Transformer Guide

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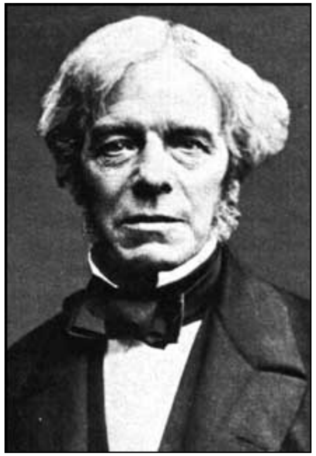
Did Michael Faraday Invent the Transformer ?

In his experiments with electricity, one of Faraday's earliest discoveries was that a current passing along a conductor produced a magnetic field around it and he called the process induction. He noted also that the polarity (N/S) of the induced field always was oriented to correspond with the polarity of the current flow (+/-). As has so often happened with contemporary researchers over the years, Oersted in Denmark observed these phenomena about the same time, even a little before, perhaps.

Both men share the honour of the discovery but Faraday's experiments also showed that if the conductor were formed into a ring or coil the strength of the magnetic field appeared to be intensified; and further that if some iron were introduced within the field, it was intensified more still. Here were two of the elements of the transformer - a coiled conductor, and an iron core. But there was a long road to where the notion of the transformer would become either possible or desirable.

Electricity had no practical applications at that time. For one thing the only practicable source of current was the primitive electro-chemical cell with a maximum potential of one volt and invariable polarity. There were no lamps to be lit, no idea of a practical heater, no reliable insulation for conductors; better than varnish or cotton covering, few instruments suitable for measuring accurately the effects he was observing; and the highest voltage attainable was what could be provided by a pile of cells -or 'battery' as we say now.



Michael Faraday

Faraday's further work did lay the foundations for the transformer to be developed eventually. His investigations pursued a very significant line: the effect of change of magnetic field. He was the man who found out that if a current-carrying conductor were moved relative to another lying parallel with it a voltage would be induced in that second circuit by mutual induction. This was intuitive brilliance of a high order.

He noted that the induced voltage in the second circuit was present only when the two conductors were moved relative to one another, and not when the motion stopped. Besides that, he found that motion of a magnet within a coil also induced a voltage and that this voltage changed its polarity when the motion of the magnet was reversed. Further he observed - brilliant man - that when there was no physical relative motion, induction nevertheless occurred in the second circuit as the first was switched on and also as it was switched off. In other words, the effect that produced induction was shown to be any change of magnetic flux.

Here at hand was the principle of the transformer and of the alternating current (AC) generator, the AC induction motor and the DC dynamo. Besides all this, Faraday showed that the induced voltage was in the same proportion as the number of turns in the secondary and primary coils.

At hand, certainly but there was a great deal of thinking and patient experimenting to do before any such thing as a transformer could become a reality. Also two other ideas would have to be conceived and these were interdependent. The first was the idea of alternating current (and Faraday did produce AC in laboratory conditions, by rotating a coil between the poles of a magnet); but here was the seed. The second idea was the very need for such a thing as a transformer. So no, Michael Faraday did not 'invent' the transformer any more than he 'invented' the induction motor, but he certainly did discover and demonstrate the principles that would make them possible.

Crucially, Faraday discovered the mathematical relationship of induced electromotive force (EMF) to magnetic flux:

$$e = N \frac{d\phi}{dt}$$

where e = induced EMF
N = number of turns in the coil
ϕ = magnetic flux

This formula is saying that Induced EMF is equal to the number of turns multiplied by the rate of change of flux - which is, of course, the frequency of an AC supply.

Types of Transformers

Power Transformer
Principal application: To deliver raw power at (usually) a different voltage from that of the supply.

Isolating Transformer
Principal application: To separate electrically the primary voltage from the (reduced) secondary in situations where the primary voltage could be a hazard. Where the primary voltage is likely to represent a hazard, a metal screen between the primary and secondary is built in and earthed.

Auto Transformer
Principal application: To take advantage of reduced cost and weight in comparison with a conventional two-winding transformer. Isolation of secondary from primary is sacrificed.

Variable Transformer
Principal application: To permit variation of the secondary voltage; basically an auto transformer.

Example of a single phase variable transformer from REO

Voltage Transformer
Principal application: To deliver a secondary voltage as closely proportioned to the primary voltage as possible, for measurement and protection applications.

Current Transformer
Principal application: To deliver a secondary current as closely proportioned to the primary current as possible, for measurement and protection applications.

Example of an AC current transformer with universal mounting from REO

Example of an AC current transformer for PCB mounting from REO

Saturating Transformer
Principal application: To saturate the flux at some chosen voltage in the primary so that there can be no further increase in secondary voltage or current.

Ferro-resonant Transformer
Principal application: To operate permanently in the saturated condition to provide a constant voltage from the secondary.

'Boosting' and 'Bucking' Transformers
Principal application: To transform the primary input to increase - 'boost' (or decrease - 'buck') the secondary output by a specified amount, usually small.

High-frequency Transformer
Principal application: To operate as a voltage transformer does, but designed to work at frequencies much in excess of mains frequency.

Example of a high frequency transformer available up to 25kW from REO

Functions of Transformers

The most obvious function is to adjust the voltage of a supply wherever it is not suitable for the purpose of the application. Examples are:

***Transmission and Distribution*:** To change from generator voltage to a high voltage for transmission over long distances, and conversely to reduce transmission voltage to voltages suitable for distribution over short distances and to provide low voltages for industrial or domestic use.

