Another EMC resource
from EMC Standards

A cable can be an effective Antenna, so you add Ferrite

Helping you solve your EMC problems

1 Brassey Road, Old Potts Way, Shrewsbury, SY3 7FA T:+44 (0) 1785 660 247 E:info@emcstandards.co.uk

A CABLE CAN BE AN EFFECTIVE ANTENNA – SO YOU ADD FERRITE

R. C. Marshall
Richard Marshall Limited, UK E-mail: richard.marshall@iee.org

Abstract: This paper examines the similarities between a transmitting antenna – an intentional radiator of electromagnetic energy – and a connecting cable – which to some extent will be an unintentional radiator. The form and function of ferrite common-mode chokes are then described and the importance of <u>not</u> locating them at current nodes is explained. Ferrite choke design principles are given together with examples and a design checklist.

I. THE TRANSMITTING ANTENNA ANALOGY

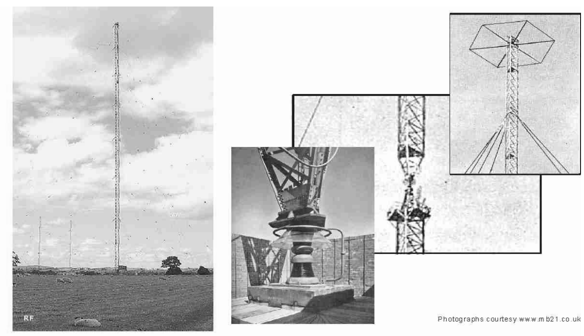


Fig. 1: A long/medium wave broadcast antenna

A low-frequency transmitter tower does not *support* a wire antenna: The tower itself is the antenna conductor. The antenna is dimensioned to be an electrical quarter-wavelength long so that energy may most effectively be delivered to it at the lower end which stands on an insulator as shown in the lower inset picture of figure 1. The low-potential transmitter terminal is connected to an earth mat extending from this point.

To achieve the necessary electrical length the mast is often loaded by an inductor across an insulated neck part-way up, as illustrated in the middle inset picture. For the same reason a "hat" of rods and wires may provide capacitive loading at the top of the mast as may be seen in the right-hand insert.

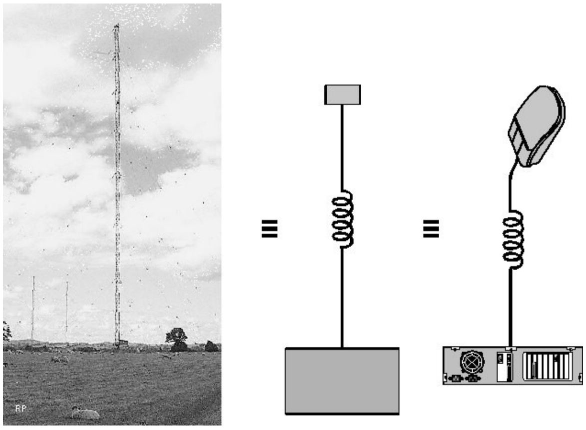


Fig. 2: A computer mouse and its cabling

In figure 2 the antenna is translated into its equivalent circuit so that this may be seen to be similar to that of a computer mouse plugged in to its computer. The mouse itself is the "top hat", the curly cable is the tower with its inductive loading, and the conductive material of the computer provides the earth mat. Only physical size and current flow are different.

The mouse cable is perhaps one-hundredth of the length of the transmitting antenna, so its most effective frequency of radiation is about one hundred times higher: 100 MHz instead of 1MHz.

II. COMMON-MODE CURRENT

A tower is a single conductor and there is no ambiguity when we talk about current flow. However, for shielded and multi-core cables we have to distinguish between the flow of differential-mode current – which is the functional current that carries power or information and which is the prime concern of the equipment designer – and the flow of common-mode current – which generally occurs by design mistake or negligence and is the prime concern of the EMC engineer. Figure 2 (next page) compares the voltages which drive these currents in the simplest case – that of a single-core coaxial cable. It will be seen that the common mode current returns via the ground connection, enclosing a large area. In the particular case of a well-shielded cable eddy-current considerations force this current to flow along the outside of the cable shield.

