Extending the low-frequency response of pulse transformers

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There are many instances where pulse transformers are used in detection systems, most commonly when the time-varying component of a signal biased at a steady or a high voltage needs to be extracted. Commonly used transformer circuits are best realised from transmission lines, although more conventional 'current' sensors are also often utilised (Figure 1). The response of these and of similar arrangements can be made to extend to high very high frequencies, in excess of several hundred megahertz. The low frequency response, however, is limited by the permeability of the core and the number of turns, i.e. the inductance L of the secondary. Since the load resistance R_{load} is usually made 50 Ω, or some similar 'standard' value, the low-frequency time constant is limited to L/50 seconds. While very high permeability toroidal cores are available, with μ_r values in excess of 5-10 x 10^3, a quick sum shows that it is not easily possible to extend the L/R time constant much above a few tens of microseconds. If a lower frequency break point is required, the only solution is to reduce the 'R' component.

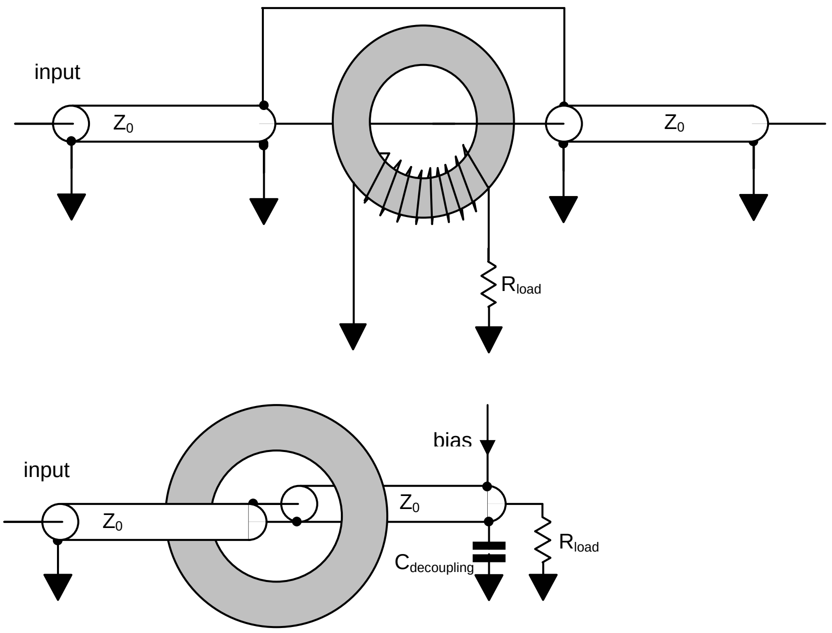

Figure 1. Top: Transmission line 'current transformer, sensing the current flowing in the inner conductor using a toroidal ferrite core. Bottom : a 1:1 transmission line inverting transformer used to apply a bias to the input inner conductor of the line.

If that is done, however, matching of the transmission line is no longer appropriate and the high frequency response will inevitably suffer. Nevertheless, it is worthwhile to consider exactly what is meant by a 'matched' line. Termination with a correct impedance is necessary to prevent reflections on the line; if the line is short compared to the lowest wavelength of interest, matching is no longer critical. This is just another way of saying that the line must remain terminated at short wavelengths (compared to its length) and that at progressively lower frequencies, 'correct' termination is less critical. A frequency-dependent termination is thus suggested to be appropriate, tending towards zero at low frequencies, thereby progressively extending the L/R time constant. A match with 50 Ω at the highest frequencies and 0 Ω at DC would thus satisfy the requirement for an extremely broadband device. It would of course provide a totally unacceptable frequency response! Nevertheless, if this line of reasoning is pursued, a practical, 'flat' frequency response circuit can be developed.

A frequency-dependent input impedance along the lines suggested can be realised with a 'virtual earth' inverting operational amplifier. This is shown in Figure 2, along with the expected frequency response. Currently available high frequency operational amplifiers allow operation at frequencies of up to 200-500 MHz, or more, relatively easily and thus pulse risetimes below 1 ns are possible, provided appropriate construction techniques are employed, i.e. proper decoupling, low inductance surface-mount components etc.