***Isolation*:** Because a two-coil transformer achieves its function through the use of two (or more) coils with only magnetic coupling and without any direct electrical connection, it therefore offers complete electrical isolation. The law of unintended consequences - but with the happy practical effect that the primary voltage is isolated from the secondary and cannot appear in the secondary circuit (unless the insulation of the windings fails disastrously). This has valuable applications, for example where hazardous atmospheres may be present, such as in hospital operating theatres.

Example of an isolation transformer for medical applications available up to 1000VA from REO

The Action of a Transformer

A transformer operates owing to the phenomenon of mutual induction discovered by Faraday.

If a voltage is applied to one coil, a current will flow. So long as the voltage is changing (and in consequence the magnetic flux is changing also) it will induce a voltage in an adjacent coil; and if the ends of that coil are connected so as to complete the circuit, a current will flow in the second coil. The essential factor is that the applied voltage is continuously changing. That is exactly the case if the supply voltage is alternating. The transformer is a strictly AC device. The alternating current need not be sinusoidal; it may be of 'square' or 'trapezoidal' wave form, but these will distort the flux wave form and will waste energy.

There is a matter to be understood about induction at the outset here. In any coil, if the applied voltage is sinusoidal, then when the voltage wave is passing through zero it is changing at its maximum rate and in a positive direction, so the flux must be at maximum. When the voltage wave is maximum, it is momentarily not changing at all and the flux is zero. Thus the flux wave is also sinusoidal but is 90 degrees late on the voltage wave - it is said to be '90 degrees lagging'. The current wave in the coil is 'in phase' with the flux wave, so the reactive (magnetising) current also lags 90 degrees on the applied voltage. This current is commonly called reactive; strictly it should be 'inductive reactive' because current in a capacitor circuit is also reactive - 'capacitive reactive' - and *leads* the voltage by 90 degrees. Inductive reactive current is sometimes called 'magnetising current'. If the circuit load were purely resistive however, the 'active' current wave would be in-phase with the voltage, as shown in figure 1 (and represented

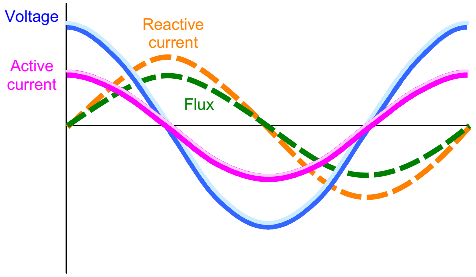


Fig 1 Voltage,flux and active and reactive current waves

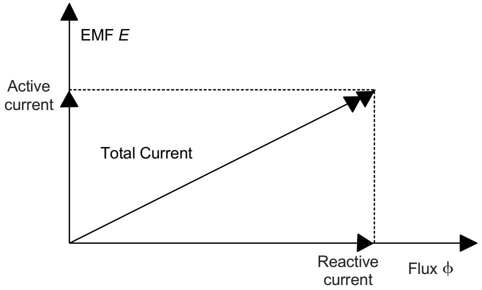


Fig 2 Impedance vector diagram

To summarise: if a circuit is purely resistive without any inductive or capacitive load at all, there is no phase displacement whatever; if it is purely reactive, phase displacement is 90 degrees; but no circuit is ever purely one or the other, so when a circuit contains both inductive (or capacitive) and resistive components the phase displacement will be less than 90 degrees.

The reason for the word 'reactive' is that, in inductive and capacitive circuits the current sets up an emf which directly opposes the applied emf - reacts against it. (Kirchoff's Law - the sum of the emfs in a circuit must be zero.) In purely resistive circuits there is no reactive component.

Ratio of Transformation

It is interesting to look closely at what happens in a coil when the voltage is applied. Current flows immediately but does not instantly reach full flow as it does in a plain conductor: it grows from zero to maximum while the magnetic field is forming.

The event can be understood if you imagine yourself grasping the handle of a large grindstone. Start to turn the handle (apply a voltage) and the inertia of the heavy mass reacts against you. It takes a definite time to get it up to speed (current). Similarly, if you try to stop and reverse the motion the inertia reacts against you again. In the same way, the growing magnetic field (flux) reacts against the voltage trying to increase it, and in the case of AC voltage it is as if you were trying to keep reversing the direction of the grindstone. Reactance can be regarded as electrical inertia.

Any coil in an AC electrical circuit is a reactor and behaves in this way, owing to the reluctance of the magnetic flux to grow within the medium available. This reluctance is greater if the coils surround an iron core. Inductive reactive loads, typically, are induction motors (most especially during the start and run-up period); typical capacitive loads are discharge lighting and capacitors. Resistive loads are heating elements and the like.

The coil to which a voltage is applied is called the primary; the other coil is called the secondary. If the number of turns in the primary and the secondary are the same, the voltage that appears at the terminals of the secondary will be, in an ideal transformer, the same as the applied voltage, and if the number of turns differs, there will be a corresponding voltage difference in direct proportion to the turns ratio.

This gives rise to the simple formula:

$$\frac{N1}{N2} = \frac{V1}{V2}$$

where N is the number of turns and V the corresponding voltage. When $N1 < N2$ so $V1 < V2$ and the output voltage is greater than the input voltage, the device is called a step-up transformer; and if $N1 > N2$, it is a step-down transformer.

In practice, transformation ratio is not exactly the same as turns ratio. Only when there is no load on the secondary side is the relationship true - and not even then, precisely because of the slight phase displacement between the primary and secondary voltages caused by the magnetising (reactive) current 90 degrees out of phase with the applied voltage.

