Broadband Transformers in HF Antenna Systems

by R H Pearson G4FHU

Introduction

Transformers wirewound on suitable ferrite or powdered iron ring cores are easy to make, and can give excellent service in HF antenna systems, but sometimes disappoint or even fail completely when insufficient attention is paid to their operating conditions, and the type of winding and magnetic core employed. Part 1 concerns impedances, voltages and currents in antenna systems. Part 2 explores transformer principles and Part 3 the properties of magnetic cores and Part 4 shows a simple practical transformer and some conclusions..

1.1 Antenna impedance

Most ordinary power transformers are designed for and used in well defined conditions of voltage and frequency. Those used in amateur radio HF antenna transmitting systems are usually required to operate over a remarkably wide frequency range and are often subjected to extremely variable, onerous and uncertain load impedances.

When a transformer is placed somewhere in line between a transmitter and an antenna, it can be difficult to predict and awkward to measure the operating conditions that the transformer will experience. For example, suppose it is used at the junction between a feeder and a dipole and that the operation is always restricted to the 80m HF band. The impedance of a typical dipole designed for that band is likely to be somewhat similar to that shown in Fig 1. This is very much like that of a "lumped" LCR series tuned circuit, having a purely resistive impedance at the frequency of resonance, and a significant reactance over most of the band. The dipole may be visualised as a kind of tuned circuit but with multiple resonances. Its inductance, capacitance and resistance are "distributed" i.e. spread out in space, so much so that most of the applied power is radiated and only a small proportion is wasted as local heating. A significant and inconvenient feature is that the reactance, though nullified at a frequency of resonance, increases in magnitude very rapidly with even a small change in frequency and as will be shown in detail later, this can greatly increase the demands upon a transformer used in the feed path.

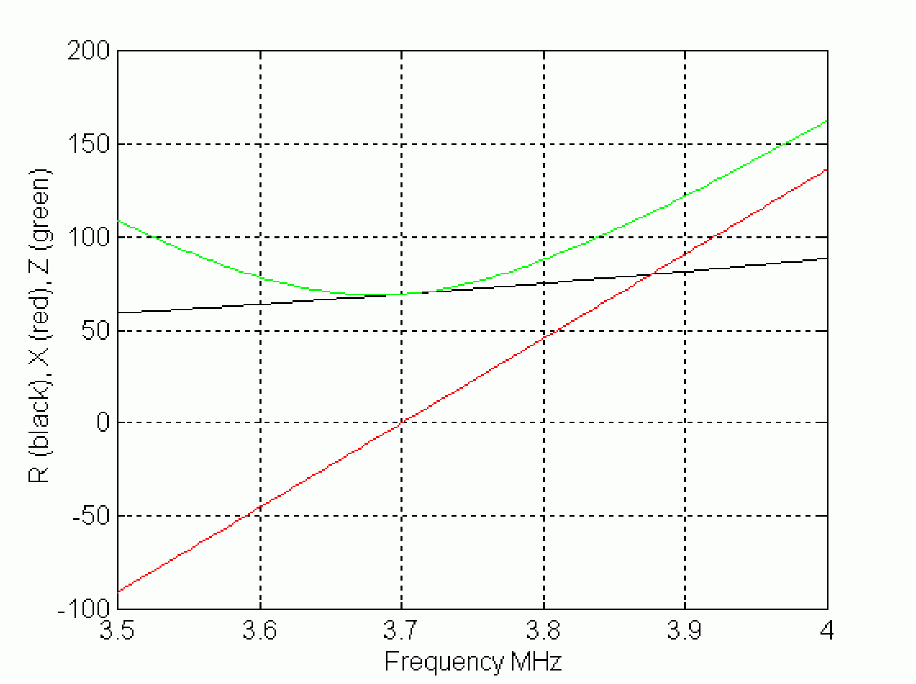
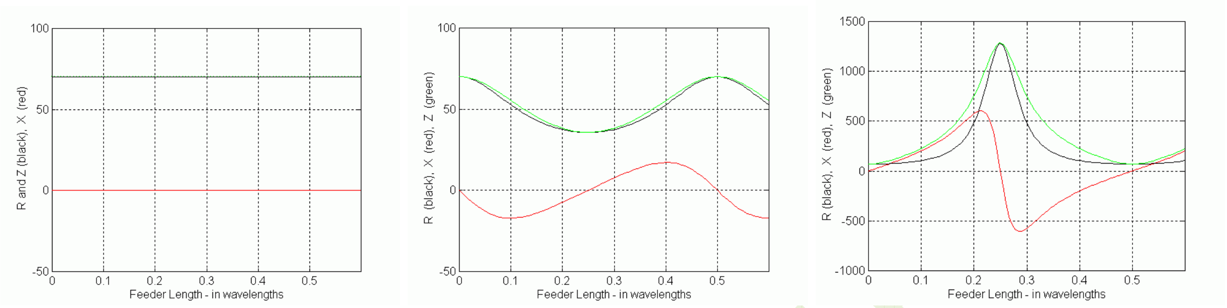


