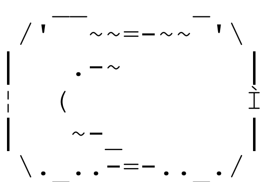
Understanding Transformers

By G8MNY (Update Aug 15)
(8 Bit ASCII graphics use code page 437 or 850, Terminal Font)

Although the principles have been known since Faraday, here are some practical pointers. Transformers have the ability to change AC voltages (& hence impedance match), isolate several different windings, saturate the core to protect against large current spikes.

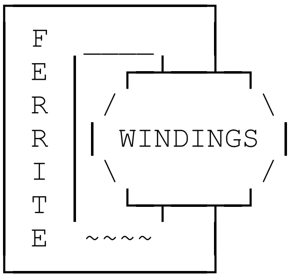
THE IDEAL TRANSFORMER

All the copper must be wrapped around all the iron, & all the iron wrapped around all the copper, as this is not possible the most efficient shape for a transformer would be a two piece chain, where one end of each link is thinned down to passes through the hole in the other link.



Copper Iron
MOST EFFICIENT

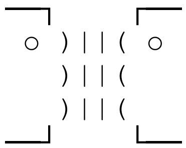
Practical Option used in Line & EHT Transformers



Maximum efficiency happens when the copper losses equals the iron losses.

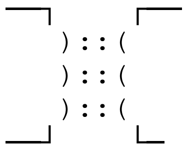
Typical power efficiency is about 95% for a modest transformer, with smaller power ones (plug top) down to about 70% & a large substation sized 3 phase ones up to 98%.

SYMBOL



the DOT o indicates same phase

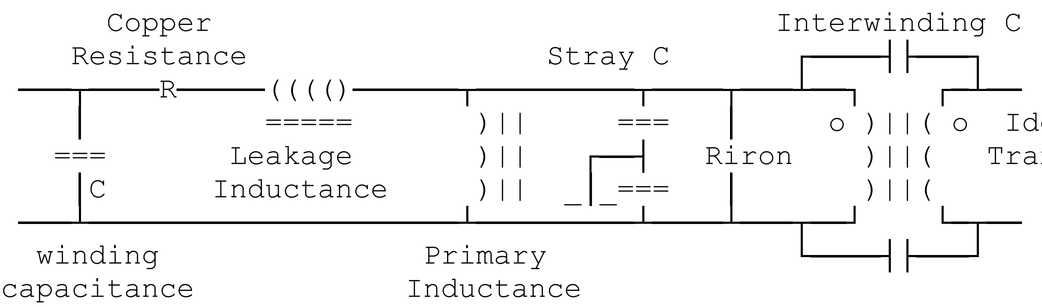
IRON CORE
The windings can have tapings



IRON DUST/FERRITE
The core can be tuned with a movable part

EQUIVALENT CIRCUIT

As transformers are in the real world they have short comings, this equivalent circuit demonstrates most of them. (for primary only!)



The iron losses are often indicated with "Riron" like this, but it represents both eddy current losses & BH curve losses, where the value is not linear with voltage but a curved relationship with the magnetising current.

```
          Flux            __.
   IRON              |    _.-~~/~            A MODERN     |      ..-——
   LAMINATE          |./'  ./'               FERRITE      |    //
            ./|    ./'                                    |  //
    ———————/——+——/——————— +H            ————————————/+/———————— +H
       ./'    |/'    Amp Turns                      //|
     ./' _./'                                      // |
  _.:..-"     |-B                            ——-''    |-B
 —~~
```

With ferrite the eddy current & BH losses are very small but have a sudden limit, & the BH curve magnetic cycle area which determine the power loss per cycle is also much smaller than for iron. (difficult to draw here).

The high frequency possibilities of ferrite means much smaller lighter transformers. For most ferrite cores the power handling is proportional to frequency up to about 250kHz. So a core handling 50W @ 25kHz can handle 500W @ 250kHz, but can the copper & insulation!

CONVENTIONAL MAINS TYPES
These are made of layers on iron sheet with a central bobbin for the windings. to reduce eddy currents..

```
  Solid iron            Laminated          Welded Laminated       Iron Dust

          __
 /|\  |  |  |    |        ||||                  ÊÊÊ
  |   |  |  |    |        ||||                  ||||
  |   |  |__|  \|/        ||||                  ||||
        <--
```

Solid iron	Laminated	Welded Laminated	Iron Dust
High circulating eddy currents flow around sides of large cross section like a shorted turn.	Little eddy current in each sheet as little area & Insulated (oxide) Surface to next Laminate.	Still little eddy currents as only welded on one side.	Very little eddy currents as only tiny area per particle.