Power and Rating

In an ideal transformer (in which losses are ignored) the power output is the same as the power drawn for the supply so that $P_1 = P_2$. This is so regardless of turns ratio. Power is voltage multiplied by current, P = V x I
Therefore: $P_1 = V_1 \times I_1$ and $P_2 = V_2 \times I_2$ so the power transferred across the transformer: $P = V_1 I_1 = V_2 I_2$
whence $\frac{V_1}{V_2} = \frac{I_2}{I_1}$
showing that current is transformed in inverse proportion to the turns ratio. Observe the parallel with a mechanical gearbox: if speed is stepped up, torque is stepped down, and *vice versa*, but the power output is the same as the power input (ignoring losses).

Power in transformers is measured in VA (volt-amperes). Why not watts (or kW, the SI standard unit of power) as with motors and generators? The reason is that a transformer is able to, in fact it is required to, deliver both active, kW, and reactive power, kVAr, (sometimes called 'wattless power') determined by the type of load. Whereas with a motor the only power of interest to the user is active, kW - the mechanical power demanded by a machine. It is therefore logical to rate transformer power as apparent power - the voltage multiplied by the total current in VA or kVA. The usable power (kW) delivered by a motor is considerably less than the total power (kVA) received, but a transformer delivers, very nearly all the power it receives.

Besides this, the internal insulation of a transformer has to be designed to counter the maximum voltage that could occur, and likewise the conductors must be able to carry the maximum current, including both active and reactive (magnetising), current that could pass.

Transformer Losses and Efficiency

Transformers are highly efficient devices: typically 98.5% or even higher. Transformer losses appear as heat. (Loss due to vibration noise is scarcely measurable). The main causes are:

Copper losses - current passing in the conductors generates waste heat;

Iron losses - made up of two kinds:

(i) *Eddy-current losses* - caused by magnetically-induced currents trying to circulate wherever they can find a path, and

(ii) *Hysteresis losses* - caused by the reluctance of the core first to accept magnetisation and then to allow it to subside. Remember that the essential changing conditions are provided by the alternating current which changes its direction of flow 50 times a second in a 50 cycle system, as also must the flux.

High efficiency is achieved by reducing losses but the very fact that transformer losses are typically low means that it is difficult to make them lower. The problem demands not only great expertise in the choosing of materials and close attention to high and exact standards of manufacture, but also the support of continuous research and development. The wide range of different types of low voltage transformer required for the various duties presented by electrical variable speed drives (vsd's), computers, programmable logic controllers (plc's) and many other industrial devices also necessitates, as a prime consideration, great expertise in design. Without skilled design all other factors in achieving accurate and efficient performance become less effective.

Regulation

The word regulation is not used in the sense of control. It is the technical term for a characteristic common to all transformers: an increase in the load causes a slight reduction of secondary terminal voltage. Transformer regulation is defined as the difference between the no-load and full-load secondary voltages; full rated voltage being applied to the primary terminals. No load is when the secondary terminals are open-circuited; full load current is circulated when the secondary terminals are short-circuited i.e. when the load is non-inductive (power factor is unity). Regulation is conventionally expressed as a percentage of the open-circuit secondary voltage. Typically, the voltage at the short-circuited terminals may vary from about 5 percent for small power transformers to perhaps 20 percent for the really large transmission transformers, which are invariably equipped with tap-changers to enable the secondary voltage to be adjusted if the load alters significantly.

Percentage regulation is as much a part of a transformers rating as is the voltage and power that it is designed for. It is an indication to the user of the transformers behaviour under load. The lower the percentage regulation, the less change there will be in secondary terminal voltage under load. In general, designers aim to keep the percentage regulation as low as possible, but there are some specialised applications for which a high percentage regulation is beneficial, and for these a transformer is designed to suit.

Since the application of a load on the transformer always pulls down the output voltage, the voltage ratio is never exactly equal to the turns ratio. Further, the more inductive the load is, the more the effect is intensified. The reason for this may be seen in the transformer vector diagram, figure 3, which shows a transformer on load. E_1 and E_2 are the primary and secondary EMFs and are equal and opposite. The induced flux Φ lags 90 degrees behind E_1, and E_2 lags 90 degrees behind the flux. The small vector triangle at the centre of the diagram represents the transformer in the no-load state (open-circuited). We shall come back to it, but to understand what is going on it is best to start by considering the secondary side. Figure 3 exaggerates the detail to make it readable.

