
DC MACHINES AND TRANSFORMERS

Chapter 6

SPECIAL PURPOSE TRANSFORMERS

Isolation Transformer • Single Phase Welding Transformer
Pulse Transformer • K-Factor of Transformers

Study Notes for Engineering Students

Detailed theory • Diagrams • Tables • Worked examples

15 Multiple Choice Questions with Answer Key • 10 Broad Questions

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Chapter 6: Special Purpose Transformers

6.0 Introduction

A general-purpose power or distribution transformer is designed for one job: to change the voltage level of a sinusoidal supply efficiently at the power frequency (50 Hz in India) while feeding an ordinary linear load. Many practical situations, however, ask for something more specific. A hospital needs a supply that cannot send a dangerous current through a patient; an arc welder needs a source that gives a high voltage to strike the arc but only a low voltage and a controlled current while welding; a thyristor or MOSFET gate circuit needs to receive sharp, undistorted pulses from a low-voltage control circuit; and a building full of computers and variable-speed drives needs transformers that do not overheat on distorted currents.

Transformers modified in construction or rating to meet such needs are called **special purpose transformers**. They work on the same basic principle as any other transformer – Faraday’s law of electromagnetic induction – but their core, windings, insulation and rating are deliberately shaped for a particular duty. This chapter covers four of them.

Table 6.0: Chapter at a glance

Section	Topic	Main idea in one line
6.1	Isolation transformer	Separates the load from the supply electrically while transferring power magnetically (1:1 ratio, earthed shield).
6.2	Single phase welding transformer	Step-down transformer with high open-circuit voltage and large leakage reactance, giving a drooping, adjustable current output.
6.3	Pulse transformer	Small, wide-bandwidth transformer that passes rectangular pulses with minimum distortion and gives isolation.
6.4	K-factor of transformers	A number that tells how well a transformer can carry harmonic-rich (non-linear) loads without overheating.

Learning Outcomes

- Describe the construction, working principle and applications of an isolation transformer.
- Explain why a welding transformer needs high leakage reactance and how its current is adjusted; use the duty-cycle idea.
- Describe the construction and working of a pulse transformer and define pulse parameters such as rise time and droop.
- Define the K-factor, calculate it from a harmonic spectrum and explain overheating caused by non-linear loads.
- Compare special purpose transformers with ordinary power transformers.

6.1 Isolation Transformer

6.1.1 Introduction and definition

An **isolation transformer** is a transformer used to transfer electrical power from a source of AC power to a load while **electrically isolating** the load from the source. Its primary and secondary windings are wound on the same magnetic core but have *no conductive (galvanic) connection* between them; energy passes only through the common magnetic flux. In most isolation transformers the turns ratio is 1:1 (for example 230 V / 230 V), so the voltage is not changed; sometimes a small step-up or step-down ratio is used (for example 230 V / 110 V for safe site tools).

Every ordinary two-winding transformer already isolates its windings from each other, so what makes an isolation transformer “special” is that isolation is the *main design objective*. Extra insulation, wider spacing between windings, an earthed electrostatic shield and low leakage current are provided so that the isolation is reliable, safe and also effective against electrical noise. By contrast an autotransformer has a single winding shared by input and output and therefore gives **no** isolation.

6.1.2 Construction

The construction is similar to that of a normal single-phase transformer, with additional features that improve insulation and noise rejection:

- **Core:** built from thin laminations of cold-rolled grain-oriented (CRGO) silicon steel, stacked and clamped, in core type or shell type form. Laminations reduce eddy current loss and silicon steel reduces hysteresis loss.
- **Primary and secondary windings:** two separate windings of insulated copper (or aluminium) wire. They are often wound on separate limbs or on separate bobbin sections, with generous spacing, so that the insulation between them is large and the capacitance between them is small.
- **Electrostatic (Faraday) shield:** a thin sheet of copper or aluminium foil placed between the primary and secondary windings, with one open overlap so that it does not form a short-circuited turn. The shield is connected to the earth terminal. Sensitive designs use a separate shield around each winding.
- **Insulation:** multi-layer insulation (kraft paper, polyester film, varnish or resin impregnation) between layers, between windings and between windings and core. It is tested at a high voltage (hi-pot test).
- **Enclosure and terminals:** a ventilated or sealed metal case connected to earth, terminal block, fuse or circuit breaker on the primary, and tappings if the secondary voltage needs adjustment.

Table 6.1: Constructional features of an isolation transformer

Constructional feature	Purpose
Separate windings with large clearance	Gives high dielectric strength and low coupling capacitance between primary and secondary.
Earthed electrostatic shield	Diverts high-frequency noise and transients to earth instead of letting them pass to the load.
CRGO laminated core	Low iron loss and low magnetising current; efficient transfer of power.
High-grade insulation, resin impregnation	Withstands high test voltage; safe against shock and moisture.
Earthed metal enclosure	Protects the user if an internal insulation failure occurs.
Low leakage current design (medical grade)	Keeps the current that can flow to earth through a patient in the microampere range.

