ELEMENTS OF PASSIVE ELECTRONIC COMPONENTS

PART 2: THE IRON-CORED TRANSFORMER

by Steve Knight, B.Sc.

THE iron-cored power transformer is usually looked on as simply a device for raising or lowering the voltage of an alternating supply, with a corresponding decrease or increase in the current but there is more to its functions in life than this simplistic view suggests The transformer is an electromagnetic energy converter, whose operation is explainable in terms of the behaviour of a magnetic circuit excited by an alternating or changing current. As such, a brief review of its operational behaviour as a passive electronic component, is justified.

Faraday, in his experiments into mutual induction, which were described in the first part of this short series, used an iron-cored transformer that differed in construction from the toroidal forms we have today in nothing but possibly the technology of the core material Essentially, in the construction of any transformer, there are two insulated windings wound upon a closed magnetic circuit of low reluctance: one winding is referred to as the primary (or input) coil, and the other as the secondary (or output) coil In practice, there may be a number of output coils, but this does not affect the basic operational principles of the transformer For clarity, Fig. 1 illustrates the input and output windings as being on separate limbs of the magnetic circuit, but however they are disposed, both windings are assumed to be linked by the same magnetic flux

There is no direct connection between input and output; the transformer isolates one circuit from the other while allowing an exchange of energy between them In addition, the transformer may be used to transform not only voltage and current, but also impedance, which enables the transfer of maximum power through impedance matching. Further, since only alternating or changing current are transformed, the output circuit can be isolated from direct-current components in the input signal. All of these functions can be performed with high efficiency and precision.

For power applications, the frequency range of operation is in general 50–800 Hz, but special design refinements make the iron-cored transformer of value over the audio range of 20 Hz to 25 kHz.

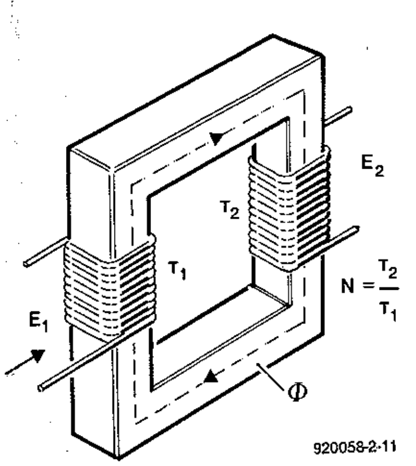

Fig. 1. Schematic representation of transformer operation.

Voltage transformation

Because of the relatively large number of primary turns and the presence of the closed magnetic circuit, the self-inductance of the primary coil of a commonplace power transformer is large; and because of the tightness of the coupling between primary and secondary, the coils have a high mutual inductance When the primary coil is connected to an alternating supply, the transformer will simply exhibit the characteristics of an iron-cored inductors A current will flow and an alternating flux will be established in the core, a high proportion of which will link with the turns of the secondary An e m f of mutual induction will be set up in the secondary and, if the secondary circuit is completed through an external load a current will flow in the load Energy is, therefore, transferred from the input to the output circuit entirely by way of the magnetic coupling

Assuming for the moment that we have a near-ideal component, the levels of the primary and secondary induced voltages, e_1 and e_2 respectively, will be proportional to the number of turns in the respective windings, since all the flux set up by the primary can be assumed to link with the secondary and is changing at the same rate, $d\phi/dt$, for both windings.

For a sinusoidal variation in the core flux of the form $\phi = |\phi|\sin\omega t$. the induced e m f.s are, from Faraday's law:

$$e_1 = T_1(d\phi/dt) = T_1\omega|\phi|\cos\omega t = E_1\cos\omega t$$

and

$$e_2 = T_2(d\phi/dt) = T_2\omega|\phi|\cos\omega t = E_2\cos\omega t,$$

where T_1 and T_2 are the turns in the primary and secondary winding respectively, and E_1 and E_2 are the r m s. values of the sinusoidal e.m.f s. Hence,

$$e_2:e_1 = E_2:E_1 = T_2:T_1 = n$$

demonstrates that the ratio of the induced e m f s is equal to the turns ratio, n For $n>1$, the transformer is a step-up, for $n<1$, it is a step-down These terms are applied to the *voltage* transformation ratio.