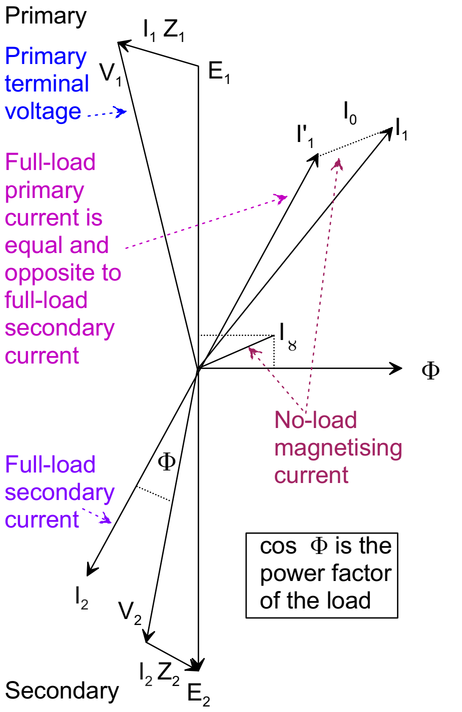


Fig 3 Regulation vector diagram for a turns ratio of 1:1

The secondary voltage V_2 is less than the secondary EMF E_2 and lags behind it because of the load which imposes a voltage drop I_2Z_2, where I_2 is the load current in the secondary and Z_2 is the leakage impedance of the secondary windings ($V = IZ$ as in $V = IR$). This vector, subtracted from the secondary EMF, makes up the secondary voltage vector triangle which is completed by the secondary terminal voltage V_2. The voltage delivered by the secondary determines what current will be delivered to the load. The load power factor, ϕ, determines the phase displacement of the load current, if any. If load power factor is unity, voltage and current are in-phase; if the load has an inductive reactive component, as with motors for example, the current will lag behind the voltage as shown in the diagram.

Now that we have the secondary current vector I_2, we can plot the primary load current vector I'_1 because it must be equal (in a 1 : 1 transformer) and opposite to I_2 to balance the system. I'_1 is not the total primary current; the magnetising current I_0 must be added to it vectorially, as shown, to give I_1 which, multiplied by the primary leakage impedance Z_1 permits the primary voltage vector triangle to be completed by the vectors I_1Z_1 and V_1. Now V_1, of course, is the *only* fixed quantity - the actual primary voltage applied to the primary terminals; all other vectors in the diagram are related to and dependent on it.

It is not easy, with a static diagram, to see at glance what happens when one part of it changes. Look at the load power factor angle, Φ; the more inductive the load, the bigger that angle becomes. Now the I_2Z_2 vector must always maintain the same *angular* relationship to the load current vector I_2; so that, as the power factor angle increases, the angle of the I_2Z_2 vector steepens, and forces the secondary terminal voltage vector V_2 to reduce, since the value of E_2 is fixed by its relationship to E_1. Furthermore, any change in load current demand, I_2, will change the length of the vector I_2Z_2. This is on-load regulation, for which tap-changing may be a necessary provision.

Perhaps the open-circuit and short-circuit voltages of a transformer may seem to have no practical application… but the percentage impedance certainly does. This quantity is the ratio of the *primary* line voltage required to circulate full load current in the short-circuited secondary over the rated *primary* line voltage, expressed as a percentage, and turns out to be very similar to the percentage regulation, not surprisingly. Regulation compares the difference in voltage on the secondary side of a transformer, whereas the comparison of the two voltages on the primary side 'sees' the *total* impedance across the transformer. To enable protection switchgear to be properly specified the percentage impedance is essential for the calculation of short-circuit levels in power transmission and distribution systems.

Saturation

Thus far we have been looking at an inherent characteristic of transformers and at the effect on them of the characteristics of the load. Now let us have a look at the other side - the effect of the primary voltage.

The density of the flux in a magnetic core is directly proportional to the number of turns and the voltage applied - up to a point. A given quantity of material is capable of being driven to a certain flux density, but at the point where it becomes saturated, proportionality is lost.

The primary voltage is what 'excites' the transformer. That is to say, it induces the magnetic flux in the core. Every core has a flux limit. It can carry just so much excitation and no more. When it reaches this point it is stuffed full, so to speak, of lines of force. The term for this state is 'saturation'. It is brought about by the increase of primary voltage. A saturated core will not respond to any further increase in primary current, no matter by how much the voltage is increased. Any magnetic core will saturate if the voltage is raised high enough. Normally, it is the concern of the transformer designer to ensure that the transformer is nowhere near the onset of saturation.

Absence of saturation is especially important with instrument transformers (ct's and vt's); their duty requires a high degree of linear correspondence between primary and secondary for the secondary output to represent the primary input accurately and this demands very careful design and construction.

Saturation can be put to practical uses. Many devices nowadays are very sensitive to overvoltages - things like computers, programmable logic controllers (plc's) and other electronic equipment, and need to be protected. If such equipment is supplied by a transformer that saturates at or near the rated primary voltage it is impossible for an overvoltage to appear on the secondary side.

Again, if saturation is deliberately designed to appear before the primary voltage wave reaches its peak value, the secondary output will approximate to a 'square wave' in effect delivering alternating positive and negative pulses.

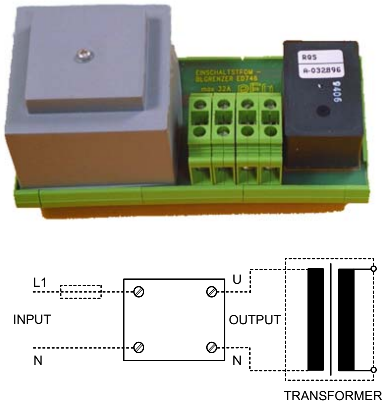
Unfortunately, there is a drawback. A saturated transformer painfully distorts the flux wave and a distorted sine wave consists of the fundamental, a pure sine wave at full voltage, plus several harmonics. Harmonics are bad news in almost all places. Happily, a cure is easily applied in the form of an auxiliary secondary circuit, (see figure 10), in which the load is a capacitor designed to resonate at the frequency of the primary circuit. This mops up the harmonics, and the result is a fine, 'clean', stabilised secondary output which can never exceed its correct voltage, no matter what 'transients' may occur in the primary due to switching events or other disturbances. However, in a saturated core, iron losses are at their maximum, so saturating transformer efficiency is lower than normal.