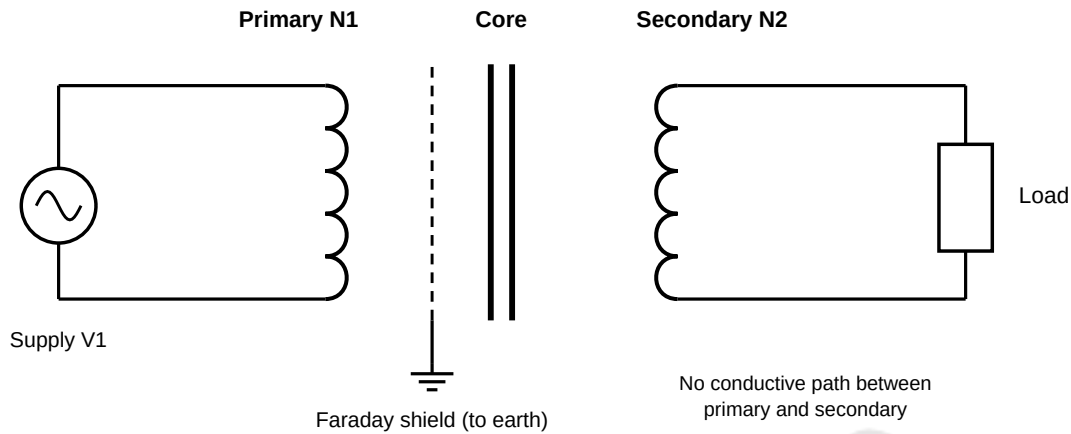


Fig. 6.1: Isolation transformer with electrostatic (Faraday) shield between primary and secondary windings

6.1.3 Working principle

The working principle is mutual induction. When an alternating voltage V_1 is applied to the primary winding of N_1 turns, a small magnetising current flows and sets up an alternating flux in the core. This flux links the secondary winding of N_2 turns and induces an emf in it. The induced emf per winding is given by the emf equation:

$$E = 4.44 f N \Phi_m \quad \text{and} \quad V_2 / V_1 \approx N_2 / N_1 = a$$

where f is the supply frequency, Φ_m is the peak core flux and a is the turns ratio ($a \approx 1$ for a typical isolation transformer). When a load is connected, the secondary current produces a demagnetising effect and the primary draws a balancing load current, so power is transferred from the primary circuit to the secondary circuit with only the usual copper and iron losses.

How isolation is achieved and why it protects:

- **No metallic path.** The only link between the two circuits is the magnetic flux. A fault or earth connection on one side does not directly appear on the other side.
- **Floating secondary.** The secondary circuit is not referenced to earth. If a person touches one live secondary conductor while standing on earth, no complete circuit exists and no dangerous shock current flows (a single earth fault does not cause a shock). Such a supply is called an ungrounded or IT-type supply.
- **Ground-loop breaking.** Two instruments connected to different earth points can create a loop in which stray current flows and adds hum or error to measurements. An isolation transformer breaks the loop.
- **Noise rejection by the shield.** Noise and fast transients from the mains travel across the winding-to-winding capacitance (common-mode noise). The earthed shield splits this capacitance into two small parts and sends the noise current to earth, so the capacitance between primary and secondary can drop from hundreds of picofarads to a few picofarads or less. Note that *normal-mode* (line-to-line) noise is passed on largely unchanged, because it is transferred magnetically like the wanted signal.

Worked Example 6.1

A 2 kVA, 230 V / 230 V single-phase isolation transformer has a full-load efficiency of 96% at unity power factor. Find the rated currents and the full-load losses.

Solution: Rated current $I = S / V = 2000 / 230 = 8.70 \text{ A}$ (both primary and secondary, since $a = 1$, ignoring the small magnetising current).

Output power = 2000 W (unity pf). Input power = $2000 / 0.96 = 2083 \text{ W}$. Total loss = $2083 - 2000 = 83 \text{ W}$ (core loss + copper loss).

6.1.4 Types of isolation transformers

Table 6.2: Common types of isolation transformers

Type	Special feature	Typical use
Basic (unshielded)	Separate windings, no shield; isolation only.	General safety isolation of equipment, test benches.
Single shielded	One earthed Faraday shield between windings.	Computers, instrumentation, noisy mains.
Double / multiple shielded	Shield around each winding plus an overall shield; very high noise attenuation.	Sensitive measurement, audio and laboratory equipment.
Medical grade	Reinforced insulation, very low leakage current, often used with a line isolation monitor.	Operating theatres, intensive-care and patient-connected equipment.
Step-down isolation (e.g. 230/110 V)	Provides isolation and lower voltage together.	Construction-site power tools, damp locations.

