The Magic Loop – Techniques of using magnetic field loops

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1. Theory

The simplest form of a transformer is a pair of wires placed in close proximity. When a changing current I1 goes through conductor 1, there is voltage induced on conductor 2 (assuming conductor 2 is open circuit). The induced voltage is defined as

$$V_2 = M\, dI_1/dt,$$

where M is the mutual inductance between the two conductors.

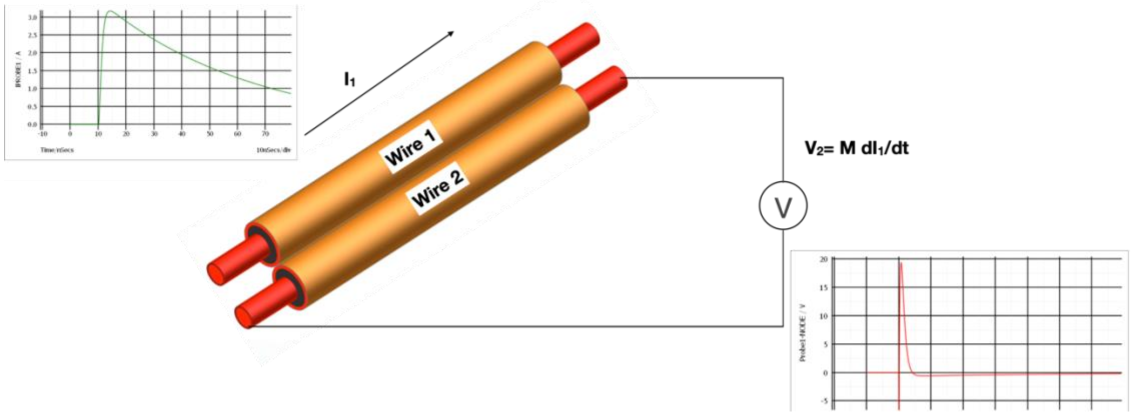


Figure 1Two conductors as a 1:1 transformer

Therefore, a square magnetic field loop shown in Figure 2 is ideal to measure the induced voltage on one side of the loop, which is proportional to the rate of change of flux generated by rapidly changing current in the wire under test. Such a loop is called magnetic field loop, or “H-field loop”. But it is more accurate to be called a “dΦ/dt” loop.

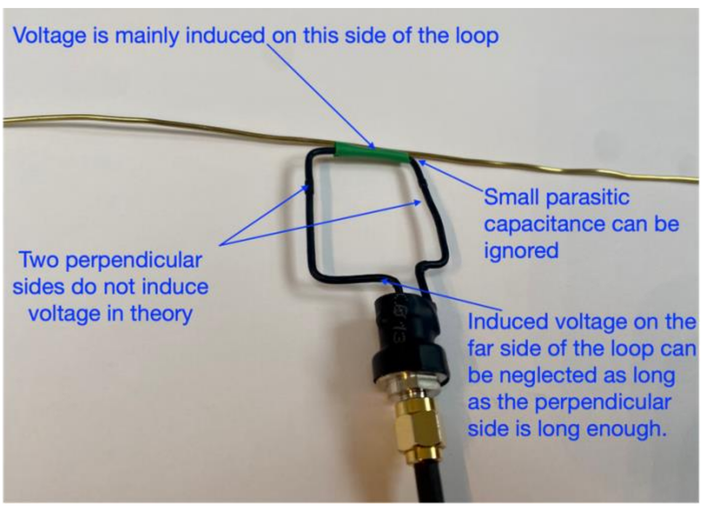


Figure 2 An unshielded square magnetic field loop placed alongside a wire

It is important to emphasize here that the output of the square magnetic field loop is a ***voltage measurement*** (assuming the other end of the coaxial cable is connected to either a spectrum analyzer or an oscilloscope with a 50-ohm impedance).

Since the mutual inductance M is less than the inductance of either conductor, the output of a magnetic field loop is a lower bound for the voltage per unit length across the inductance of a current carrying conductor [1].

Note, a few assumptions are needed to make the sense of a magnetic field loop.