An important safety warning here: capacitors can be dangerous. Even when a ferro-resonant transformer is switched off, the capacitor remains charged and may deliver a lethal voltage at the secondary terminals. The charge will decay of course, but it may take a long time - perhaps half an hour, or more.

Inrush Current

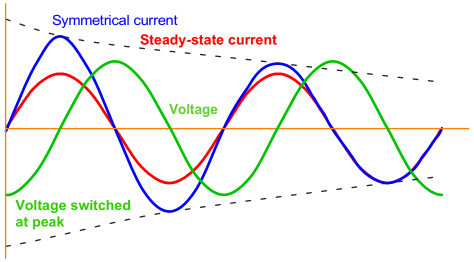
At the instant of switching on a transformer an inrush current will flow because the core is not fluxed and therefore offers no impedance. The inrush current may be several times normal full load current - but is rapidly suppressed as the flux builds up. Once the core is fully magnetized, the transformer presents a constant impedance to fault currents in the secondary circuit. In a case where a high inrush current would be especially undesirable it can be controlled by a series resistor automatically switched into the primary circuit when the primary voltage is removed and automatically switched out when the primary is fully excited.

The amount of the inrush current is determined by a factor which is, unfortunately, outside the operator's control; this is the point on the voltage wave at which the primary circuit is closed. The inrush is least if switching takes place when the voltage wave is at its peak - when the rate of change is zero. The lagging current then starts at zero and rises 'symmetrically', figure 4a.



Example of a REO soft start module for transformers

Fig4a Symmetrical start - voltage at peak



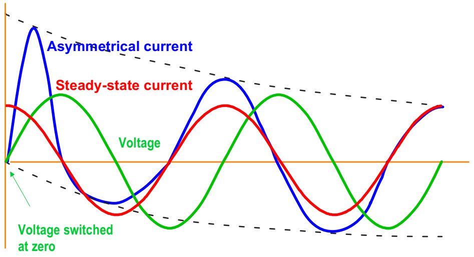


Fig4b Asymmetrical start - voltage at zero

But if switching takes place when the voltage is zero, that is, when the current would in normal operation be at its maximum, the case is altered. Clearly, the current *has* to start from zero but its acceleration, so to speak, is maximum.

The result is that its first maximum is much higher than it otherwise would be because it is 'asymmetrical', figure 4b. It is damped down to normal in a few cycles, but momentarily it is very high. Here is an unavoidable problem that the transformer designer must take into account and provide for, because a current so greatly bigger than normal will, or probably will, saturate the core in any transformer. Furthermore if the core has retained any magnetisation - which will in all probability be out of phase with the 'starting' current - the effect will be worse. It's a matter that demands the highest design ability.

Impedance Matching

So far, transformers have been considered from the point of view of voltage and current, and as a means of isolating one circuit from another. Another application (which does not require any special type of transformer) is in matching the impedance of a source to the impedance of the load. The power source in these applications would be an amplifier, not a main power system.

This is a requirement in applications involving audio and transmitter circuits, the objective being to achieve maximum power transfer, without which the load would be operating at low power. A speaker or an antenna which is under-powered will give a poor performance.

Maximum power transfer occurs when the resistance of the load is equal to the internal resistance of the source, or, in this type of application, for 'resistance' read 'impedance'. If these are *not* equal, an interposing transformer can be used to achieve the maximum power transfer.

Suppose the load impedance is Z_2 and the source impedance is Z_1. The required transformer ratio $N_1 : N_2$ is the *square root* of the impedance ratio $Z_1 : Z_2$

The reason for this is that the flux density in the air gap between the primary and secondary windings (the reactance) is proportional to:

$$X = \frac{k\,f\,N^2\,r\,g}{h}$$

where f is the frequency and r, g and h are the dimensions of the air gap - all being constants - showing that flux density is proportional to the square of the number of turns. If the reactance X is proportional to the square of the number of turns, so must the impedance Z be also, and the impedance ratio is therefore the square root of the turns ratio.

For example, if the source impedance is 500Ω and the load impedance is 10Ω, the required turns ratio is:

$$\sqrt{500} \text{ divided by } \sqrt{10}$$

$$= \sqrt{50} = 7.07:1, \text{ (not 50:1)}$$

The Structure of a Transformer

In the simplest form, a transformer consists of two coils of insulated wire, one being supplied from a power source and the other delivering power. Commonly, the primary and secondary windings are placed one inside the other. Alternatively, they may be adjacent on one limb of the core, or placed one on each of two limbs. There may be a core to intensify the magnetic field or there may not, depending on the duty for which the transformer is designed. If a core is used, both coils are usually placed on one limb of it, and may be interleaved. The core will have three limbs so that the magnetic circuit is complete and minimises leakage flux which would increase losses by encouraging eddy currents to flow in adjacent components.

The core shape and material will be chosen with regard to the intended duty of the transformer as well as its efficiency and voltage regulation.

For convenience of manufacture, the core is formed in two separate parts. To avoid introducing even a partial air gap or discontinuity, the mating faces of the two parts are machined to close tolerances and clamped firmly together after the cores are in place.

Some of these difficulties are avoided in the design known as toroidal, where where core is shaped like a doughnut. The conductors are wound on the ring (lower voltage inside as usual). A particular advantage of this construction is that it gives rise to less leakage flux than the more-conventional structures.

Encapsulation as a final process can be successfully done on the smaller sizes of transformer (generally < 3.5kVA) and is an excellent finish, giving good heat dissipation and excellent protection against mechanical damage as well as rigid support to the transformer components.