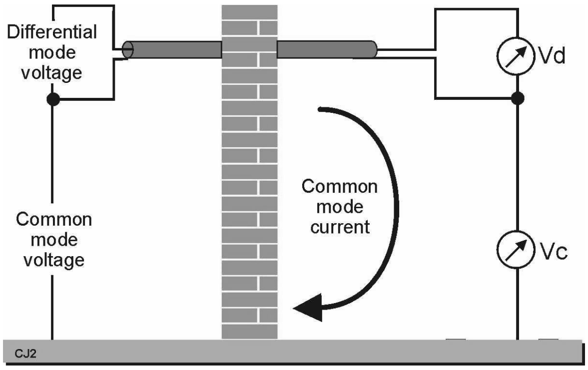


Fig. 3: Differential-mode and common-mode voltage on a coaxial cable

Common-mode current flow can arise by many mechanisms – capacitance from live parts of apparatus to ground, unbalance within cables or connectors and excitation of current loops formed by multiple cables serving a single apparatus to name but a few – and it is the common-mode current in the mouse cable that validates the comparison with the transmitting antenna in figure 2.

In this paper we are concerned with the reduction of common-mode current by adding common-mode impedance in series with the cable concerned. It is fortunate that it is possible to do this by using a core of ferrite material external to the cable, and it is even more fortunate that to do so has no effect upon the differential-mode currents flowing *within* the cable.

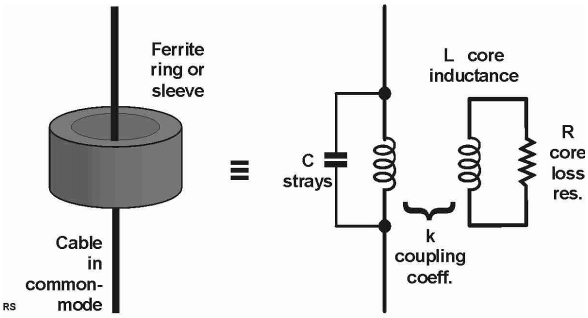


Fig. 4: The equivalent circuit of a ferrite common-mode choke

Manganese-Zinc and Nickel-Zinc ferrites are commonly used. The equivalent circuit of a ferrite common-mode choke is shown in figure 4. At the frequencies of importance to EMI suppression (above a few Megahertz) the resistive losses of these ferrites swamp their inductive impedance – so that they damp circuit resonance as will be described below rather than provide inductive loading that would merely lower the antenna resonance. When a ferrite choke is to be effective at very high frequencies there are two further effects which may limit the choice of core and winding configuration: First, the stray capacitance between the cable entering and leaving the core leads to a preference for using a single "turn" of cable passing straight through a ferrite tube. Second, the possible de-coupling of the ferrite by leakage inductance between the cable and the core argues for a tight fit here.

III. POSITIONING FERRITE CHOKES

An antenna is most effective when it is resonant – that is when the radio-frequency current returns *in phase* upon reflection from either end to add to the effect of the original current. In the case of a practical *quarter-wave* antenna tower this reflection leads to the current distribution shown in the diagram in the middle of figure 5.

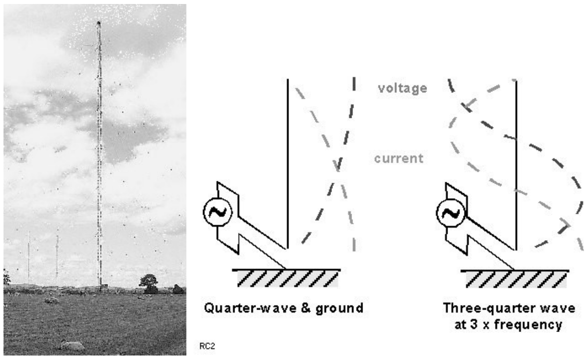


Fig.5: Resonance with one free end

It is easy to see that the current must be zero at the top: From there it has nowhere to go.