In practical transformers, the *terminal* voltages designated V differ slightly from the induced e m f s owing to the presence of effectual internal resistance in both the primary and the secondary coil; the terminal voltage ratio is, therefore, not the same as the turns ratio, but the difference can be considered as negligible for most applications

The unloaded transformer

We have noted that when the secondary terminals of a transformer are open-circuit the primary winding behaves as a large inductive impedance through which a small no-load current I_o will flow that lags the applied voltage, V_1, by an angle θ_o which will be close to 90° A component of this current will set up an alternating in-phase flux ϕ in the core that in turn produces primary and secondary e m f s, E_1 and E_2 There will be a hysteresis loss in the core when the flux is established and this loss will appear as heat, unaffected by the lamination of the core which is designed to reduce the other loss component, eddy currents. The no-load current, I_o must, therefore, contain an iron-loss component in addition to the true magnetizing component. I_m.

The phasor diagram for the unloaded transformer is shown in Fig 2. where ϕ is taken as the reference phasor since it is common to the primary and secondary circuits. Ignoring the small difference between the applied voltage, V_1. and the primary induced e.m f., E_1, the latter will be in anti-phase with the for-

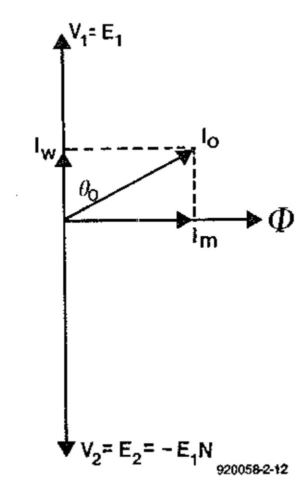

Fig 2 Phasor diagram of the unloaded transformer

mer. Further, the alternating flux that links with the primary turns and induces a back-e.m.f. of $-E_1$ volts also links with the secondary; consequently, there is induced in the secondary an e m f E_2 that is in phase with the primary back-e m f For a transformation ration of n, therefore $E_2=-E_1n$.

The two components of I_o are $I_o\sin\theta_o$ in phase with the flux, which is the magnetizing current I_m, a purely reactive component that is just sufficient to establish the flux; and the loss component, $I_w=I_o\cos\theta_o$ in phase with the applied voltage. This component supplies the iron losses

Under no-load conditions, the I_oR copper loss is very small and the overall losses are found in the iron circuit, so that I_o is almost equal to I_m Strictly, the magnetizing current is not sinusoidal for a sinusoidal input, since the B–H magnetizing curve for the core material is non-linear, but for small I_m the phasor representation is perfectly valid.

What is important to appreciate at this stage is that, since the induced primary e m f must depend on the magnitude of the alternating flux, it follows that this magnitude is determined *solely* by the magnitude of the applied primary voltage. Therefore, if V_1 is constant, ϕ is constant This has two important consequences: ϕ must remain constant *irrespective* of any other currents that may be caused to flow in either the primary or the secondary winding when the transformer is loaded; and on full load, the core flux is the same as on no load, so that the full-load iron losses are identical to the no-load iron losses. What does increase with loading are the I^2R copper losses in both windings It can be demonstrated that the efficiency of the transformer is a maximum when the copper losses are equal to the iron losses.

The loaded conditions

In Fig. 3 the secondary terminals of the transformer are connected to a load that, as an example, is assumed to be a positive impedance (the most common circumstance). Ignoring the copper losses, the secondary terminal voltage, V_2, will be identical to the secondary induced e m f. E_2 and the primary applied voltage V_1 will be equal to and in anti-phase with, the induced (back-)e m f in the primary winding

The induced secondary e m f., E_2, will cause a current I_2 to flow through impedance Z_2 This current will lag E_2 by an angle θ_2 by which the secondary current lags the secondary e m f is then practically equal to θ_2 This means that the power factor is roughly the same for both the primary and the secondary winding and that the transformer does not to any great extent alter the phase relationship between current and voltage Because, in practice, θ_2 is always slightly greater than θ_1, the use of a transformer tends to decrease the overall power factor of a system.

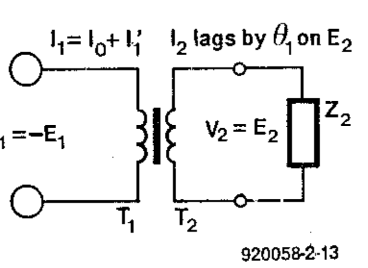

Fig. 3. Transformer operation with a complex secondary load

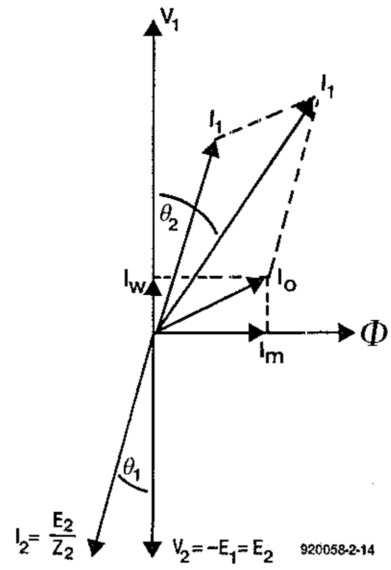

Fig. 4. Phasor diagram of the loaded transformer.

