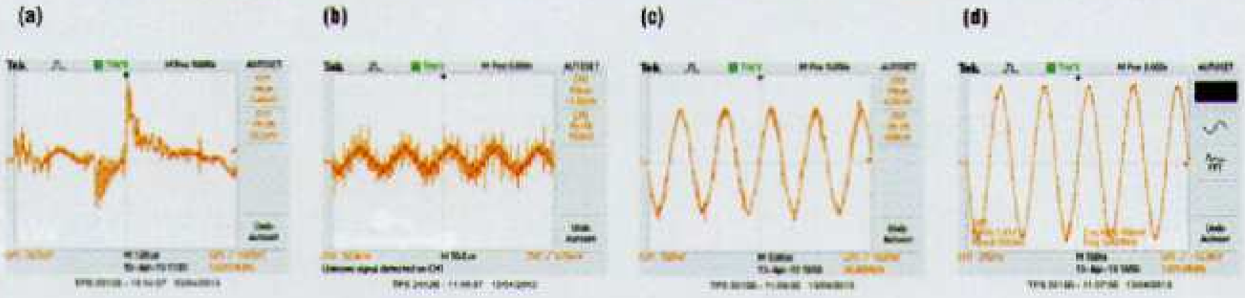


Figure 5: (a) Voltage across the victim wire for 1kHz; (b) Voltage across the victim wire for 10kHz; (c) Voltage at the terminals of the victim wire for 100kHz; (d) Voltage across the victim wire for 1MHz

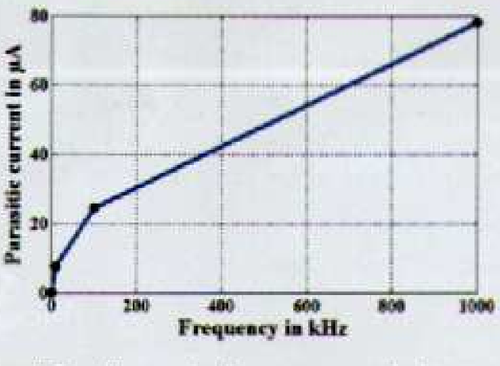


Figure 6: Parasitic current vs frequency source of noise

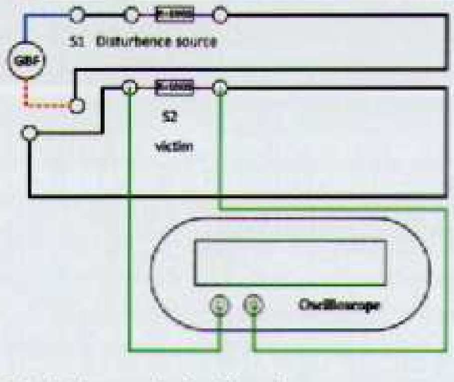


Figure 7: Inductive coupling test-board

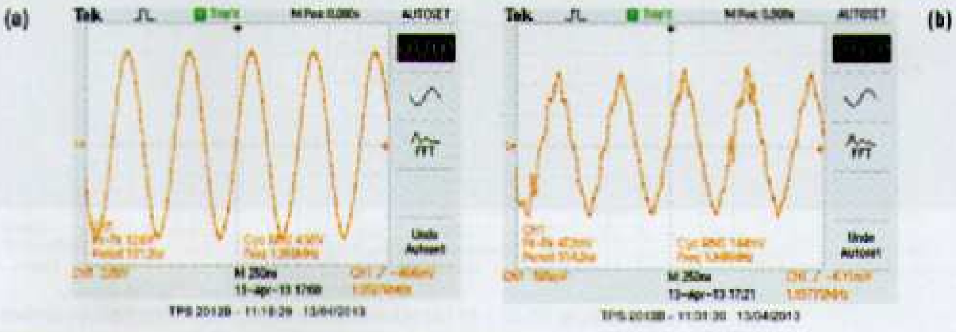


Figure 8: (a) Input voltage applied to the first loop Ve = 12.6V (peak-to-peak); (b) Induced voltage in the second loop Vi = 472mV (peak-to-peak)

$$\underline{V_i} = j.2.\pi.fB.S.\cos(\theta) \qquad (9)$$

We assume that θ = 0; so, factors that can reduce the inductive coupling are: magnetic field B, surface of the loop S and the frequency f of the disturbing signal.

As shielding we use 5mm-thick aluminium plate to reduce the magnetic field B, as shown in Figure 9. The use of an aluminium plate as a shield reduces the inductive crosstalk to a value of 186mV (peak to peak). Experimentally, to eliminate the parasitic effect of the inductive coupling we must choose the thickness of shielding depending on the intensity of the magnetic field.