Fig 1 Resistance, Reactance and Impedance of a typical wire dipole around its resonant frequency

1.2 Impedance Transformation by the Feeder Cable

The transmission line used to connect the antenna to the transmitter, the "feeder", behaves as yet another kind of distributed LCR network. The impedance at its input end, another place where one might want to connect a transformer, will often be considerably different from that of the load to which it connects. Indeed, transmission lines themselves are sometimes used quite deliberately as impedance transformers, though they only function satisfactorily in that role, over a very narrow ranges of frequency.



(a) (b) (c)

Fig 2 Impedance at the feed point of an antenna system consisting of a 3.7 MHz 70 Ω dipole operating at resonance, via a cable having Characteristic Impedance Z_0
(a) $Z_0 = 70$ (b) $Z_0 = 50\ \Omega$ (c) $Z_0 = 300\ \Omega$

In some circumstances the feeder will modify the antenna impedance to advantage, but in many others it makes the impedance less convenient as shown in Fig 2.

1.3 Antenna System Tuning Units and Baluns

For the above reasons, most amateur radio antenna systems incorporate an adjustable network of low-loss inductors and capacitors that can be adjusted automatically or manually to achieve the correct impedance transformation at any desired frequency. Ideally, it ensures that the load presented to the transceiver is free of reactance and has the optimum resistance required by the transmitter to enable it to deliver its full normal power.

It tunes the whole system, including itself, and so may be called an "Antenna System Tuning Unit", but this is usually contracted to "ATU" despite that fact that it does not tune the antenna alone. Some prefer to use the term "Matching Unit" or "Impedance Matching Unit", but the word "Matching" can trigger what has from time to time proved a rather unprofitable and sometimes heated controversy that is best avoided here!

Quite often the antenna is nominally a balanced structure in respect of impedance, i.e. it has equal impedances between each terminal and earth, or impedances are so high as to have negligible effects, in which case it is said to be "Floating". When an unbalanced feeder, such as a coaxial cable, is used with a balanced antenna, a special kind of transformer called a "balun", i.e. a balance to unbalance transformer, is sometimes used at the junction, so that the balanced impedance condition of the antenna is not disturbed. The advantages include less risk of feedback down the feeder sending RF power into the operating room, less received interference from nearby sources, and less disturbance to the anticipated radiation polar diagram of the antenna, caused by the feeder.

A good alternative is to use a balanced feeder and to shift the balance/unbalance connection problem to the more accessible operating room end of the system. Transceivers are almost always arranged with unbalanced output terminals, with one side maintained at Earth potential for safety reasons when connected to the main electricity supply. Many commercial ATUs have unbalanced ports at both ends, in which case a broadband balun will best be located between the ATU and a balanced feeder.

One splendid type of ATU though old as the hills is still favoured by experienced constructors and operators. Often called a "Link Coupler", it uses an input winding coupled via mutual inductance to a tuned winding at the output end which serves both as part of the reactance network, and as a voltage balun if so arranged. When driving a balanced feeder this completely avoids the need for a broadband type of balun, and being part of the adjustable network does not suffer at all from being a narrow frequency band device; indeed it confers useful extra selectivity on both transmission and reception. Although it has gradually disappeared from books and magazines over the last 30 years or so, it recently appeared again in an interesting RadCom article by Peter Dodds [1].