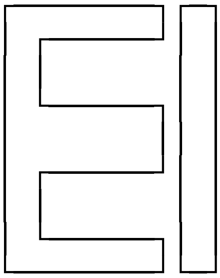
```
     _|   |_
    / | I | \
   |  | R |  |
   |  | O |  |
    \_| N |_/Bobbin
```

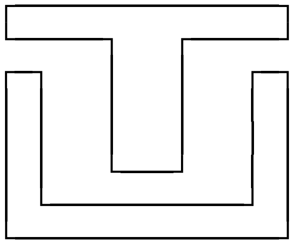
The weight of the transformer determines the energy through put for 1 cycle, so a 60Hz transformer is 20% smaller & lighter than a 50Hz one of the same rating. Ratings also depend on maximum safe enamelled wire temperature & the dissipation. E.g. a fan cooled one in a projector would catch fire without the fan!

The laminates are either E I or U T shaped to form the core, with a copper wire wound bobbin placed on the middle leg. Note the size of the centre limb is about 2x the outer part as it has to cope with 2x the magnetic flux. These transformers are normally run close to the core saturation point, so increases & voltages or a drop on supply frequency soon cause problems. E.g. a 2x 110V primary 60Hz designed transformer run at 242V across the winding on series & at 50Hz, would have the magnetic flux increased by 10% from the voltage, & a further 20% from the frequency change, This could take the iron beyond super-saturation & cause the inductance to drop many times, producing a heavy magnetising load current, high harmonic currents & associated heavy heating of the core & copper windings!

A heavily saturated cores cause high 3rd harmonic line currents & increased no load powers in the transformer. But properly utilised & choke fed, a saturated tuned transformer makes the heart of a good voltage regulator/line conditioner.

The EI format is often made with 2 x I shapes cut out of 2 Es, so it is efficient in material usage.



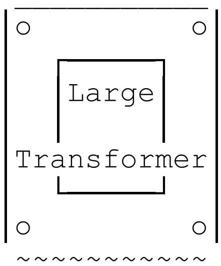


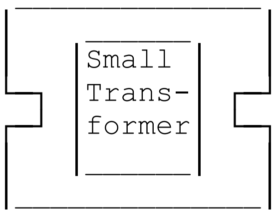
Not Popular

Each lamination is oxidised on one side to produce a poor conductor to the next lamination to reduce eddy currents. Also to minimise magnetic losses further the laminations are normally interlaced so that the joining gaps are covered in the adjacent layers.

To hold the transformer together you can get away with welds across the laminates provided no electric loop is formed.

More conventional methods are to use bolt holes in the corners or centre of the laminates sides, but the hole area must not degrade the magnetic circuit.





The bolts hold down 2 clamping plates to squeeze the laminations together, as when magnetised the laminations will oppose each other & try to push the laminations apart. The end plates can be fully enclosed to provide full electrical & some magnetic shielding.

```
    _____
  _//~~~\\_ Outer
 Ì|~~~~~~~|¦Copper
 Ì|_______|¦Shorted
  ~\\___//~ Turn
    ~~~~~
```

Further magnetic shielding can be proved by a copper strip around the whole bobbin former, but outside the laminations.

Transformer acoustic hum is made from the steel & copper movement due to the magnetic forces, both at 2x the frequency (6x for 3 phase), but also from magneto-striction where the steel parts actually shrink & expand as their magnetic domains in each crystal of iron rotate, so clamping does not reduce this noise!

Quite often the whole lot can be varnished dipped/impregnated to provide the best low noise transformers & corrosion & dampness resistance. But repair is normally impossible afterwards!

End plates or crimped folded steel tabs casing, provide mounting holes eitheraround frames or just 2 holes on Tabs.

```
            _n_n_n_
       ____/_______\___
 Side >¦0  0        0  0Ì         /~~~~~~~~\
 frame |~~~~~~|▒|~~~~~~|    Tab |_|~~~~~~~~~~~~|_|      ┌────────┐
 holes |      |▒|      |  holes |0|Folded Case|0|   ┌─┴────────┴─┐
  as   |______|▒|______|        |_|___________|_|   │   P C B    │
 well >¦0  0        0  0Ì          \_______/        └─┬────────┬─┘
        ~~~\~~~~~~~~/~~~                              └Ê─Ê─Ê─Ê┘
            ~u~u~u~
```

PCB mounts can be by soldering the connection pins moulded on to the plastic bobbin former.