1. The circumference of the loop is significantly less than ½ wavelength at the frequency of interest. This is because the loop could self-resonate. For instance, for a 8 cm long loop, the self-resonant frequency is about 2GHz. This means the loop can be useful up to at least 1 GHz.
2. The opposite side of the loop is far enough away so the induced voltage on the far/opposite side of the loop is neglected (see Figure 2).
3. The perpendicular sides of the loop do not induce voltages (see Figure 2).
4. The parasitic capacitance between the magnetic field loop and the wire is ignored.

According to [1], a magnetic field loop can be modelled as shown in Figure 3. In this case, a 8 cm magnetic field loop is simulated (with circa 2 cm long conductors on each side). The 10 nH inductance value is the mutual inductance M. The 70 nH is the self-inductance of the loop. The 50 ohm impedance (of either a spectrum analyzer, or an oscilloscope with 50 ohm impedance) forms an L-C filter with the inductance of the loop. This causes the cut-off frequency shown in the frequency response.

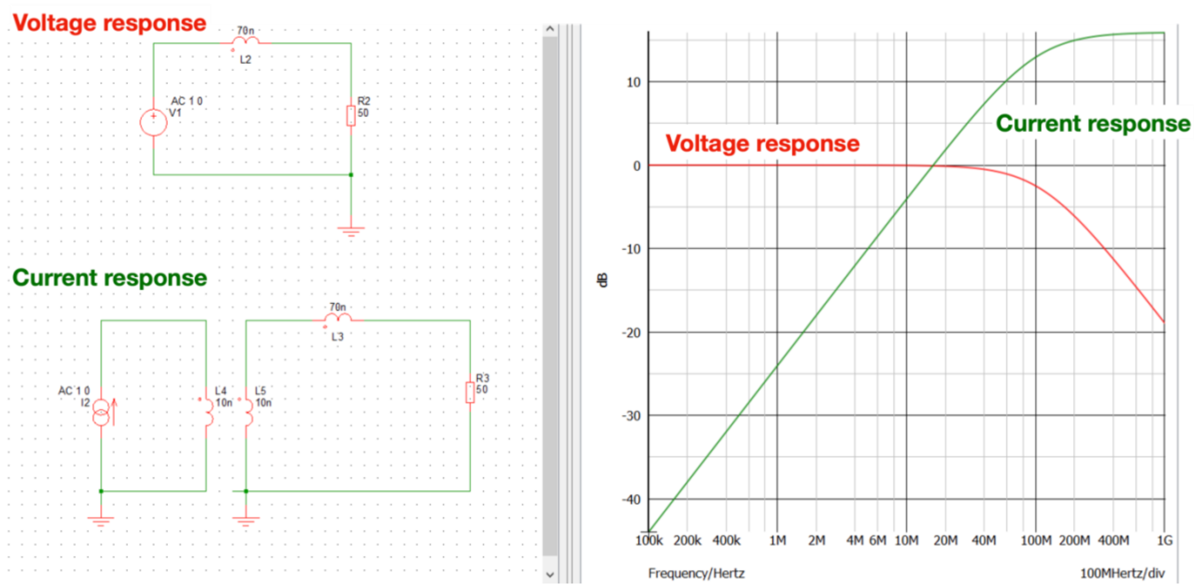


Figure 3 Voltage and current responses of a magnetic field loop

As it can be seen, the voltage response of a magnetic field loop is flat until the cut-off frequency (in this case, around 100 MHz). Above this frequency, the sensitivity of the loop starts to drop at a rate of -20dB/dec. This means the loop is useful for voltage measurement till at least 100 MHz.

The current response of the magnetic field loop (shown in green in Figure 3) means that a magnetic field loop can be used to measure (or to put it more precisely, estimate) high frequency current (whose frequency contents extend beyond the cut off frequency of the magnetic field loop). However, in general, this is not a preferred approach. This is because the mutual and self inductance of a loop is difficult to quantify (really depends on the loop construction and how one places the loop on the PCB, or next to a wire). Thus, the transfer impedance (the ratio between measured voltage to the current) of a magnetic field loop is almost impossible to calculate.

2. Types and Constructions

Round shape or square shape?