Another possibility is to use an ATU that is a balanced circuit at both input and output. Then a balun interposed between the transceiver and the ATU will always be loaded by a well adjusted and convenient impedance that enables it to work well with modest and predictable requirements. This is an ideal arrangement for a QRP station but rarely seen in higher power systems owing to the need for some extra precautions in the layout and controls of the ATU to ensure that no high voltages become accessible outside the box.

1.4 The importance of load reactance

It is sometimes thought that there is some inherent reason why a wirewound transformer will not work properly when feeding a reactive load. That is not really so but reactive loads can indeed be the cause of a transformer operating problem for related reasons that will now be explained more precisely.

In most domestic power circuits, the supply voltage V is pretty constant, so that adding some series reactance X to a load resistance R will not only increase the load impedance $Z = \sqrt{R^2 + X^2}$ but will also reduce the load current I = V/Z. But in an antenna system the ATU is used deliberately to override this limitation by cancelling the reactance and adjusting the effective resistance so that full power is transmitted *throughout the whole system* and is therefore applied to any and all transformers in that system.

We can calculate exactly what will happen at any point in the system where a power P is passing via an effective resistance R in series with a reactance X, (though alas in real life, we are most unlikely to *know* those figures).

Since $P = I^2R$, the current $I = \sqrt{\frac{P}{R}}$ so that the voltage will be:

$$V = IZ = \sqrt{\left(P/_R\right)\left(R^2 + X^2\right)} = \sqrt{PR\left(1 + \left(X/_R\right)^2\right)}$$

This expression is plotted in Fig 3 as a contour map, showing how the RMS maximum voltage V depends upon both R and X when transmitting a power of 100 W_{PEP}. For a power of 400 W_{PEP} double the voltages shown.