The bobbin can be either over wound with an insulating layer separating primary & secondary, or a single bobbin with 2 wind areas, so the insulation integrity is maintained even in a burnt out state (meets double insulation safety standard).

```
    ____________        |~~~~~~~~~~~~~~~~~~~~~~~~~~~|
   /  Secondary \       |                           |
  /   __________  \     |    _____        _____     |
 |   /          \  |    |   |Ð═══¤══════¤═══Ð|     |
 |  |   ________ | |    |   | |  Primary      |     |
 |  | |         || |    |   | |               |     |
 |  | |  CORE   || |    |   | Ï═══════════════Ï     |
 |  | |_________|| |    |   | | Secondary     |     |
 |  | Primary    | |    |   | |               |     |
 |   \__________/  |    |   | ¤═══Ð══════Ð═══¤     |
 \ Insulation^   /      |   ~~~~~  CORE ~~~~~~      |
  \_____________/       |___________________________|
   LAYERED BOBIN              SPLIT BOBBIN
```

Another safety feature often included nowadays is a thermal fuse fitted inside the transformer primary layer. These protect from fires & should not be bypassed, replacements are available.
The enamelled copper wire windings must be wound fairly tight as like the laminations there is forces between wires & any movement will eventually rub through the enamelling & cause a shorted turn & an instant failure.

Connections
These can be wired remotely or tags mounted on the bobbin etc.

TURNS PER VOLT (from Tom GM4PRO)
A blanket approximation of 7 turns per volt, even for the fairly small transformer.

$$E = 4.44*f*B*A \text{ Volts}$$

Where "E" is the e.m.f. per turn (NOT turns per volt),
"f" is the supply frequency (i.e. 50 Hz.),
"B" is the peak flux density of the core material (typically 1.5 Tesla for cold rolled grain orientated silicon steel, as used in most modern transformers),
"A" is the cross sectional area of the core in square metres.

For a typical small mains transformer, this can be reduced to:

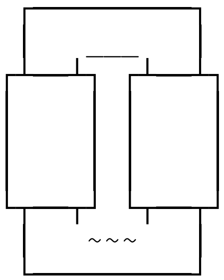
Turns per volt = 4.65/A

Where "A" is the core sectional area in square inches.

TURNS RAIIO & MATCHING
For AF transformers in audio stages, an output transformers tapings sets the load line seen by the output valves. Impedance ratio is just the winding ratio squared. So a 20:1 transformer turns or voltage ratio gives a Z ratio 400:1
e.g. used on a 15Û LS, the Anode sees a 6k load.
Or to match a 17Û ribbon mic to 600Û AF preamp input, that is a Z ratio of 36:1 or 6:1 turns ratio, so an AF transformer with 1mV input that gives 6mV output may do.

UNCONVENTIONAL TYPES
In some applications other designs have reduced fields or offer low profile etc.

L Shaped Core
These are magnetically inferior depending whether the primary & secondary overlap on common bobbins or are on different legs.



The core can be made from flat laminations or from U curved sections where each lamination is a different shape! In that case the magnetic flux leakage is much reduced.

Toroidal
These are very popular nowadays & offer a much lighter transformer as less steel is used & they have quite magnetic low flux radiation.

The main problem is in winding them, as this has to be done once the core is put together. The core is just very long a strip of laminated steel with an oxide layer on one face to reduce eddy currents, wound on itself in spiral fashion with an insulating layer on the outside.

```
  .-~~~~~-.  The primary is wound first, as it is normally the thinner wire &
 /  .--.  \  more able to bend around the square cross section of the core.
(  (    )  ) Very thick wire for a high current secondary can be difficult &
|\  '--'  /|  either several thinner wires used in parrellel, or flat strip
 \'-,__.-'/   used, as the whole secondary has to be on a winding machine's
  '-.__.-'    bobbin shuttle & has to pass through the centre of the toriod.
```

The cross section looks the same as a conventional layerd bobbin transformer.
Primary to secondary insulation failure is always a possibility with a toroidal. So using an earth on kit using them is recommended!