The coils are two quite separate circuits without any direct electrical connection, insulated from each other and from the magnetic core if there is one. Conventional transformers have one primary and at least one secondary coil. Current transformers for instrumentation and protection have, of course, only the low voltage coil since the primary is a power conductor, and high voltage. It may pass straight through the secondary as a single-turn primary or it may be a solid bus bar formed into two or sometimes three turns, according to what ratio is required.

For some applications an air gap is deliberately introduced into the core. The purpose of this is to increase the leakage inductance such as in the case of power factor correction (PFC).

Example of a REO encapsulated toroidal transformer

Magnetic Core Construction

The first cores were solid soft iron; that is iron from which most of the carbon has been burnt off. It was then discovered that savage eddy currents were sapping a lot of the energy. The next idea was to slice up the core into thin plates and to insulate them from one another so that eddy currents were isolated within each lamination and were, in total, much reduced. At the same time it was found that if, in the process of producing the laminates, the iron was rolled repeatedly, the grain was orientated unidirectionally with the result that the energy needed for magnetisation was reduced because some of its work was already done. At about this stage it was found that alloying the iron with nickel or other metals made the material not only more permeable but also able to support a denser magnetic field, once again reducing the amount of reactive current required to form and maintain the field, further reducing the size of the impedance vector, with benefit for regulation.

The core of a toroidal transformer is made from grain-orientated low-reluctance alloy, rolled into a tight coil like a Swiss Roll cake, then formed into a ring and welded.

Nowadays there are many possibilties in the choices of magnetic materials available to the transformer designer. It includes more-recently devised materials such as ceramic magnetic materials incorporating ferrous particles, milled almost to dust, which enable cores to be formed accurately, both dimensionally and in shape and to have excellent magnetic properties; this compound provides an especially easy path for magnetic lines of force, and also low eddy current losses because every particle is insulated from the others. It is readily formed into a pot-shape with a stem up the middle to hold the coils, and a lid for the top.

This construction enables quite minute but very efficient transformers to be produced for use in, for example, printed circuit boards (pcb's). A similar technique is applicable to the ring-shaped core of a toroidal transformer.

An electromagnetic field naturally is perfectly circular, looked at in end view ie. from one of the poles. Any magnetic material within the field tends to distort it and gives rise to leakage flux - stray lines of force that contribute to losses. Materials that can be moulded can obviously be formed so as to fit the shape of a magnetic field and so reduce leakage flux losses.

In larger transformers where moulded cores are not an option because of cost, laminated cores have to be used, and obviously the limbs for the windings cannot be circular in section. They are therefore built up from different widths of laminations to approximate as closely as possible to the circular.

Example of an open style fixed toroidal transformer from REO

Auto and Variable Transformers

When the transformation ratio is fairly close, say 3:1 or closer, there is a cost advantage in combining the primary and secondary windings on a single core as shown in figure 9. The primary and secondary windings are connected within the transformer and the connection is brought out to a common terminal. The supply may be connected across the whole of the winding and the secondary to the common and the intermediate terminal to step the voltage down, or the other way about to step up.

Other advantages are that the net current in the common part of the winding is the difference between the primary and secondary currents. For example, if the ratio were 3:1 and the primary current 100A, the secondary current would be 300A but the net current would be 200A. So the winding can be of lighter construction compared with a normal double wound type. Further, there is less leakage reactance because of the closer linkage of primary and secondary so the reactance of an auto transformer is less than that of the double-wound type of the same power.

Although an auto transformer can be used to either step up or down, exactly like a normal double-wound transformer, the isolating function of the double-wound transformer is lost.

If the tapping could be moved, the ratio would change, this is exactly what is done with a variable transformer (commonly known as a 'Variac' although this is a trade name). The winding and its core are formed into a ring, and the tapping is a brush that can be moved to make contact with the windings at any point between the ends of the winding. Of course, as it is now possible for maximum current to be drawn from any part of the winding, it must all be of a suitable wire gauge. The variable transformer is very much like a potentiometer, except that the variable transformer is able step the voltage up as well as down, which a potentiometer cannot do. Also the potentiometer has much greater losses.

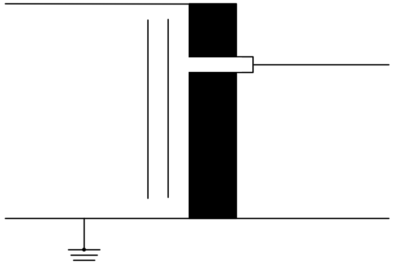


Fig 9 Auto-transformer

Example of a REO column transformer

Ferro-resonant Transformers

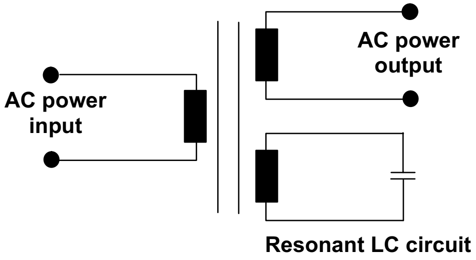
This type of transformer is deliberately designed to operate in a permanently-saturated condition to exploit the fact that in this state the output voltage cannot increase no matter what happens on the input side. The objective is to protect voltage-sensitive equipment - computer, pcb etc.