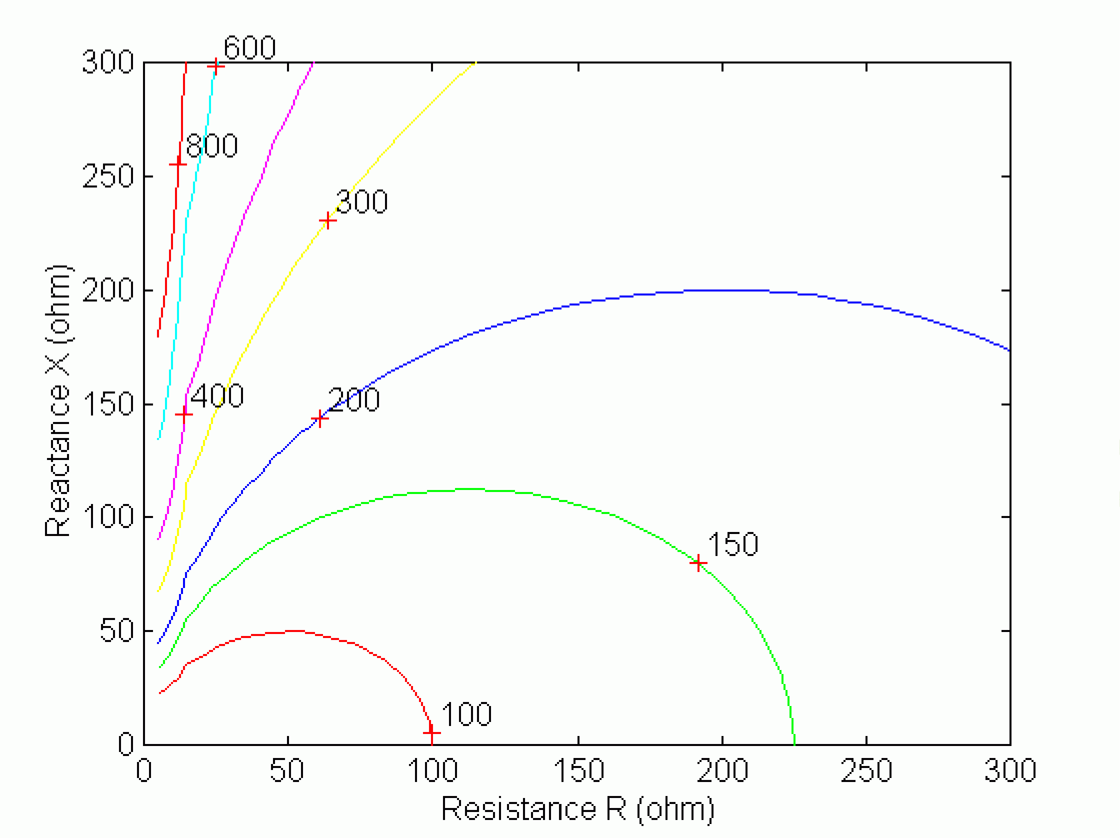


Fig 3 V_{RMS} that can arise in parts of an antenna system carrying 100 W

To put this into a practical perspective, bear in mind that when feeding a 50 Ω resistive load, a 100 W_{PEP} transmitter has an output voltage of 70.7 V_{RMS} and a 400W_{PEP} one 141.4 V_{RMS}. As can be seen in Fig 3, a load consisting of an abnormally low resistance and high reactance can result in a remarkably high voltage that will arise just as the tuning operation succeeds in producing the desired impedance transformation to suit the transmitter.

2.1 Broadband Transmission-Line Transformers (TLTs)

To make a wirewound transformer that works at high frequencies it is necessary to try to make every turn of every winding link with the exactly same magnetic flux. Inadequacy in this respect is equivalent to putting inductance (so called "leakage inductance") in series with the output. This is why such transformers almost always use identical windings wound in multi-wire groups.

Ways of analysing the HF behaviour have been devised by regarding the windings as transmission lines and using the standard transmission line equations to obtain accurate predictions. Though many articles and books have been published on this rather specialised subject, anyone deeply interested in TLTs can do no better than begin by reading the most frequently quoted original papers; by Ruthroff [2] and Guanella [3]. Though more formally presented than later interpretations, they are "The Real McCoy" and reliable guides when encountering doubt or confusion. They show how to combine the properties of an ordinary transformer with those of a transmission line, to produce an impedance transformer that works satisfactorily over a far wider range of frequency than either a conventional transformer or a transmission line alone could achieve.

Controversy sometimes arises in amateur radio circles, caused perhaps by over-simplified accounts of what is to be found in these seminal publications. Though it is true that the low frequency

response of a TLT is maintained by ordinary transformer action, and the high frequency response by transmission line action, it is simply untrue to say that the magnetic core is unimportant for high frequency signals. That misconception has encouraged countless radio amateurs to attempt the construction of TLTs using ring cores that are unsuitable for high frequency usage owing to inadequate permeability and/or excessive power loss at HF.
It may be that vital details of diagrams in the original papers are sometimes overlooked. For example, in Ruthroff's paper, his Figure 15 (reproduced as Fig 4 here), contains an easily overlooked condition warning that the reactance of the windings is assumed to be much larger than the load or source resistances, and in Guanella's paper Figures 1(a & b), (Figure 5 here), the crucial inductive effect of the magnetic core is shown as an additional part (B) of the circuit diagram.

If one uses circuit simulation software (such as "SPICE") to aid design work it is vital to add appropriate inductances to the circuit net list to avoid becoming seriously misled.