Due to the reduced amount of steel & efficient use of copper they also suffer "randomly" from very high fluxing up turn on currents, as a full half cycle at turn on looks like "DC" & will keep the core saturated over several cycles, greatly reducing the inductance. E.g. a 230W transformer, will take about 1A on full load, including a very low 50mA magnetising current, but up to 13A surge on turn on. So fusing MUST be a slow blow type.

Mounting them is a problem, as too high a clamping force can damage the windings. & too little pressure will allow for transit movement & winding damage "CATCH 22"! So a bolt clamp & plate with rubber mats are normally used.

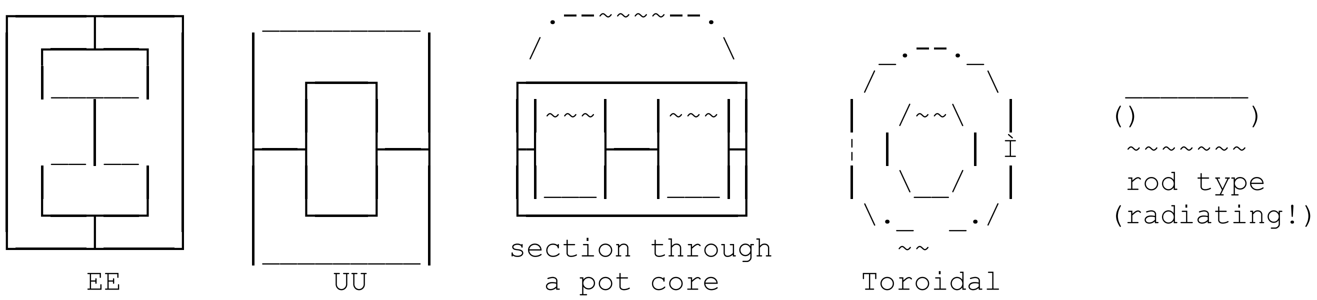
```
Circular      Shaped metal plate
rubber mat ======┐    ▒    ┌======= _   W A R N I N G
           /~~~~\ \_[~]_/ /~~~~\ |\   Low AC Voltage @
          |toroid|    ▒   |toroid|     VERY HIGH CURRENT
Circular  |      |    ▒   |      |     available over 1 turn
rubber mat \____/     ▒    \____/ |/_  DO NOT SHORT
-----------==========▒===================-----------
     Chassis        ▀▀▀Bolt
```

OTHER TRANSFORMER USES
In audio work they are still used where... good isolation, balancing, phantom powering, impedance matching are needed, well as provide good RFI protection.

```
                Phantom supply
                          |  1:10     10mV       |\
Mic     ──────────────────)──┐  ┌────────────────┤ >───
with      1V of RF & hum  |  )||(      Z=10K >   |/
Preamp     pickup on a    |__)||(
100Û      long screened      )||( Magnetically    AF MIXER
nominal   balanced cable     )||( Screened        With no RFI
1mV     ─────────────────────┘| | Case            & no hum
        -------------------------|─────────────────
     Dirty Earth return      _|_ RF Ground
```

There are costs of course, as it is difficult to proved a wide frequency range needed for really super audio, but 40Hz - 15kHz @-1dB is quite achievable, with >60dB common mode hum & RFI rejection.

RF TRANSFORMERS
These iron dust cores or shaped ferrite cores. Shapes can be EE or UU, pot core, toroidal, or even just a rod.



For switch mode applications at 10-100kHz the power capability can be enormous compared to conventional mains frequency type of the same size.

Several stacked ferrite rings can be used to provide useful broadband HF power output transformer.

```
              .=====.                       O/P 1__    ____
   O/P 1─▄▄▄▄//▄▄ ▄▄\\▄▄▄▄─O/P 2                   )::(
          ( | | ) ( | | )                   +12V___)::( Aerial
          ( | | ) ( | | ) -6x rings                )::( Secondary
          ( | | ) ( | | )                   O/P 2__)::(____
  +12V███████\\█████//████               2x 1/2 turn    5 turns
Primary is    '=====\\ Secondary
brass tubes inside   \\ turns inside
rings connected         the tubes
to end pates.
```

For higher frequencies & low power, bead types (miniature toroid), or double hole versions give extended frequencies up to 1GHz. The 2 hole one offers complex RF hybrid possibilities used in mixers etc.

```
 __     _ __
((o)   ( (oo)
 ~~     ~ ~~
```

Why don't U send an interesting bul?

73 De John, G8MNY @ GB7CIP

/EX