6.1.5 Applications

Table 6.3: Applications of isolation transformers

Application area	Why an isolation transformer is used
Medical and hospital equipment	Limits shock current through a patient or operator; a first earth fault does not interrupt life-support equipment.
Servicing and testing of electronic equipment	A technician working on a live chassis that is connected directly to mains (such as a switch-mode supply) is protected from earth-referenced shock; test instruments are also protected.
Computers, PLCs and data equipment	Shielded units block mains noise, surges and transients from reaching sensitive electronics.
Audio / video and measurement systems	Breaks ground loops that cause hum and measurement errors.
Construction sites and workshops	110 V (or lower) isolated supplies for hand tools reduce the risk of fatal shock.
Industrial control and automation	Isolates control circuits from the power circuits and from different earth potentials.
Marine shore-power and laboratories	Protects against galvanic corrosion currents and gives a safe, isolated supply.

6.1.6 Advantages and limitations

Advantages

- Complete galvanic isolation between supply and load; improved electrical safety.
- Attenuates common-mode noise and surges (with shield); reduces nuisance tripping and malfunction.
- Eliminates ground loops; allows a floating secondary.
- Simple, rugged, no moving parts, long life and almost maintenance-free.

Limitations

- Heavier, larger and more costly than an autotransformer of the same kVA rating.
- Has losses (core and copper) and some voltage regulation; draws magnetising inrush current at switch-on.
- Does not remove normal-mode noise, voltage sags or harmonics by itself; it is not a voltage regulator.
- Does not prevent a second fault: if both secondary conductors reach earth, protective devices are still required.

6.1.7 Isolation transformer compared with autotransformer

Table 6.4: Isolation transformer vs autotransformer

Parameter	Isolation transformer	Autotransformer
Windings	Two separate windings	One common winding with a tapping
Electrical isolation	Yes – complete	No – input and output are connected
Shock safety	Secondary is floating; safer	Output can be live with respect to earth
Size, weight and cost	Larger and costlier	Smaller and cheaper
Efficiency	Slightly lower	Higher
Noise rejection	Good (with shield)	Poor; noise passes through the common winding
Typical use	Safety, noise control, medical	Voltage variation, motor starting

Key Points – Isolation Transformer

- Turns ratio is usually 1:1; power is transferred only by mutual induction.
- An earthed electrostatic shield between windings reduces coupling capacitance and common-mode noise.
- Secondary is floating, so a single contact with a live conductor does not cause shock current.
- Used in medical equipment, electronic servicing, sensitive instrumentation and site power tools.

6.2 Single Phase Welding Transformer

6.2.1 Introduction

In **arc welding** two metal pieces are joined by melting their edges with the intense heat of an electric arc (the temperature in the arc exceeds 5000 °C) and usually adding molten metal from a consumable electrode. The supply for the arc must be quite different from the ordinary mains: a high voltage is needed only for a moment to strike the arc, after which a low voltage and a large adjustable current are needed to maintain it. A **single phase welding transformer** is a step-down transformer designed to supply this kind of power from a 230 V or 415 V single-phase mains. It is the commonest and cheapest source for manual metal arc (stick) welding.

Requirements of a welding power source

- **High open-circuit voltage (OCV)** of about 55–100 V to strike the arc easily. It cannot be made very high because of the shock hazard to the welder.
- **Low arc voltage** of about 20–40 V during welding.
- **Large current** (tens to several hundred amperes) that can be adjusted to suit electrode size and plate thickness.
- **Drooping voltage–current characteristic** so that the voltage falls rapidly as the current rises (constant-current behaviour).
- **Limited short-circuit current** when the electrode touches the job, only a modest multiple of the welding current, so that the transformer and electrode are not damaged.

6.2.2 Construction

The welding transformer is a step-down transformer, but its design is intentionally different from a distribution transformer. In a power transformer leakage reactance is kept small to get good voltage regulation; in a welding transformer a **large and adjustable leakage reactance** is built in to get the drooping characteristic.

- **Core:** laminated CRGO silicon-steel core of core type or shell type. A larger air gap or a magnetic shunt may be included in the leakage path.
- **Primary winding:** many turns of insulated copper or aluminium wire (relatively thin) connected to the 230 V or 415 V, 50 Hz single-phase supply. Tappings are often provided for coarse adjustment.
- **Secondary winding:** only a few turns of heavy copper strip or thick conductor to carry hundreds of amperes at 20–100 V.
- **Winding arrangement:** primary and secondary are placed on separate parts of the core (or are separated by a gap) so that a large fraction of the flux leaks and does not link both windings.
- **Current-control device:** movable core or magnetic shunt, movable coil, tapped winding or a saturable reactor (see Table 6.5).
- **Insulation and cooling:** class F or class H insulation; natural or fan-cooled air-cooled design for small units and oil-cooled design for heavy-duty sets.
- **Accessories:** output terminals, welding cables, electrode holder, earth (work) clamp, ammeter or current scale, thermal cut-out.