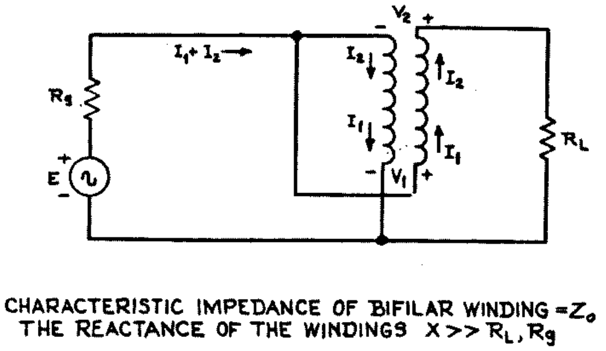


Fig 4 One of Ruthroff's TLTs

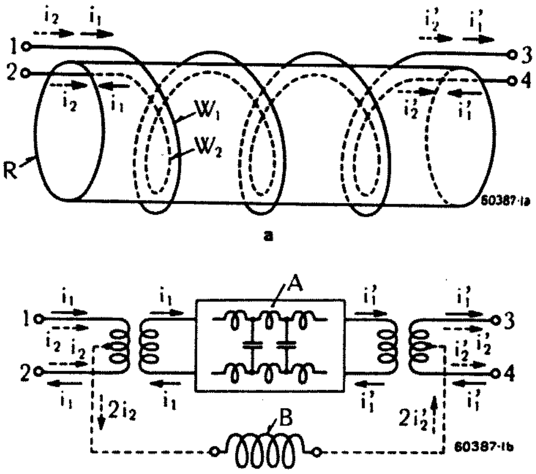


Fig 5 One of Guanella's TLTs and its equivalent circuit

Another very important factor is that in those early papers and in many recent ones, all the theory and all the practical tests assume that the source and load impedances are perfectly resistive and of a carefully calculated magnitude. In the simple Ruthroff example shown above, the design and analysis assumes that the signal source is a pure resistance Rg, the load is a resistance R_L= 4Rg and that the winding is a transmission line with a characteristic impedance Z_0 = 2Rg. Such circumstances rarely exist in an amateur radio station antenna system.

2.2 Transformer windings: number of turns

When designing an ordinary 50 or 60 Hz power transformer, one can usually specify its operating conditions very precisely in terms of supply voltage and maximum current. Inescapable in the design process for any transformer primary winding (or indeed any inductor used in an AC. circuit) is what is often called "The Transformer Equation". It states in modern terms and relating to AC circuits, precisely what Michael Faraday so famously discovered; the relationship between an induced alternating voltage and rate of change of a magnetic flux linking a winding.

$$V_{RMS} = 4.44\ f\ B_{MAX}\, A\ N$$

In this relationship,

V is the voltage applied to the primary winding, or induced in a secondary winding,
f is the frequency (hertz, Hz),

B_{MAX} is the peak magnetic flux density in the core (tesla, T),
A is the cross sectional area of the core (square metres, m^2),
N is the number of turns of the winding.

Thus the minimum number of turns required is $$N = \frac{V_{MAX}}{4.44\ A\ f\ B_{MAX}}$$

The most important thing to know about a transformer is that if you apply a voltage to a winding then the peak magnetic flux $\Phi_{MAX} = A\ B_{MAX}$ (weber, Wb) will have to satisfy that equation *whatever the core, or even if there is no core* ! Of course in extreme situations (such as an absent core), the consequence may well be such an enormous current that a fuse or circuit breaker or a wire, will interrupt the supply and V will not be maintained.

2.2 Ratings

A broadband transformer used in an antenna system whether for impedance changing or to serve as a balun, must be able to handle the full transmitter output power at any of a huge range of frequencies. Some transformer configurations necessitate one or more windings being connected directly across the signal path and therefore experience the full applied voltage which then determines the magnetic flux in the core. Others are arranged so that the core remains un-magnetised and with no significant voltage across any winding, except when feeding an unbalanced load impedance. But even these need to be designed so that they work correctly when the load *is* unbalanced and so that they do not fail if subjected accidentally or deliberately to a complete unbalance such that the full voltage is applied to a winding.

If a transformer is placed at a location where the impedance is particularly low, the voltage will be low and the current high. That will affect the gauge of wire needed for the transformer, and the size of core required to allow enough space for the winding. Less obvious, but more important, is that if the impedance is unusually high, the voltage will be high and determine the required combination of magnetic core properties, the number of turns of wire and the rating of wire insulation. This is more demanding than what usually happens in more common systems, such as a domestic electricity supply in which transformers can all be designed for a supply of standard known voltage and frequency such as 230 V 50 Hz.

Therefore, when a transformer is for use in an antenna system, it is not sufficient to give it simply a power rating and a frequency range. An impedance range is also required. Usually that is tacitly assumed to be and very commonly is 50 Ω resistance and zero reactance, as reflected at the input port, and the transformer would be tested under that condition. Connected in a practical antenna system, it will usually be subjected to a very different operating condition that may or may not prove satisfactory. So when buying a transformer, it is usual to choose a power rating considerably greater than the actual power it will normally have to bear.

One sometimes encounters reports of 1:1 current baluns that have demonstrated incredibly tiny power losses, and on further investigation finds that the tests were done while feeding a perfectly balanced load, or as often occurs, with two baluns connected back to back between an unbalanced source and an unbalanced load. In such tests, there is no net magnetic flux in either transformer and so no core loss !