One of the parameters in Equation 9 is the surface of the receiving loop, which we have to reduce to minimize the interference. The model we made (Figure 10a) has two circuits, equivalent to two loops of different surfaces, the first one being $S_1 = 322\text{cm}^2$ and the second surface $S_2 = 451\text{cm}^2$. According to the two previous curves, we can see that the induced voltage $V_i = 368\text{mV}$ of S_1 is smaller than that of loop S_2 ($V_i' = 472\text{mV}$).

Frequency is the most important factor in EMC. As frequency increases all the phenomena of electromagnetic incompatibility appear. If we vary the frequency, the inductive effect appears only above 1MHz; below that the oscilloscope displays only parasitics, as shown in Figures 11a and 11b. ●

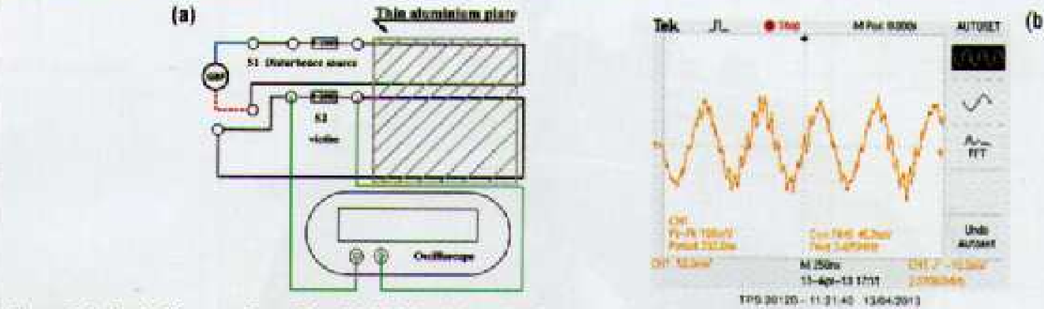


Figure 9: (a) Inductive coupling with a shield (aluminium plate);
(b) Induced voltage with a shield (aluminium plate) Vi = 186mV (peak-to-peak)

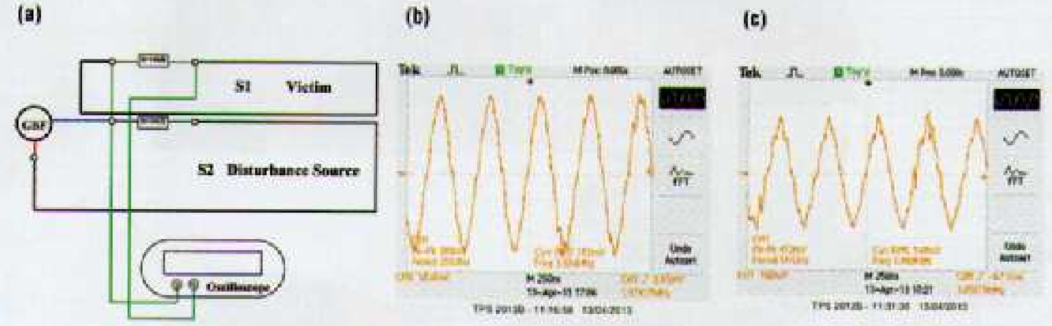


Figure 10: (a) Test board for reduction of surface; (b) Voltage Vi (peak-to-peak) measured on S1;
(c) Voltage Vi' (peak-to-peak) measured on S2

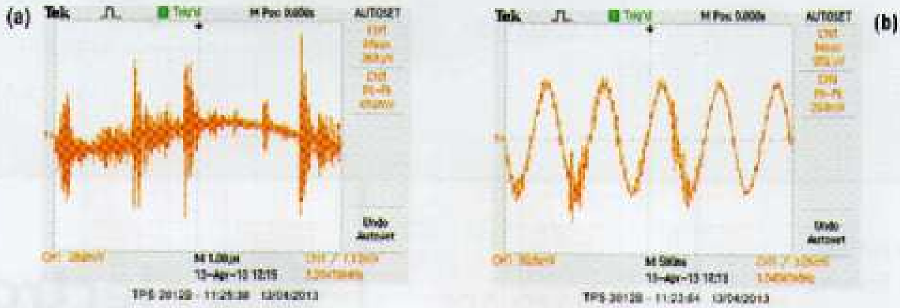


Figure 11: (a) Inductive coupling for f = 100kHz; (b) Inductive coupling for f = 1MHz (Vi = 204mV peak-to-peak)