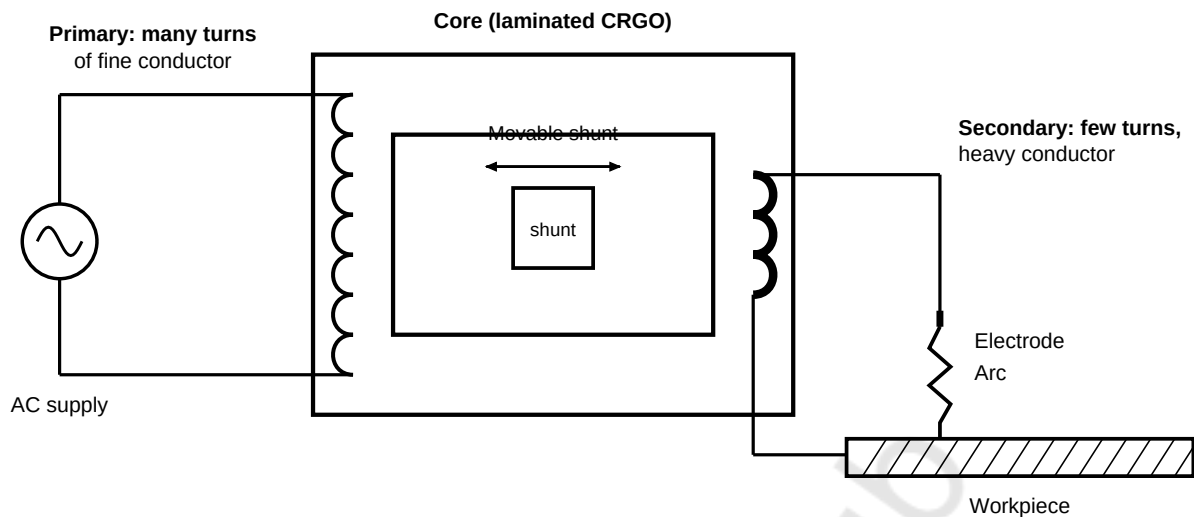


Fig. 6.2: Single phase welding transformer with movable magnetic shunt for current control

Table 6.5: Methods of controlling welding current

Method of current control	How it works	Remarks
Tapped primary or secondary	Changes the number of turns, so changes the open-circuit voltage and current in steps.	Simple; coarse control in steps.
Movable core / moving magnetic shunt	A magnetic shunt moved between the windings changes the leakage flux and hence the leakage reactance.	Smooth control; mechanical movement by a hand wheel; widely used.
Moving coil	The distance between primary and secondary coils is changed; larger distance gives more leakage reactance and less current.	Smooth control; used in older and heavy-duty machines.
Saturable reactor in series	DC in a control winding changes the reactor inductance.	Smooth and remote control; more complex.
Tapped reactor (series choke)	An external choke with tapings gives different reactance steps.	Cheap; used for current setting in small sets.

6.2.3 Working principle

The transformer steps down the mains voltage and provides a large current at low voltage on the secondary side. The secondary is connected between the electrode holder and the workpiece (through the earth clamp). The working can be understood in the following stages:

1. **Electrode away from the job.** No current flows in the secondary and the full open-circuit voltage (about 60–100 V) appears across the electrode and the work.
2. **Striking the arc.** The welder touches the electrode on the job. This short-circuits the secondary and a large current starts to flow. The large leakage reactance limits this current to a safe value, and the terminal voltage falls almost to zero.
3. **Establishing the arc.** The electrode is lifted a few millimetres. The air gap ionises under the high voltage and an arc is formed. The arc voltage settles at about 20–40 V and the heat of the arc melts the electrode tip and the work.

4. **Maintaining the arc.** If the arc length varies a little as the hand moves, the arc voltage changes, but because the characteristic is steeply drooping the current changes very little. The heat input and the weld stay steady.
5. **AC arc re-ignition.** The AC arc extinguishes at every zero crossing of the current (100 times a second at 50 Hz). It re-strikes again each half-cycle because of the high OCV and the ionising substances in the electrode coating, so electrodes designed for AC use must be selected.

Drooping characteristic. If the secondary induced emf is E_2 and the total leakage reactance referred to the secondary is X , the terminal voltage at a load current I is approximately

$$V_t \approx \sqrt{E_2^2 - (IX)^2} \quad \text{and} \quad I_{sc} \approx E_2 / X$$

Increasing X (by moving the shunt in, or the coils apart) makes the curve droop earlier and lowers the welding current; decreasing X raises the current. An arc has a nearly straight characteristic of the form $V_{arc} \approx 20 + 0.04 I$ (V, with I in amperes), and the **operating point** is where the arc line cuts the drooping source curve, as shown in Fig. 6.3.