3. Magnetic Core Materials

Most broadband transformers are wound on ring-shaped cores. Most practical ring shaped cores have a near rectangular rather than circular cross-section and so are not strictly toroidal in shape like a doughnut. The word "Ring" is more appropriate than "Toroidal", simpler and less often misspelt. Ring cores have the merits of simplicity, symmetry and completion of the magnetic circuit without any gaps. Among countless modern ferrite materials there are relatively few that are suitable. The three most important parameters that need to be acceptable simultaneously are (a) a high relative permeability μ' (b) a high saturation flux density B_{SAT} and (c) the lowest possible power loss at all frequencies to be used. Some powdered iron cores manage criteria (b) and (c) very well but suffer from lower permeability than most of the usable ferrites. Nevertheless, by using large diameter cores and more turns of wire they can often serve satisfactorily.

Though the SI system of units became the international standard for all important scientific and engineering research and education by the early 1960s, practical magnetic engineering has been among the very last to change and some catalogues are still published in old units while others are up to date. Here is just a snapshot of relevant units of the modern system. (One curious feature of the SI system is that proper names, used for units, are recommended to be used entirely in lower case, reserving the capital solely for the unit abbreviation, hence “ampere (A), tesla (T), Celsius (C) etc.)

Flux density B and B_{SAT}, the level at which the material reaches magnetic saturation, is usually given in tesla (T) or for the present applications, more often in millitesla (mT). 1 mT is equivalent to 10 gauss in the old system and 1 T equivalent to 10,000 gauss.

Typical B_{SAT} figures for suitable HF transformer materials are in the range 200 to 400 mT for ferrites and up to 1 T for powdered iron. The effects of non-linearity in the BH curve arise far below the specified saturation figure and it is always necessary to operate at far lower levels (e.g. 10 mT) to avoid significant power loss at HF and sometimes waveform distortion problems.

Power loss (very much a function of frequency) is often quoted in kilowatts per kilogram ($kW.kg^{-1}$), though for our present purpose it is convenient to note that this is equivalent of watts per gram ($W.g^{-1}$). It is often not easy to find this figure at all for the higher reaches of the HF frequency range of interest. One can extrapolate from given information about lower frequencies but this is unreliable and tedious. Fortunately as an alternative to power-loss specifications, a more familiar kind of data is starting to appear in ferrite catalogues, it involves what a radio engineer calls the "Q-factor" (which fundamentally is a measure of 2π times the energy stored each cycle divided by the energy dissipated per cycle). In circuit terms, it more simply understood as a ratio of reactance to resistance. A low loss tuned circuit in a VFO might be expected to have a Q of 200 or more. For a frequency standard crystal it might be thousands or tens of thousand. For an antenna system broadband transformer, one might manage quite well with a Q of only 10 or more. For making transmission line transformers and baluns, all the vast number of EMC application ferrite cores especially designed to *absorb* and dissipate energy, materials with a very *low* Q-factor e.g. 1 or less are of course extremely unsuitable.

Modern ferrite catalogues often include a most useful kind of chart showing how the relative permeability μ' varies with frequency, and also another quantity μ" the so called "imaginary" or "quadrature" permeability. It so happens that the ratio of these two permeabilities is our old friend $Q = X/R = \mu' / \mu''$. Fig 6 shows such a chart for one of the most useful HF ring-core materials Philips 4C65. The curves cross at about 50 MHz where their ratio has fallen to a Q of 1, but is still as high as about 40 at 30 MHz.