The shapes of a magnetic field loop don't matter that much. However, it is highly recommended that square shaped magnetic field loops should be used for EMC troubleshooting purposes. The reason is simple, as demonstrated in Figure 4, square shaped magnetic field loops have the advantages of being easy to couple to the subject under test. The mutual inductance of a square shaped loop is also relatively easier to quantify compared with that of a round shaped loop.

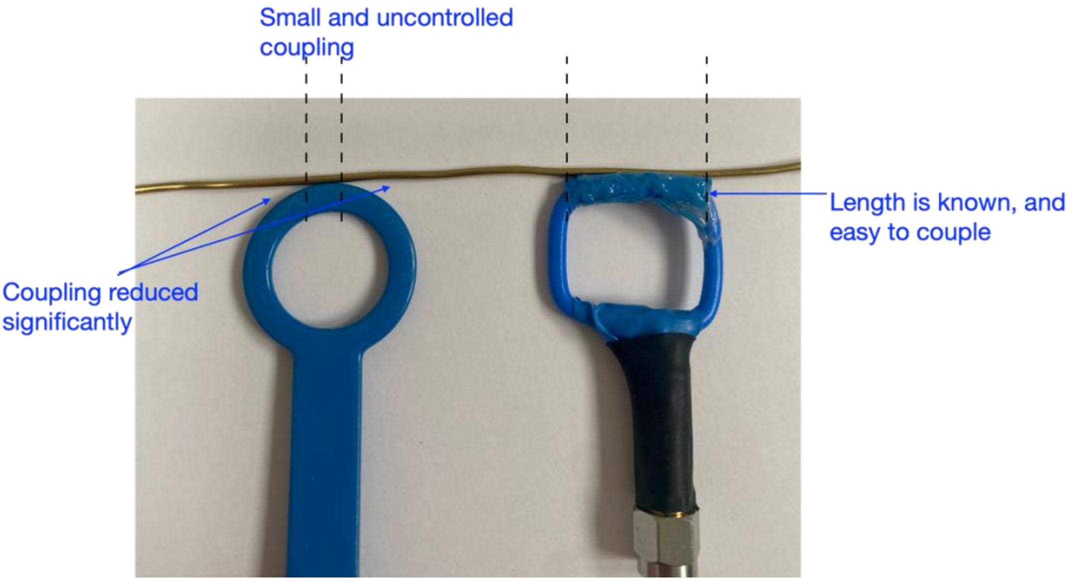


Figure 4 Square shaped vs round shaped magnetic field loop

Shielded or unshielded?

The debate of shielded or unshielded magnetic field loops can be found in [2]. According to [2], unshielded loops work well as the shielded types in most applications. They are widely used for noise injection purposes during the pre-compliance immunity test.

Construction of a simple unshielded magnetic field loop and instructions of making shielded types can be found in [2]. Compared with unshielded loops, making a shielded loop takes much longer time and cost more. The trick of making shielded magnetic field loops depend on the semi-rigid coaxial cable. The best cables for making shielded magnetic field loops are

1. Mini-circuits Hand-flex Interconnect, 0.086’’ centre diameter coaxial cables for making a 8 cm magnetic field loop.
2. Mini-circuits Hand-flex Interconnect, 0.047’’ centre diameter coaxial cable for making a 4 cm magnetic field loop. A larger diameter such as the 0.086’’ cable cannot be bent to form a small loop such as the 4 cm loop.