and will attempt to create a flux of its own in the transformer core It is here that the constancy of the flux, ϕ, must be taken into account since there has been no voltage change in V_1 Some action must, therefore, take place to neutralize the effect of the secondary load current on the core flux; what happens is that a primary current flows of such a magnitude and phase the the effect of the secondary current is nullified The demagnetizing magnetomotive force, m m f., I_2T_2 ampere-turns, is neutralized, in effect, by an additional primary current that increases the primary m m f to $I_1'T_1= I_2T_2$ ampere-turns Current I_1' is known as the balancing current and must, therefore, be 180° out of phase with I_2 and of such a magnitude that the total effective resultant flux introduced by the two currents is zero This implies that the new effectual m m f must equal the m m f caused by I_m alone, or,

$$I_mT_1-I_2T_2+I_1'T_1=I_mT_1,$$

so that,

$$I_1'T_1=I_2T_2$$

or

$$I_1'/I_2=T_2/T_1$$

Notice that the current ratio $I_2/I_1'=1/n$ This accords with the well-known fact that a transformer converts a high-voltage, small-current power into a low-voltage, high-current one, and vice versa

The phasor diagram for the loaded transformer under discussion is given in Fig 4 For convenience and clarity, n is taken as 1 The total primary current, I_1, is the phasor sum of the no-load current, I_o, and the balancing current, I_1', lagging the primary voltage by an angle θ_2. In practice, I_1' is much larger than I_o, and I_1' and I_1 can be looked on as being equal in magnitude Angle θ_1

Impedance transformation

When the primary current increases owing to the application of a secondary load, the primary impedance effectually falls There is clearly a relationship between the load impedance and that seen at the primary terminals when such a load is connected

In Fig 5, suppose the secondary load impedance to be Z_2; the secondary e m f. will then be E_1n volts and the secondary current will be E_1n/Z_2 The primary balancing current will consequently be $n(E_1n/Z_2)=$ $=E_1n^2/Z_2$ and this will equal the primary current if the magnetizing current is small. Therefore, $I_1=E_1n^2/Z_2$ and $E_1/I_1=Z_2/n^2$. Thus, since $E_1/I_1=Z_1$, the impedance seen at the primary terminals is $Z_1=Z_2/n^2$.

For a step-up turns ratio, Z_1 will be smaller than Z_2; for a step-down ration, Z_1 will be larger than Z_2 Impedance is, therefore, transferred across the transformer from secondary to primary and is increased or decreased (from the primary viewpoint) according as the turns ratio, n, is (looking from the secondary side) up or down respectively

The impedance matching abilities of a transformer have little relevance in power transformers, but are of importance in audio-frequency transformers

Audio-frequency transformers

When a transformer is designed for a range of frequencies, unlike power transformers that are made for a single frequency, the equivalent circuit that the transformer presents to the input system is often quite different at one end of the range from what it is at the other If a reasonably uniform response over, say, the audio-frequency range is desired, the transformer, including interstage types, output types, input matching devices, and so on, requires careful design considerations In a practical transformer, there are a number of losses that may be represented as

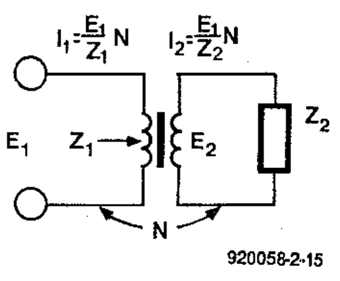

Fig. 5. The transformer used an impedance transfer device.

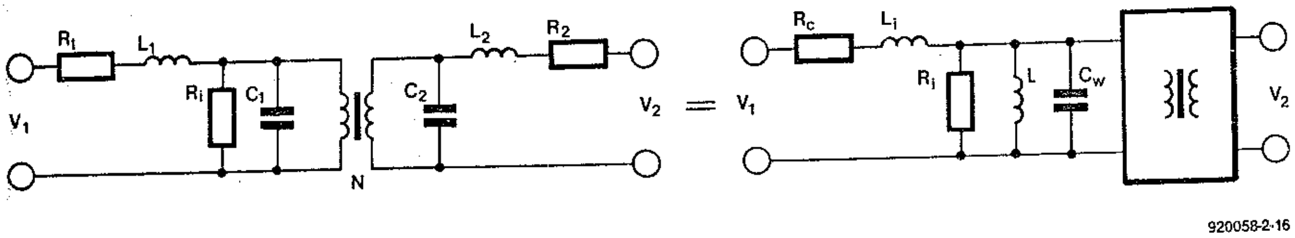

Fig 6. Deriving the equivalent of a transformer model with losses isolated from an ideal device