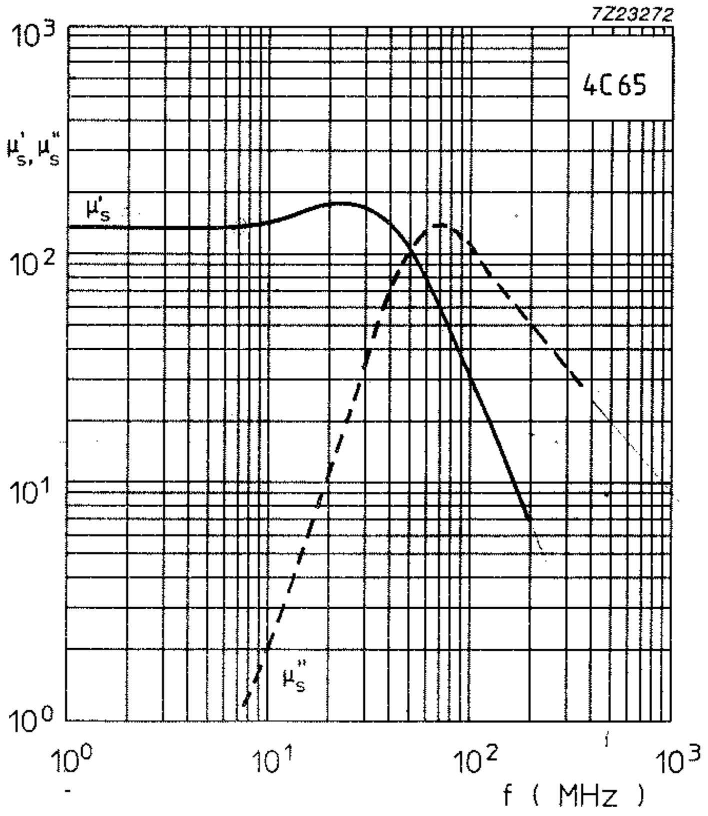


Fig 6 Relative permeabilities μ' and μ'' versus frequency for a useful Philips ferrite material

The ring core sizes most commonly found suitable for 100 W power (and up to 400 W if located and used carefully) are between 25 and 35 mm outside diameter when using ferrite materials with a relative permeability of, say, 100 or more, such as Type 4C56, and from 35 to 50 mm for iron powder cores such as the "red grade 2" types with relative permeability 10. The latter are sometimes taped together in a pair to get a large cross section to compensate for the lack of permeability. The effective inductance L needs to have a reactance ($X_L = 2\pi fL$) of at least 3 times the relevant associated circuit impedance at the lowest frequency of operation. The design dilemma is to keep the number of turns as few as possible while attaining sufficient inductance.

Manufacturers of magnetic materials offer precise methods of calculating nominal inductance. One method is to give a figure for the inductance produced by a single turn, often represented by the symbol A_L usually in units of nanohenry (nH) such that the inductance produced by N turns will be N^2A_L. For example, a Philips core RCC36/15 (and a very similar Farnell TN/36/23/15) having diameter 36 mm and thickness 15 mm, made of 4C65 ferrite material has $A_L = 170 \pm 25\%$ and so, with an 11 turn winding would give a nominal inductance of

$$L = 170 \times 11^2 = 170 \times 121 = 20570 \text{ nH} = 20.57\ \mu\text{H}$$

but note the 25 % manufacturing "spread", so that this particular result would imply nothing more precise than an inductance in the range 15.4 to 25.7microhenry. Even those figures assume operation at an extremely low flux density and that every turn of the winding links with the same flux as all the others. I have a sample of this type of core on test as I write. With 11 turns close spaced, tested at 3.5 MHz I measure L = 23.4 μH and Q = 220. Rearranging the winding to use the whole space more or less evenly, the inductance drops to 21.9 μH though the Q is unchanged.

A slightly different method of specifying inductance, used in particular for many of the best known powdered iron cores is to show an A_L figure for 100 turns (far more turns than would ever be used in the present applications) and microhenry units. For example an Amidon 2 inch diameter Red grade powdered iron core is rated as $A_L = 120$ microhenry for 100 turns and having an initial permeability of 10 . Therefore one would calculate the nominal inductance of an 11 turn winding as

$$(11/100)^2 \times 120 = 0.0121 \times 120 = 1.45\ \mu\text{H}$$

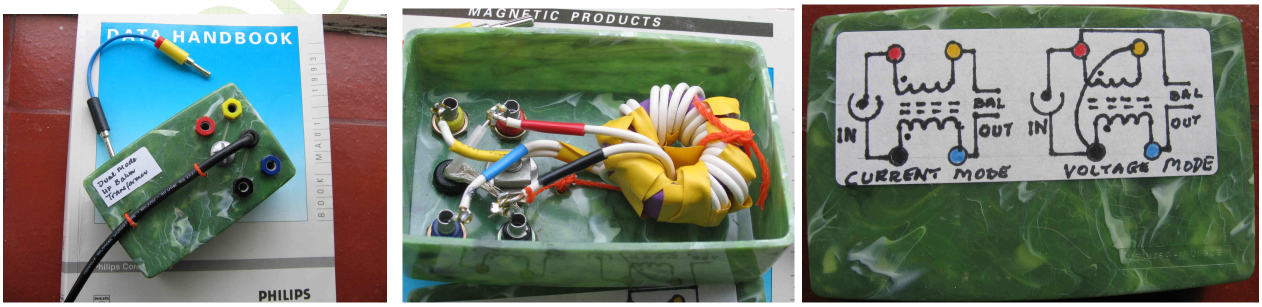
As you can see, the main snag with powdered iron cores is that one needs more turns than with comparable ferrite cores.