The principle of operation is most easily understood by assuming certain simplifications, and practically relevant complications are subsequently introduced. We thus assume a perfect operational amplifier and an infinite transformer source impedance. For convenience, the transmission line termination, R_{load} is made up from two identical terminations, 2 x R_{load}, one of which is part of the virtual earth input. At low frequencies, the load presented to the line is zero, and all the current flows through the feedback resistor, while at low frequencies, half the line current is 'lost' in 2 x R_{load}, but the line is correctly terminated. The sensitivity is thus doubled at low frequencies. It is noted however that the value of load inductor must be chosen such as to encompass the 'normal' frequency range of the transformer, i.e. subject to the aforementioned L/R limitations. It is thus apparent that all we need to do is to restore the gain at high frequencies, by inserting a similar frequency-dependent network in the feedback path, as shown in Figure 3.

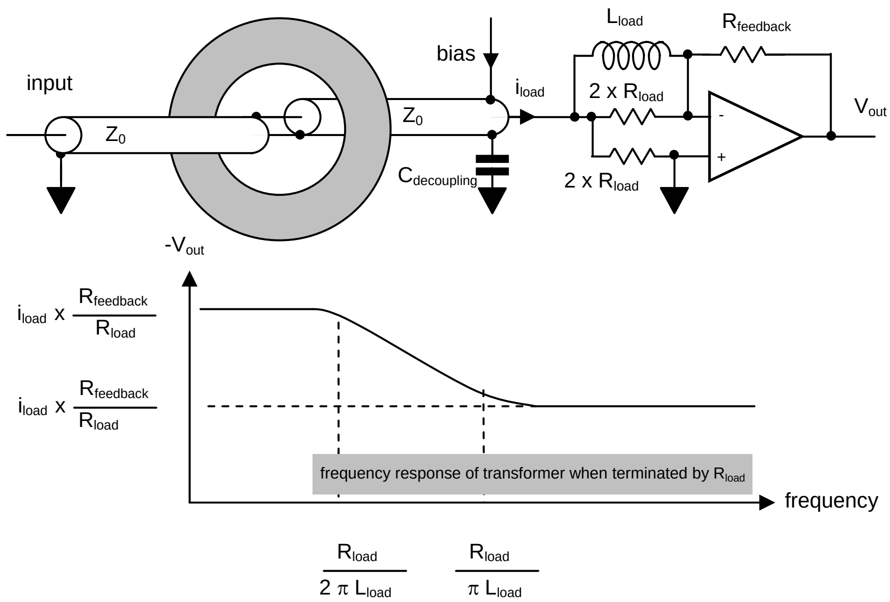

Figure 2: An inductor at the non-inverting input of an operational amplifier provides a frequency-dependent load to the transformer output current, but distorts the overall frequency response.

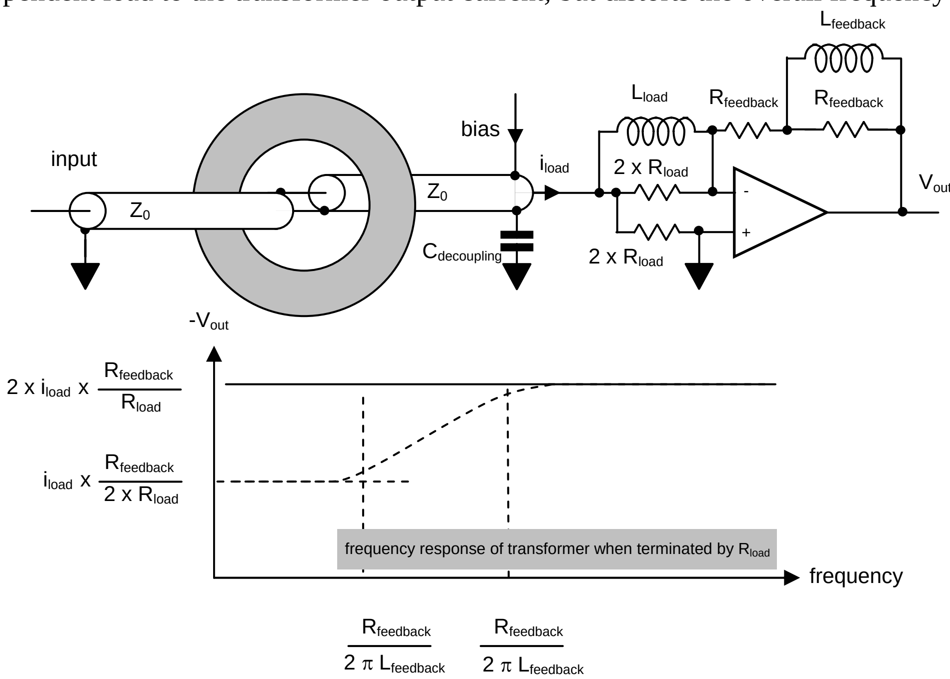

Figure 3: The addition of complementary network in the operational amplifier feedback path restores the gain at high frequencies and provides a 'flat' response, within the limitations of the amplifier