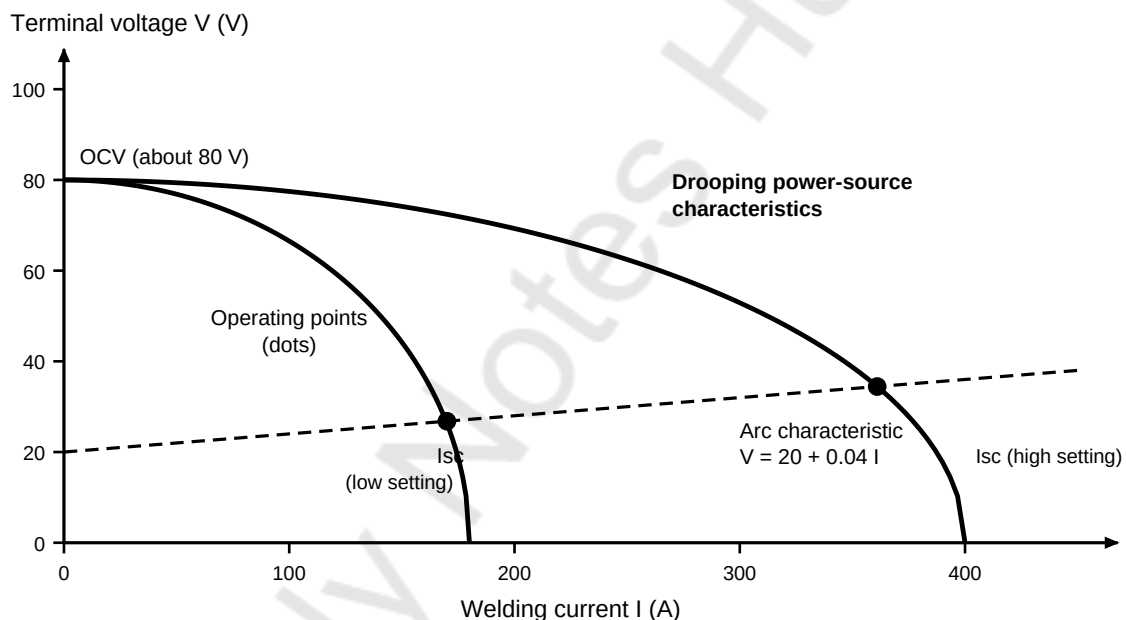


Fig. 6.3: Drooping V - I characteristics of a welding transformer for two current settings

6.2.4 Rating and duty cycle

A welder is never used continuously: part of the time the electrode is changed, the job is positioned or the slag is chipped. The rating therefore includes the **duty cycle**, which is the percentage of a 10-minute period for which the machine may deliver its rated current without overheating:

$$\text{Duty cycle (\%)} = (\text{arc-on time} / \text{total cycle time}) \times 100$$

Since the heating is proportional to $I^2 \times \text{time}$, the permissible current at a different duty cycle D_x is obtained from $I_x = I_{\text{rated}} \sqrt{(D_{\text{rated}} / D_x)}$.

Worked Example 6.2 (duty cycle)

A welding transformer is rated 300 A at 60% duty cycle. Find (i) the time it may deliver 300 A in each 10 minutes and (ii) the current it can supply continuously (100% duty).

Solution: (i) On-time = $0.60 \times 10 = 6$ minutes of welding and 4 minutes of rest.

(ii) $I = 300 \times \sqrt{(60 / 100)} = 300 \times 0.775 = 232$ A (approximately).

Worked Example 6.3 (input rating)

A single-phase welding transformer on a 400 V supply delivers 200 A at an arc voltage of 25 V. Its efficiency is 85% and the input power factor is 0.5 lagging. Find the input kVA and the supply current.

Solution: Output power = $25 \times 200 = 5000$ W. Input power = $5000 / 0.85 = 5882$ W. Input VA = $5882 / 0.5 = 11\,765$ VA = **11.8 kVA**. Supply current = $11\,765 / 400 = 29.4$ A.

Note the low power factor of a welding set: this is a consequence of its large leakage reactance.

Table 6.6: Typical specification of a manual arc welding transformer (indicative values)

Parameter	Typical value
Supply	230 V or 415 V, 50 Hz, single phase
Open-circuit voltage	55 – 100 V
Arc (working) voltage	20 – 40 V
Welding current range	about 40 – 600 A, depending on model
Rated duty cycle	60% (manual welding); 100% for automatic duty
Power factor	about 0.4 – 0.6 lagging (uncorrected)
Insulation class / cooling	Class F or H; air-cooled or oil-cooled

6.2.5 Arc welding transformer and spot welding transformer

The term welding transformer is also used for the transformer of a **resistance (spot) welding machine**. It too is a step-down transformer, but works on a different principle: heat is produced by the I^2R loss at the contact between two sheets pressed together, not by an arc.