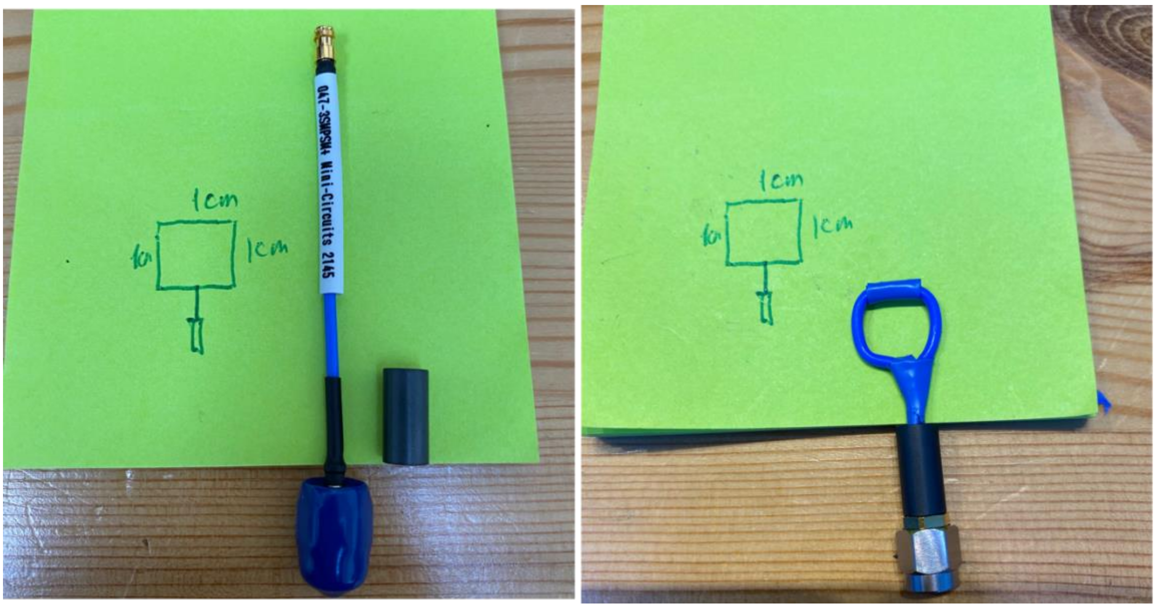


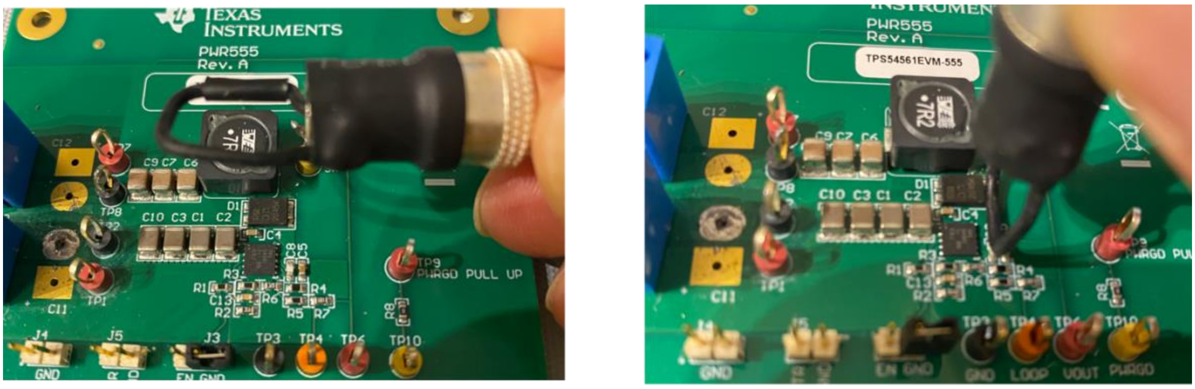
Figure 5 Using a mini-circuits hand-flex coaxial cable to make a 4 cm shieled magnetic field loop

3. Measurement

Positioning

There are two ways of positioning a magnetic field loop over a PCB. When positioned horizontally to the PCB (shown in Figure 6 (a)), a magnetic field loop picks up the changing magnetic field using the whole loop area. This is what the EMC engineers called “sniffing”. The purpose is to identify the “hot” area (maximum changing magnetic field area) on the PCB. The magnetic field loop can be connected either to a spectrum analyzer or an oscilloscope with 50 ohm impedance. The “hot” area is identified when the results on the scope/spectrum analyzer shows maximum values during the “sniffing” exercise.

When positioned perpendicularly to the PCB (shown in Figure 6 (b)), a magnetic field loop is used to measure the induced voltage on a particular trace/track on the PCB. The reason that the loop needs to be placed perpendicularly is to minimize the induced voltage on the side wires of the loop. In this case, the magnetic field loop should be connected to a high bandwidth oscilloscope as the measurement is in the time domain.



(a) (b)

Figure 6 Positioning of a magnetic field loop over a PCB (a) horizontal position to "sniff" (b) perpendicular position to measure induced voltage on a trace

Demonstrations

For a typical buck converter, the current waveforms of the switch side and the load side are shown in Figure 7. Both the switch node and the "hot loop" area are shown. A Texas Instrument buck EVM board is used for demonstration purposes.