Clearly, the breakpoints of the feedback network must match those of the input network and in practice it is convenient to choose to split the transformer termination in a 1:2 ratio as described above. Furthermore, it is convenient to choose feedback resistors such that the same value inductor can be used in the input and feedback paths: this simplifies adjustment of the breakpoints if variable inductors are used, since they are likely to have comparable losses and stray reactances.

The above description applies if the source impedance of the transformer is infinite. In instances where the source impedance is finite, it must be taken into account when 'splitting' the transformer load impedance, since the relative amplitudes of the operational amplifier input current will no longer be in a 1:2 ratio. But the principles remain the same and component values will be of a similar order of magnitude.

The addition of two resistors and two inductors to a standard inverting amplifier circuit can thus extend the low-frequency response considerably, by presenting the transformer with essentially a zero load impedance. The obvious conclusion is that the system will thus operate down to DC. This however is not the case, for two equally obvious reasons: the virtual earth input is not truly at zero impedance due to the fact that the operational amplifier open-loop gain is not infinite and even if it were, the R term in the L/R time constant is ultimately defined by the finite DC resistance of the transmission line. Nevertheless, in practice, the effective R term can be reduced to a fraction of an Ohm, and a 100 fold reduction in the lowest operating frequency is easily achieved.

So can we do better than that? Surprisingly, the answer is yes! The effect of the finite cable resistance, termed 'r', can be further eliminated by placing a negative resistance in series with the input. If the 'virtual-earth' impedance is made very nearly equal to –r, then a further dramatic reduction in the low-frequency break point can be achieved. There are many ways of achieving this, but it is most convenient to apply frequency-dependent positive feedback around the operational amplifier, as shown in Figure 4.

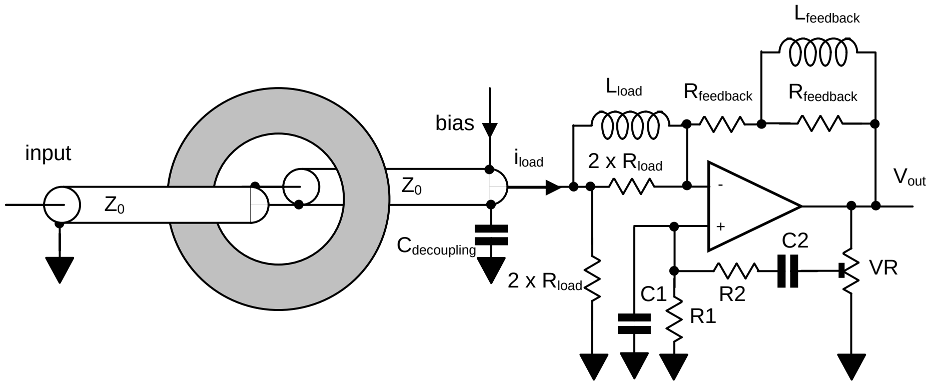

Figure 4: Addition of positive feedback through VR, C2, R2 and R1 to generate a negative input impedance at the inverting input.

A variable amount of positive feedback is introduced to the non-inverting input through the variable resistor VR and the attenuator formed by R1 and R2. Capacitor C2 ensures that positive feedback does not extend down to DC, and is generally of large value, several microfarads. Capacitor C1, typically 10 nF, similarly eliminates positive feedback at high frequencies by decoupling the non-inverting input to ground. Actual component values depend very much on the details of the transformer and moreover a certain amount of experimentation is needed to optimise a given system. It should be pointed out that additional components, such as power supply decoupling capacitors, offset trimming etc. have not been shown in the above figures for reasons of maintaining clarity. It is assumed that anyone attempting to construct such arrangements will be experienced enough to be aware of the multitude of other pitfalls associated with high frequency analogue electronics. These ‘tricks’ actually do work rather well in practice and it is relatively straightforward to extend the low-frequency time constant in a given system from around 20 μs to well above 20 ms.