Table 6.7: Arc welding transformer vs spot welding transformer

Feature	Arc welding transformer	Spot (resistance) welding transformer
Heat source	Electric arc (20–40 V)	I^2R heating at contact of pressed sheets
Secondary voltage	OCV 55–100 V	Only about 2–20 V
Secondary current	Tens to hundreds of amperes	Thousands to tens of thousands of amperes
Secondary turns	A few turns; large leakage reactance	One or very few turns; low leakage reactance
Characteristic	Drooping, adjustable	Nearly constant voltage, current set by taps and timer
Cooling	Air or oil	Usually water-cooled secondary and electrodes

6.2.6 Comparison with an ordinary power transformer

Table 6.8: Welding transformer vs power transformer

Parameter	Welding transformer	Power / distribution transformer
Secondary voltage	Low (20–100 V)	Fixed standard level (for example 415 V)
Secondary current	Very high, adjustable	As per load, not adjustable
Leakage reactance	Large and adjustable	Kept as small as possible
Voltage regulation	Very poor (drooping) by design	Good (about 2–5%)
Short-circuit	Occurs every time the arc is struck; current limited by design	Abnormal fault condition
Duty	Intermittent (duty cycle)	Continuous
Power factor	Low	High

6.2.7 Advantages, limitations and applications

Advantages

- Simple construction, low initial cost, rugged and almost maintenance-free.
- Higher efficiency (70–90%) than motor-generator or rectifier sets; no idle running loss other than the small no-load loss.
- No arc blow problems, which occur with DC welding.
- Wide current range and easy adjustment.

Limitations

- Low power factor and a single-phase load, which causes unbalance on a three-phase supply.
- AC arc is less stable; special electrodes are required; not suitable for some metals and processes (for example thin sheet and non-ferrous work).
- High OCV creates a shock hazard; proper safety precautions are necessary.

Applications

- Workshops and fabrication shops: structural steel, gates, grills, frames and tanks.
- Repair and maintenance of vehicles, farm machinery and pipelines.
- Shipbuilding, bridge and boiler work (heavy-duty oil-cooled sets).
- Spot-welding versions: sheet-metal and automobile-body assembly.

Key Points – Welding Transformer

- Step-down transformer: high OCV (about 55–100 V) to strike the arc, low arc voltage (20–40 V), high current.
- Large leakage reactance gives the drooping characteristic and limits short-circuit current.
- Current is adjusted by taps, movable core/shunt, moving coil or saturable reactor.
- Duty cycle: rated current may be delivered for a stated percentage of a 10-minute cycle; $I \times \sqrt{\text{duty}}$ is the equivalent heating current.

6.3 Pulse Transformer

6.3.1 Introduction

Digital circuits, radar, thyristor-triggering circuits, switching power supplies and communication links all use **pulses** – short, rectangular bursts of voltage or current. A **pulse transformer** is a transformer optimised to transfer such rectangular pulses from its primary to its secondary with minimum distortion of the pulse shape (rise time, flat top and fall time). It also provides electrical isolation, a change of amplitude, polarity inversion or impedance matching between the pulse source and the load.

A rectangular pulse is made up (Fourier analysis) of a fundamental frequency and a very large number of harmonics. To reproduce the sharp edges the transformer must pass a wide band of frequencies, from a low frequency (which decides how flat the top stays) up to many megahertz (which decides how quick the edge is). An ordinary 50 Hz power transformer has far too much leakage inductance and winding capacitance to do this, so a pulse transformer is built quite differently: it is small, uses a high-permeability low-loss core and has very few turns.

6.3.2 Pulse terminology

Table 6.9: Pulse parameters

Term	Meaning
Pulse amplitude	Peak value of the flat top of the pulse.
Rise time (t_r)	Time taken for the leading edge to rise from 10% to 90% of the amplitude. Shorter is better.
Pulse width (t_p)	Duration of the pulse measured between the 50% points of the leading and trailing edges.
Fall time (t_f)	Time for the trailing edge to fall from 90% to 10% of the amplitude.
Overshoot	Amount by which the output exceeds the final flat-top level just after the leading edge.
Ring	Damped oscillations after the edges, caused by leakage inductance resonating with winding capacitance.
Droop (sag, tilt)	Fall of the flat top during the pulse because the magnetising current rises; expressed as a percentage of amplitude.
Backswing (undershoot)	Reverse-polarity swing after the trailing edge, as the stored magnetising energy is released.
Pulse repetition frequency (PRF)	Number of pulses per second. Duty ratio = $t_p \times \text{PRF}$.