As EMC engineers we need to be aware that resonance also occurs at approximately 3, 5, 7….times the basic quarter-wave frequency: The three-quarter wave case is shown at the right hand side of the figure: Once again the current is at a maximum at the bottom and zero at the top but there is now an additional zero-point one third of the way up.

Since a ferrite choke adds a relatively small series resistance it will have the greatest effect where the current is largest. In the case of the above antenna that would be at ground level. It is easy to perform an experiment to demonstrate this in an EMC situation using two identical lengths of coaxial cable plugged into a spectrum analyser with a tracking generator as shown in figure 6.

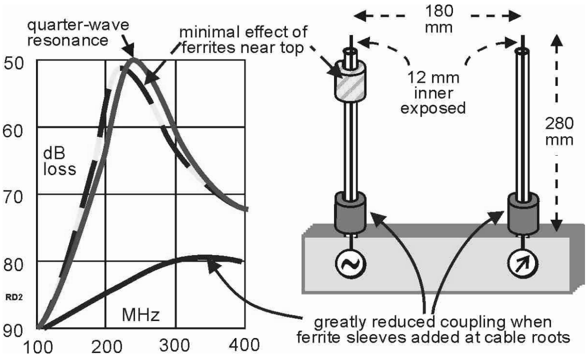
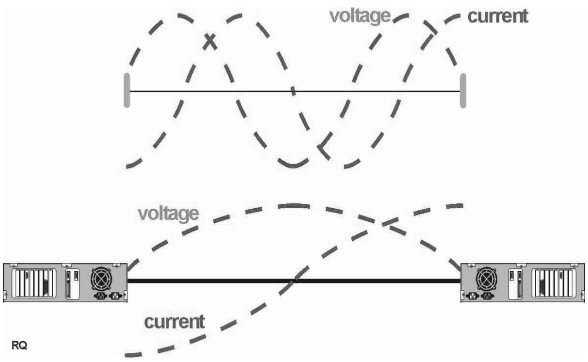


Fig.6: Damping cable resonance

Here the common-mode current injection and detection is provided by the capacitance to ground of the 12mm length of co-axial cable inner exposed at the open end of each cable – a simulation of the first route mentioned earlier. It will be seen that ferrite sleeves at the bottom of each cable reduce coupling by 15dB for each sleeve, whilst sleeves at the top have negligible effect. This illustrates, for example, that it is difficult to improve the medium-wave susceptibility of telephone subscriber instruments by placing ferrite sleeves upon the instrument cable.
More commonly electrical cabling extends between two relatively massive objects both of which may be seen in antenna terms as ground mats. In this case the resonance is that of two antennae as discussed above joined at their tops. The current distribution at the first and third resonances is then as shown in figure 7.



Figs. 7: Some resonances with both ends "grounded"

Resonance occurs when the cable has an electrical length equal to any multiple of a *half* wavelength. At every resonance there is a current maximum at each end, but other maxima occur in various places at the various frequencies. It should be noted that the electrical length of a cable is greater than its physical length because of the dielectric of the cable insulation. In general the only place where we may be sure to find a current maximum at all resonant frequencies is adjacent to a low-impedance connection to a substantial object. Ferrite chokes should be positioned accordingly, and it should be recognised that galvanic isolation (using for example an opto-isolator) may nullify the effect of an adjacent ferrite choke. However, ferrite chokes at specific positions along a cable may be effective at dealing with resonance at a specific frequency such as a data transmission clock frequency.
The treatment of cables within emc test environments is discussed further by Marshall [1], [4].

When cables are in close proximity to other cables, or in ducts or cable trays, the resonance effects discussed above are qualitatively similar although the common-mode characteristic impedance (or voltage/current ratio) will be lower. The radiation efficiency relative to an antenna will be much lower but there will be the strong possibility of energy transfer to other cables.