4. A Practical Example

Using a Philips 4C65 type ferrite core RCC36/15 and a bifilar pair of 11 turn windings, I have made several simple transformers like that shown in Fig 7. They have proved useful for coupling balanced antenna systems to an unbalanced transmitter or tuner in the frequency range 3.5 – 7.5 MHz. They can be used either as the simplest current mode balun without a change of low impedance (e.g. 50 or 75 Ω), or as a voltage balun for connecting an impedance about 4 times higher.

The choice of a traveller's soap dish was not so much inspired as the only thing available that day! The use of 4 mm wander plug sockets allows convenient choice of configuration without the need for a switch. A short input coaxial lead ends in a PL259 plug.

The twin windings of very ordinary 1 sq mm cross-section stranded wire with stout insulation are wound as a bifilar pair but are too bulky to be spaced well and have a completely unknown characteristic impedance. In more recent experiments taking using more suitable wire and spacing the turns carefully the useful range has been extended to the 21 MHz band. I have been using 1 mm OD, PTFE insulated silver (plated ?) wire (7 strands each 0.25 mm diameter); ex military stock I guess, that one sometimes finds at radio rallies. I have also added some very thin PTFE sleeving to increase the voltage rating and to increase the characteristic impedance. About a dozen turns spaced in 4 groups of 3 turns or 3 groups of 4 turns gives best results. For the higher frequency HF bands, one would need to use fewer turns and could not expect to manage a dual usage design or to be careless with winding materials and layout. One would have separately to make the current balun using twin wire with a low characteristic impedance e.g. $Z_0 = 75\ \Omega$ and the voltage balun using wire with Z_0 of twice that figure.



(a) (b) (c)

Fig 7 G4FHU Simple Dual-Purpose Balun

5. Conclusions

Specialised designs for use between very well defined and specific impedances require just the right materials and a lot of know-how; far more than is presented here. Nevertheless, many, perhaps most Amateur Radio requirements involving the kind of wire aerial system that can be slung cheaply and conveniently across a modest garden are usually far less demanding. The most common and urgent requirement is to get rid of the many problems that arise when a balanced horizontal HF antenna or system of antenna plus feeder is connected directly to an unbalanced transmitter or tuning unit. In most such cases the user does not know what impedance the antenna system presents at that interface, and is obliged simply to experiment, hoping to obtain a satisfactory match and get rid of feedback problems and excess sensitivity to vertically polarised interference. In such circumstances it is quite easy to make a transformer that may solve the problem or at least reduce it.

It is generally a bad plan to expect such a transformer to act as an impedance transformer over a huge range of frequency when connected as a voltage transformer (i.e. with one or more windings directly across the line) in any location where the impedance is unknown and likely to be extremely variable. However, a simple current balun used to separate balanced and unbalanced parts of the system can often be useful and remain very lightly stressed and trouble free. Success with a simple home made transformer can sometimes be a good enough reason for investing in a better quality professionally made one.

It is impossible to progress to experimentation with very high quality broadband transformers without a lot of study and in particular quite significant measurement equipment, but it is possible to follow professional designs to be found in books, especially those published by the RSGB and the ARRL and magazines if only one can obtain precisely the right materials. Alas, even in the rather long time it has taken to complete this article, supplies have declined alarmingly and firms have been transferred to new ownerships with different priorities. Indeed it now appears that the only sources of new materials require one to buy from the USA, or take quite a chance buying secondhand from eBay

I have reluctantly omitted almost all mention of testing methods, because it is quite a big and tricky subject in itself, involves more test gear than most may have available, and not least because of manifold dangers to both the person and the equipment when using the kind of power necessary to be meaningful.

Cont'd

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