extra components added to the external circuits of an otherwise 'ideal' transformer, as illustrated in Fig. 6. The copper losses are shown as external resistances, R_1 and R_2, in the primary and secondary circuits respectively; hysteresis and eddy current losses are represented by a parallel primary resistance, R_i; flux leakages by series inductors L_1 and L_2; and the self-capacitances of the windings as parallel capacitors C_1 and C_2. At power frequencies, the self-capacitances and the leakage inductances are not particularly important.

By transferring the secondary loss components to the primary circuit, the equivalent model becomes as shown in Fig 6(b), where R_c, the total copper loss, $= R_1+R_2/n^2$; the total leakage inductance, $L_i=L_1+L_2/n^2$; and the total effective winding capacitance $C_w=C_1+C_2n^2$ There is also L, the effective primary inductance with the secondary on open-circuit, such that $V_1/\omega L$ gives the magnetizing current The remaining ideal transformer is then a component without the imperfections of the real device.

What happens to this model when it is used over the audio-frequency range? At very low frequencies, the input impedance will approximate that shown in Fig. 7, where the series inductance L_i is neglected along with the shunt resistance and the winding capacitance. C_w Hence the ratio of the terminal voltage, V_1, and the effective primary voltage V will be small, so the output voltage, V_2, will be small. At some mid-frequency in the range, the transferred load resistance, Z_2/n^2, will be very much larger than the resistance of L_i and there will be a tendency for C_w and L to resonate, so making the ratio V_2/V_1 approach n At high frequencies, the shunt capacitance, C_w, has a low reactance relative to that of L_i and becomes dominant This means that the response falls relatively rapidly.

The high-frequency response can be extended by sectionalized windings to reduce the self-capacitances and by getting the resonant condition to fall in the upper third of the range. In the same way, the low-frequency fall-off can be curbed by maintaining a high primary inductance (often achieved by barring direct currents from the winding) and by keeping the winding resistances small, though there is a conflict of requirements here. The choice of core material and thin laminations or ferrite is also important ■

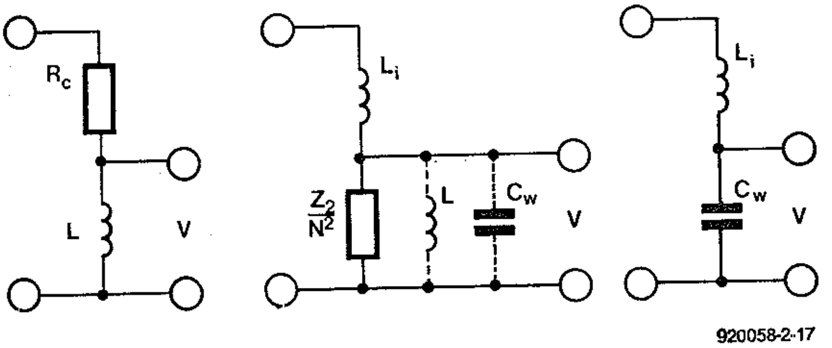

Fig. 7. The simplified audio-frequency model.

Next month's final instalment of this short series will deal with the capacitor.

SCIENCE & TECHNOLOGY

MEDICAL LASER TECHNOLOGY

by Douglas Clarkson

THE application of lasers in medicine is all about the interaction of photons of radiation with tissue. It is the ability to precisely deliver such energy at sufficiently high continuous power levels or in the form of discrete pulses of energy that has led to the significant use of such systems in medicine. This use has largely come about as a spin-off of technology originating in industrial and military applications

The human body can be considered to be an Aladdin's cave of diverse types of tissue: muscle, fat, bone, cartilage, and so on. Conventional surgical procedures have evolved from using the scalpel, surgical diathermy, saws, drill and ultrasonic fragmentator systems to cut through the various types of tissue. Each of the various disciplines of surgery tends to develop standard techniques for its various procedures. Table 1 gives a brief 'snapshot' of the various surgical procedures associated with a range of surgical specialities.

The medical laser is finding particular application in areas where it allows specific procedures to be undertaken with reduced patient stay in hospital and incidence of complications.

Degree of 'unique' role of laser systems

It is important, also, to appreciate the degree of 'uniqueness' of laser technology in medicine This factor can range from the one extreme of 'entirely unique', where the laser is the only way to undertake the procedure to 'non unique', where several alternatives are available One such 'entirely unique'