IV. FERRITE CHOKE DESIGN

A net flow of low-frequency ac or dc through a ferrite choke will result if any circuit in the contained cable has a return path that is not in that cable. This situation should be avoided if at all possible by proper system design since it can lead to saturation of the choke core. Otherwise a gapped core or a core material that does not saturate easily may be required: Either course will increase the size and cost of the choke assembly.

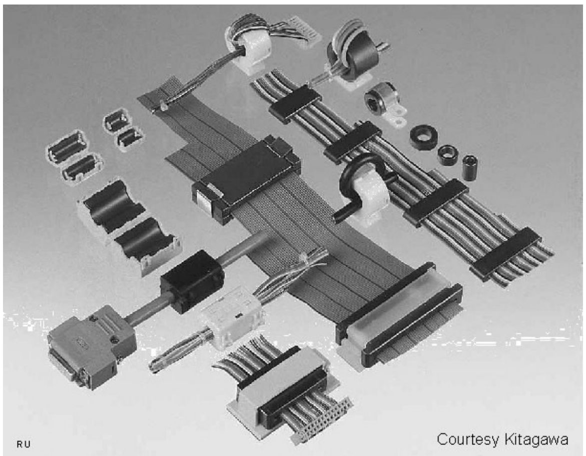


Fig. 8: Examples of ferrite chokes on cables

Figure 8 shows chokes on round and flat cables.
Those towards the bottom left use split cores clipped on to the cables in a manner well suited to retrofit application. The small air gap that results slightly reduces the impedance but can reduce the risk of core saturation by common-mode current. Split cores are relatively long and should only be used with a "single turn" since otherwise the short-circuiting effect of the stray capacitance that was identified in figure 4 will be substantial. The toroids at the top right of figure 8

are more suitable for multi-turn windings.

Even when wound on short fat toroids the effect of stray capacitance of multi-turn windings is sufficient to nullify the advantage of the increased turns at high frequencies: Figure 9 shows the impedance-frequency characteristic of a typical ferrite choke: The frequency of greatest impedance corresponds to the resonance of the winding inductance with the stray capacitance. As one should expect from theory a 3-turn winding has nine times the impedance of a single turn at low frequencies. However this advantage is progressively lost above 100MHz and above 400MHz the impedance is actually lower than that of a single turn.

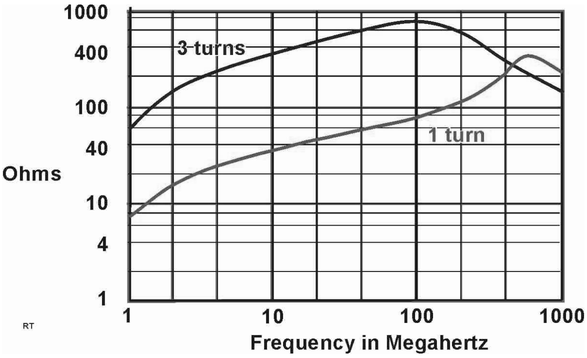


Fig. 9: Impedance of single-turn and 3-turn windings

This stray capacitance may be minimised by keeping apart the ends of the winding by use of the "Supertoroid" winding layout described by Gross [2].

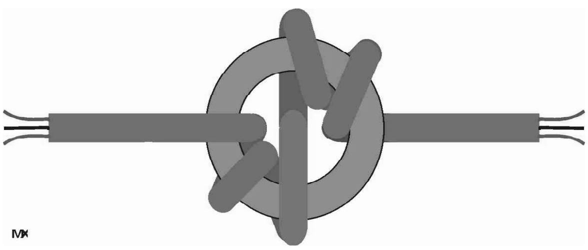


Fig. 10: The supertoroid

The winding crosses the the centre hole near the middle turn as shown in figure 10. This causes most of the stray capacitance to fall across just half of the winding.