A saturated core severely distorts the flux sine wave, and a distorted sine wave is a pure sine wave ('fundamental') *plus* several harmonics of higher frequency as mentioned in the section on Saturation, page 10. Harmonics are wholly undesirable on the system as they may interfere with the correct operation of whatever equipment is the load and are reflected back into the supply system, not to mention reducing the efficiency of the transformer itself and generating extra heat. Ferro-resonant transformers are equipped with an extra secondary coil whose only load is a capacitor tuned to the resonate at the frequency of the supply voltage. This has the effect of suppressing the harmonics, and conveniently acting as a power reservoir.

Constant Voltage Transformers

The subject of saturation has been covered earlier in this book; on pages 10 and 16. This phenomenon can be employed in transformer design to produce some desirable effects, such as a constant secondary voltage, from a variable supply to the primary. This can be achieved by running a transformer in a state of persistent core saturation; also referred to as ferroresonance. The sine wave distortion associated with saturation is corrected by the use of an additional winding connected to a capacitor. This additional circuit is tuned to run in resonance with the power supply frequency.

Fig 10 Ferroresonant transformer



In addition to providing a constant output voltage, there are a number of other benefits to be gained for the ferro-resonant transformer; it filters out harmonics; both its own and those created by the load; cleans up the sine wave; protects against surges (transients) and over voltages; and provides ride-through during voltage sags and dips. One could say that it is a “good all-round power conditioner”.

There are some drawbacks however; such as the considerable hysteresis losses in the saturated core that cause excessive heat losses; and because the resonant circuit is tuned it is susceptible to supply frequency changes. There are also some hazards associated with ferroresonant transformers because the voltage of the resonant circuit is; by necessity; very high and extreme care is required during servicing.

Example of an Advance AGT 15000VA Constant Voltage Transformer (CVT)

Example of an Advance AGT 1000VA Constant Voltage Transformer (CVT)

Boosting and Bucking Transformers

These are two variants of the conventional two-coil transformer. They are designed to deliver a fixed-ratio step up (boosting) or step down (bucking) at a ratio that is quite close to provide a slight modification of the supply voltage. An auto transformer could do the same, but the advantage of isolation would be lost. These are used in voltage stabilisers where the transformers need only be rated for a fraction of the line power.

The "Buck and Boost" technique is also used in voltage regulators and stabilisers. A combination of fixed and variable transformers can be connected to give a constant output voltage from a variable supply. The buck and boost, fixed transformer is connected with its secondary winding(s) in series with the supply to be regulated; and the primary winding(s) are connected to a servo-driven variable transformer with a zero volts centre tap. By driving the variable transformer; clockwise or anticlockwise; in response to a correction signal generated from an electronic comparator, the voltage can be held within close limits, irrespective of supply variation by as much as +/- 25%.

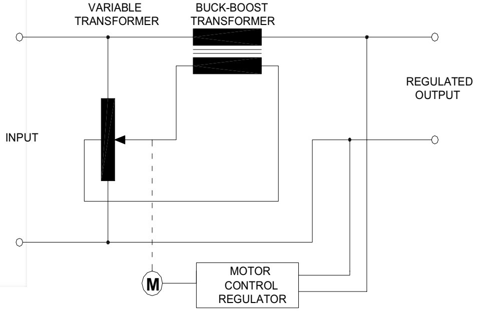


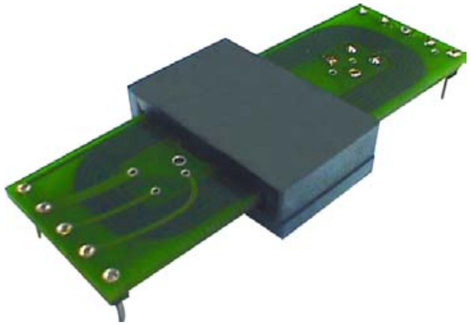
Fig 11 Typical single phase voltage stabiliser circuit

Example of a REO 3-phase voltage stabiliser with separate control of each phase

High Frequency Transformers

The frequency of the supply voltage is an important factor governing the *rate of change* of the inducing voltage. The rate of change governs the iron losses (eddy current and hysteresis losses) of which hysteresis losses are the more important. For this reason, high frequency transformers usually have a core made from very thin laminations or dispense with a core altogether and are wound on a non-magnetic former, often hollow to provide an air core.

High frequency transformers are used predominantly in switch-mode power supplies after the switched DC stage to reduce the output voltage level.



Example of a REO Planar transformer available up to 60 W

Heat Dissipation

Whenever a current flows in a conductor, heat is generated in accordance with the I^2R law. All electrical equipment uses insulation, and insulation has definite temperature limits, beyond which it begins to break down. Plainly, it is necessary to ensure that these limits are not breached when a transformer is in normal service.

Cooling method depends on the construction of the transformer:

Power transformers are usually, if >250kVA, liquid filled. The liquid circulates by convection. Radiators may be fitted to assist with cooling. Provision may be made to force air over the radiators; if so, the cooling fans are more than likely to be automatically switched by temperature sensors. Most commonly, the liquid used is oil, but when transformers have to be installed in a hazardous area, such as an oil or gas treatment installation, a non-flammable liquid is used such as silicone.

The larger sizes of liquid-filled transformers are fitted with a 'conservator' - *ie* a header tank to accept expansion or contraction of the liquid. The conservator is always fitted with a breather and a filter containing a silica-gel dessiccant, itself containing an agent to identify (by colour change) the need for its regeneration or replacement. Note that present regulations require that the agent must not contain cobalt dichloride, a known carcinogenic.