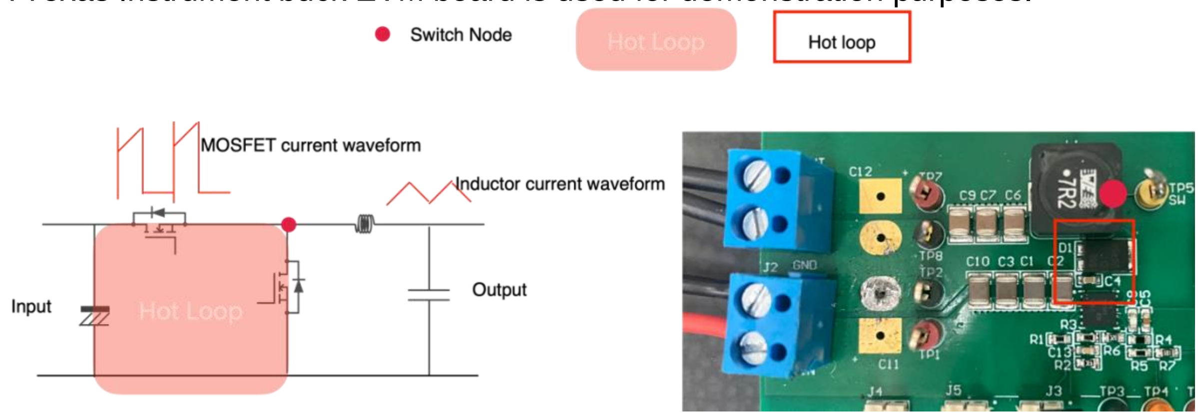
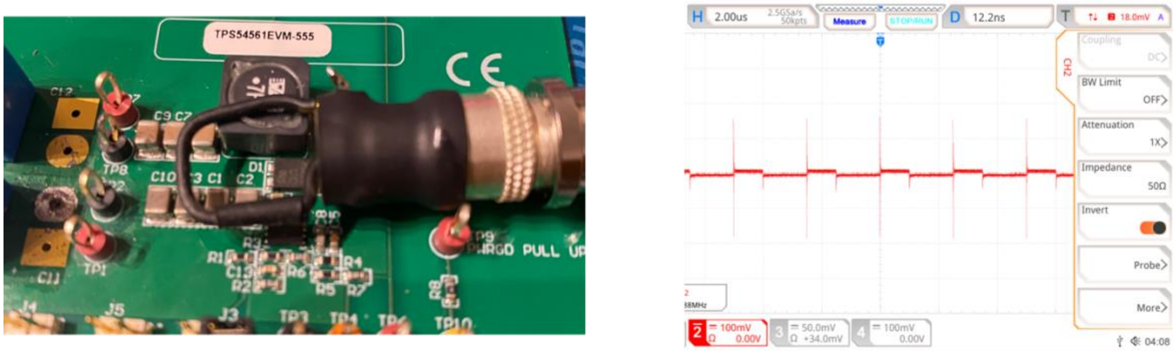


Figure 7 The "hot loop" area in a buck converter

Moving a magnetic field loop horizontally over the PCB, one can easily identify the "hot loop" area. In Figure 8, the induced peak to peak voltage reached 300 mV for a small magnetic field loop, indicating a sharp rise time during the hard switching events. If one were to integrate the result, a current waveform similar to that is shown in Figure 7 (the MOSFET current waveform) can be arrived at. Remember, the magnetic field loop outputs a voltage reading (V=Mdi/dt). To get the current waveform, one need to do an integration.

$$I = 1/M \cdot \int V dt$$



(a) a magnetic field loop is placed over the "hot loop" area (b) Results shown in the oscilloscope

Figure 8 Placing a magnetic field loop horizontally over the PCB and move along the loop until the maximum induced voltage is seen in the oscilloscope

Similarly, when placing the loop over the inductor, a smooth voltage waveform is seen as shown in Figure 9. Using the integration function in the oscilloscope, one can calculate the inductor current waveform (shown in green triangular waveform in Figure 9).