The following example of a composite ferrite choke assembly forms part of an instrument product that has been described in more detail by Marshall [3]. However it does illustrate most of the techniques described above and so is shown below in figure 11. It acts as a wideband common-mode choke on a cable comprising 4 conductors rated at 50amps each and 5 conductors rated at 6amps.

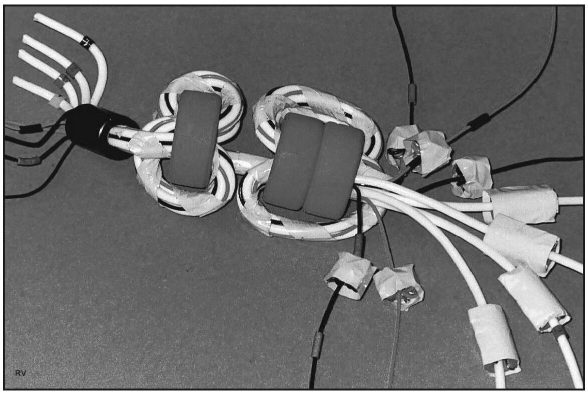


Fig. 11: A composite wide-band high-power ferrite choke

In the top left hand corner is a long sleeve choke to provide UHF isolation with very low stray capacitance. The desired low-frequency performance required windings on three large toroids. To ensure that the parallel resonances in the windings of these toroids are well separated yet at the highest possible frequencies the cores are deployed as a single core with a 4 turn supertoroid winding and a double core with a 4 turn winding (The latter is in the centre of the figure). Use of an even number of turns forces the crossing point of the winding to be unsymmetrically placed, ensuring different resonant frequencies for each portion of each winding.

The components described above do not have to tolerate any net current flow. However there are also smaller chokes to the right of the figure that are fitted to individual cores of the cable and so must tolerate the magnetising effect of the rated current without reaching magnetic saturation. These use a different grade of ferrite in the form of multi-turn toroids on the 6 amp wires. For the 50amp wires the risk of saturation dictates the use of the single-turn sleeve devices that may be seen on the white wires.

V. CONCLUSION

The ferrite common-mode choke is a valuable aid to electromagnetic compatibility. Its successful application should take account of the design considerations set out on the next page.

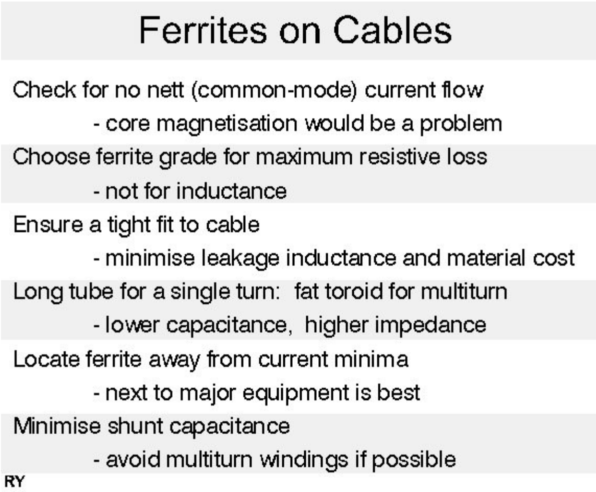


Fig. 12: Ferrite choke design checklist

VI. REFERENCES

[1] Marshall R C, 2002, *“Equipment Cabling and EMC Testing”,* EMC Compliance Journal, May 2002 pp28-34.

[2] Gross T A O, 1976, “Super toroids with zero external field made from regressive windings”,Electronic Design, September 1st 1976

[3] Marshall R C, 2003, *“Reducing errors due to resonances in radiated and conducted EMC testing”,* Paper 4F1, Industrial Forum, Zurich EMC Symposium, February 2003

[4] Marshall R C, 2003, *“Cable resonance in EMC test chambers”,* EMC – it’s nearly all about the cabling: IEE Colloquium, London, 22nd January 2003

An earlier version of this paper appeared in the digest for "EMC- it's nearly all about cabling" Copyright 2003: The Institution of Electrical Engineers.