Sealed power transformers, cooled by toxic but non-flammable liquids, have been built for use in hazardous environments but are being phased out. A space is left above the liquid level and filled either with dry air or inert gas. Such transformers have to be fitted with a pressure relief valve designed to deliver a trip signal as well as to release pressure.

Dry type transformers are those which are not liquid-cooled, obviously, but the same temperature-limit requirement still applies, and for the same reason. Dry type transformers exist in a wide range of sizes, from the smallest up to power transformers of 500MVA or even bigger. The larger sizes of the are likely to be equipped with forced-air cooling fans, thermostat controlled.

Adequate cooling of smaller dry type transformers is normally provided by the surrounding air. In industrial installations, care may need to be taken nevertheless, as the ambient air may reach too high a temperature especially if the transformer is installed in an enclosure in which there is other heat-producing equipment. Enclosure ventilation may be necessary, and possibly forced ventilation. This sort of situation can easily arise in industry when it is decided to put some new device into an existing enclosure.

Cooling systems are identified by a four-letter code:

1st & 3rd letter-cooling medium.
Code letters:
0 - Mineral oil
L - Synthetic insulation liquids
G - Gas
W - Water
A - Air
S - Solid insulation

2nd & 4th letter-circulation method.
Code letters:
N - Natural circulation
F - Forced circulation

Thus the code for a dry-type, encapsulated, fan-cooled transformer is SNAF, and oil natural air natural is ONAN

Temperature

The maximum temperature of the windings of dry type transformers depends on the material used for insulating the conductors of the windings. The materials are classified accordingly, with a maximum temperature allotted to each. The classifications are identified by a code letter and the temperature class is marked on the rating plate. The following classes are quoted in BS171:1970 and BS2757:1956 now superseded by EN60742

The original three classes were A, B, and C, E, F, and H were added developments, interpolated.

Class A
Material: Impregnated cotton, silk etc, paper, enamel
Max temp.105°C

Class E
Material: Paper laminate, epoxys
Max temp.120°C

Class B
Material: Glass fibre, asbestos (not impregnated), mica
Max temp.130°C

Class F
Material: Glass fibre, asbestos (epoxy impregnated)
Max temp.155°C

Class H
Material: Glass fibre, asbestos (silicone impregnated)
Max temp.180°C

Class C
Material: Mica, ceramics glass; with inorganic binders
Max temp.>180°C

The temperatures listed in the standard are maximum so the permitted temperature rise in service must be based on the ambient temperature. For test and rating, this usually taken as 40°C. This means that a Class B transformer is designed for (130 - 40) = 90°C temperature rise and will be within limits in any ambient temperature <40°C.

Liquid-filled transformers do not fall under the classifications above. There is simply a requirement that the temperature rise of the windings shall not exceed 65°C and that the temperature rise at the top of the liquid shall not exceed 60°C if the transformer has a conservator or is sealed.

Protection

Small-power transformers such as those used in industrial distribution systems and within equipment are either not protected at all (if they are very small) or protected by fuses on the primary side against overcurrent and on the secondary side against short circuit faults. The primary side fuses are a convenient means of isolating the transformer and the secondary circuit after it has been disconnected.

The protection of high-power transmission and distribution transformers is a wide and specialised matter, and is outside the scope of this guide.

Markings of Transformer Terminals

Because the flux lags 90 degrees behind the primary voltage and the secondary voltage lags another 90 degrees behind the flux, there is an inherent phase shift of 180 degrees between the primary and secondary voltages of a transformer. Usually this is of no importance but for some practical applications it is necessary to know the phasing of single-phase transformers so that the outputs of two or more transformers will be in synchronism and may be paralleled.

For this reason it is common practice to 'dot-mark' the terminals - one of the two on each side of the transformer being so marked. There is then no doubt that the phasing of the outputs of transformers supplied from the same source must be correct.

The terminals of three-phase transformers are conventionally marked A, B, C on the high-voltage side, and the corresponding phases marked a, b, c on the low-voltage side. If there is a third winding, it is marked 3A etc (or 3a etc).

If either set of windings (or both) are star-connected the terminal of the star point is marked YN or yn.

The Future

It is inevitable that more efficient transformers will be required in the future; especially with the introduction of legislation such as the EUP (Energy-using Products) directive, which is due to come into force on 1st July 2006 and will have to be implemented by 2008. In simple terms this directive will apply to all energy using products and amongst other things the amount of energy consumed will have to be evaluated and reduced to a minimum.

The problem with conventional transformers is the high leakage flux, caused by traditional core construction, which has square edges. By rounding these edges the losses caused by flux leakage can be reduced considerably and this results in a transformer that is consistently > 90% efficient even when working at a very low power (stand-by mode for example). The 'A' transformer manufactured by REO is such a transformer with a core that has rounded edges. The whole assembly is encapsulated for mechanical stability and fits in the same footprint as a conventional transformer.

The Author

From the beginning in the heavy electrical industry as an apprentice in Manchester, A.W. Richmond has been a close observer of the highest points in development of the industry - and its lowest. Now, he believes, the past few years have seen an inspiring revival of British electrical innovation, design and production, taking the industry into the world class again.

His own engineering experiences have compassed such diverse activities as managing the sales of high voltage switchgear, setting up two manufacturing plants, in South Africa and in the Middle East, ranging the world as a freelance consultant, and latterly, being involved in high level training for engineers in the offshore oil industry.

This guide is one of a series. Email us if you would like to receive all of our mini guides and to be entered onto our mailing list at main@reo.co.uk