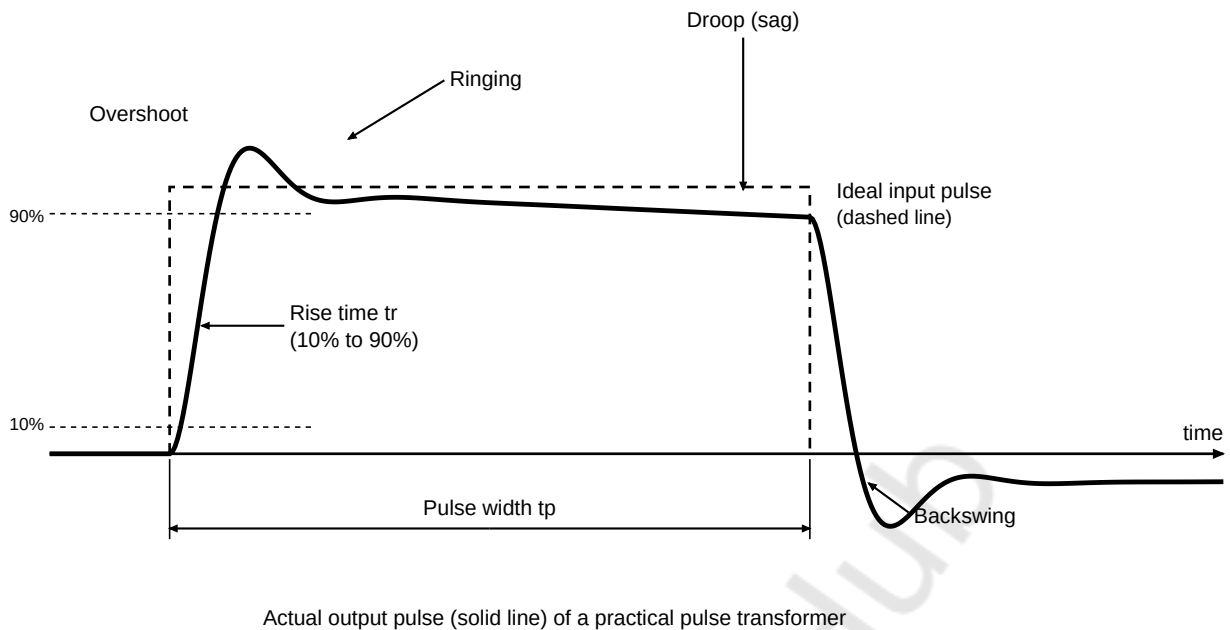


Fig. 6.4: Ideal input pulse and actual pulse-transformer output showing rise time, overshoot, ringing, droop and backswing

6.3.3 Construction

The aim of the design is to keep **leakage inductance** and **distributed (self) capacitance** as small as possible and the **magnetising inductance** as large as possible:

- **Core material:** ferrite (Mn–Zn or Ni–Zn) in toroidal, E, pot or bead shapes for small and medium pulses; tape-wound very thin nickel-iron or amorphous/nanocrystalline alloy for high-power microsecond pulses. The material has high permeability and low loss at high frequencies. Usually there is no air gap (or a very small one).
- **Windings:** only a few turns of enamelled copper wire (primary and secondary turns are in the ratio required for the output amplitude). Few turns mean low leakage inductance and low capacitance.
- **Tight coupling:** bifilar, trifilar or twisted-pair windings, sandwich (interleaved) windings, and single-layer windings wound over each other give a coupling coefficient close to 1 and so a very small leakage inductance.
- **Insulation:** for high-voltage pulses (radar modulators) oil immersion, potting resin and large creepage distances are used. Small signal and gate-drive types use polyimide tape and triple-insulated wire for the isolation voltage.
- **Small size:** because pulse transformers handle a small volt-second product, they are usually miniature components (surface-mount or through-hole) or a few centimetres in size.

Table 6.10: Effect of construction on pulse behaviour

Construction feature	Effect on pulse performance
Few turns	Low leakage inductance and low distributed capacitance; faster rise time.
Bifilar / interleaved windings	Better coupling; reduced leakage inductance and ringing.
High-permeability ferrite core	High magnetising inductance; low droop.
Adequate core cross-section	Prevents core saturation for the required volt-second product.
Very thin lamination or tape (metal core)	Reduces eddy currents during very fast flux changes.
Large winding spacing and good insulation	High isolation voltage; but increases capacitance, so a compromise is necessary.

6.3.4 Working principle

A pulse transformer works on Faraday's law: a changing flux produced by the primary pulse induces a voltage in the secondary proportional to the turns ratio. Its behaviour is explained with the equivalent circuit of Fig. 6.5 (all quantities referred to the secondary side), where R_s is the source resistance, L_l the total leakage inductance, C_d the distributed capacitance, L_m the magnetising inductance and R_L the load resistance.