Figure 9 Placing the loop over the inductor gives the induced voltage caused by current going through the inductor. The integration of the waveform gives the inductor current waveform

After the "hot loop" area is identified, the next step is to place the magnetic field loop perpendicularly to the PCB and move it slowly across the suspicious area. Note down areas where large voltage spikes are seen during the exercise. Because the area on the PCB is rather small, a smaller size shielded loop is used instead. A few areas on the PCB were probed, all showed similar induced voltage level as shown in Figure 10.

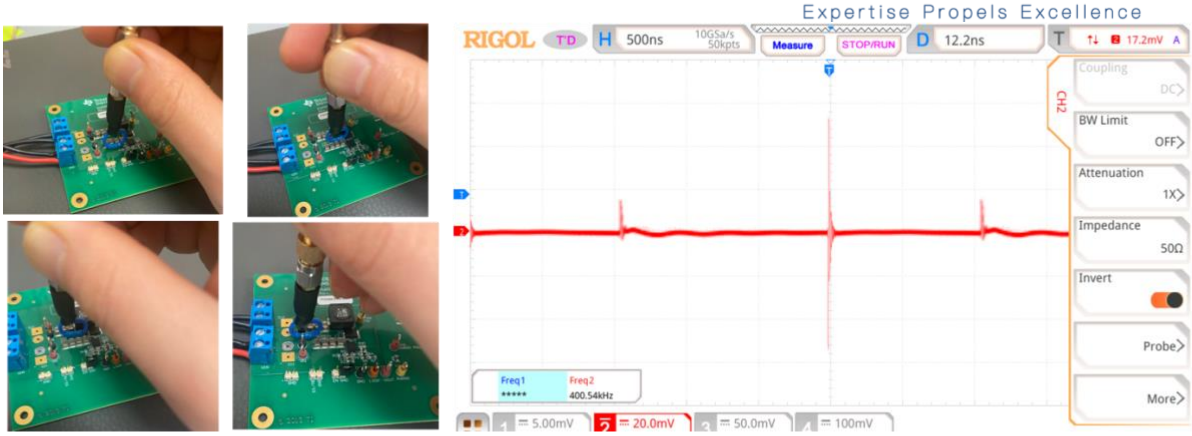


Figure 10 Use a smaller size loop and place it perpendicularly on the PCB, traces/tracks where large di/dt can thus be measured, the result is shown here.

4. Can we predict the EMI results based on this technique?

This is basically asking if there is any correlation between the near-field measurement and far field measurement result. And the answer is no. Any attempt to use the near field measurement to predict far field performance would lead to either under-estimation or over-estimation. Thus the proposed technique in this article is most suited for a few scenarios listed below:

a. If a product/system is known to have failed EMC test, using a magnetic field loop can quickly help locate the noise source and propagation mechanism.
b. If a probe is well calibrated, then using the loop ***might*** give you a Pass/Fail indication.

But how to calibrate a homemade magnetic field loop? Since each loop is made differently in size. For shielded magnetic field loops, the diameter of the coaxial also plays a role in affecting the mutual inductance. Many factors could affect the reading of a magnetic field loop. Therefore, the loop method result should only be treated as a qualitative indicator.

One method the author often uses is to test the loop on a known product. For instance, both the conducted and radiated emission test results of the EVM board in this study were known to the author. Therefore, for products that need to pass the automotive EMI test standards such as those defined in CISPR 25, any induced voltage over 100 mV on a small magnetic field loop certainly will raise a red flag. If the product is a home appliance product, then even 200mV induced on the same loop will most likely be okay.

References

[1] D. C. Smith, High Frequency Measurements and Noise in Electronic Circuits, New York: Van Nostrand Reinhold, 1993.
[2] Doug Smith, Arturo Mediano, "Shielded vs unshielded square magnetic field loops for EMI/ESD Design and Troubleshooting," InCompliance Magazine, vol. July, no. July, 2014.

Training

If you want to learn more about EMC and become an expert in troubleshooting EMI problems. Why not attend our video course? Priced from $199, you can get 10 hour lessons. Check https://mach1design-shop.fedevel.education/itemDetail.html?itemtype=course&dbid=1644339825702&instrid=us-east-2_4pKkzzNo1:fe56227a-47c8-4ea8-ba6f-2930d01d7db8