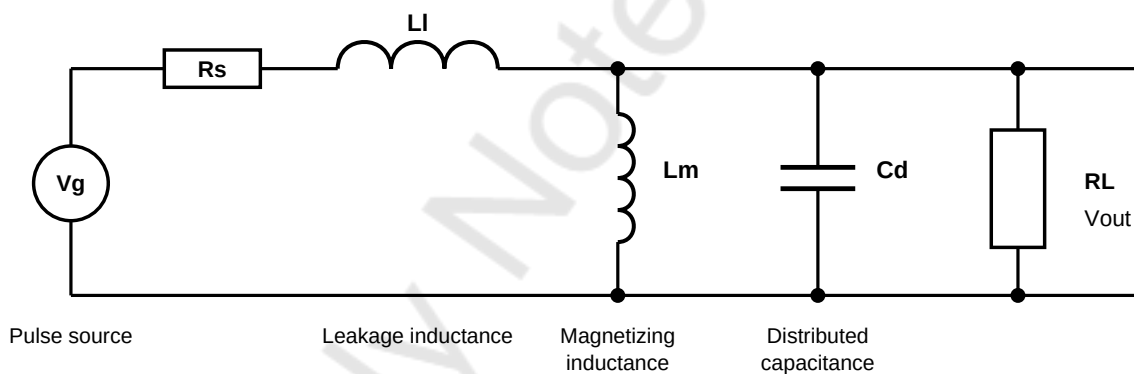


Fig. 6.5: Equivalent circuit of a pulse transformer (referred to the secondary)

The three parts of the output pulse are controlled by different elements:

Table 6.11: Which element shapes which part of the pulse

Part of the pulse	Controlled by	Explanation
Leading edge (rise time, overshoot, ringing)	L_l and C_d	High-frequency components pass through the L_l - C_d network. Large L_l and C_d slow the edge; low damping gives ringing at $f_0 = 1 / (2\pi\sqrt{L_l C_d})$.
Flat top (droop)	L_m and R_L	During the pulse the magnetising current rises and takes a share of the current, so the output falls with time constant L_m / R_L .
Trailing edge (fall, backswing)	L_m , L_l , C_d	Stored magnetising energy is released and drives the output below zero before it settles.

Droop. The voltage across L_m decays as $e^{-t R_L / L_m}$. For a pulse width t_p much shorter than L_m / R_L the fractional droop is

$$\text{Droop} \approx t_p R_L / L_m$$

Hence a large L_m (many turns, high-permeability core) is needed for a flat top, while small L_1 and C_d (few turns, close coupling) are needed for a fast edge. These two demands conflict, so pulse-transformer design is always a compromise.

Volt-second product and core reset. The core flux must not saturate during the pulse. By Faraday's law

$$\int V dt = V t_p = N A \Delta B$$

where A is the core cross-section and ΔB the permitted flux-density swing. For unipolar pulses the flux rises in one direction only and, unless it is returned to its starting value between pulses (core reset, using a reset winding, a diode-resistor clamp or bipolar drive), it creeps towards saturation, droop increases and the output is lost.

Worked Example 6.4

(a) A pulse transformer has $L_m = 50 \text{ mH}$ and feeds $R_L = 500 \Omega$ with a $10 \mu\text{s}$ pulse. Find the droop and the L_m required to bring it down to 2%. (b) A 12 V , $20 \mu\text{s}$ pulse is applied to a 20-turn winding. Find the minimum core area for $\Delta B = 0.2 \text{ T}$.

Solution: (a) Droop $= (10 \times 10^{-6} \times 500) / (50 \times 10^{-3}) = 0.1 = \mathbf{10\%}$. For 2% droop: $L_m = t_p R_L / 0.02 = (5 \times 10^{-3}) / 0.02 = 0.25 \text{ H} = \mathbf{250 \text{ mH}}$.

(b) $V t_p = 12 \times 20 \times 10^{-6} = 240 \mu\text{V}\cdot\text{s}$. $A = V t_p / (N \Delta B) = 240 \times 10^{-6} / (20 \times 0.2) = 6 \times 10^{-5} \text{ m}^2 = \mathbf{0.6 \text{ cm}^2}$.

6.3.5 Types of pulse transformers

Table 6.12: Types of pulse transformers

Type	Characteristics	Typical use
Low-power signal / data transformer	Miniature ferrite core; isolation about 1.5 kV typical.	Ethernet and telecom line interfaces, ISDN, data isolation.
Gate-drive / trigger transformer	Small, with one or several secondaries, high isolation; handles microsecond pulses.	Thyristor, TRIAC, MOSFET and IGBT gate drive in converters and inverters.
Switching-power pulse transformer	Higher power, ferrite core, carries rectangular waveforms at tens or hundreds of kHz.	Switch-mode power supplies, DC-DC converters.
High-power modulator transformer	Oil-filled or potted; kilovolt to hundred-kilovolt pulses with microsecond width.	Radar transmitters, particle accelerators, pulsed lasers.

6.3.6 Applications

- **Triggering of thyristors and TRIACs:** the firing circuit is at low voltage and must be isolated from the mains-level power circuit (Fig. 6.6). The transformer passes the gate pulse and gives the isolation.
- **Gate drive of MOSFETs and IGBTs** in half-bridge and full-bridge inverters, where the upper switches float with respect to the control ground.
- **Digital communication:** isolation and coupling of Ethernet, telephone-line and data-bus signals (isolation about 1500 V).
- **Radar and pulse power:** high-voltage modulator pulses for magnetrons and other tubes.

- Switch-mode power supplies, flash and strobe circuits, ignition and trigger circuits, and blocking oscillators.

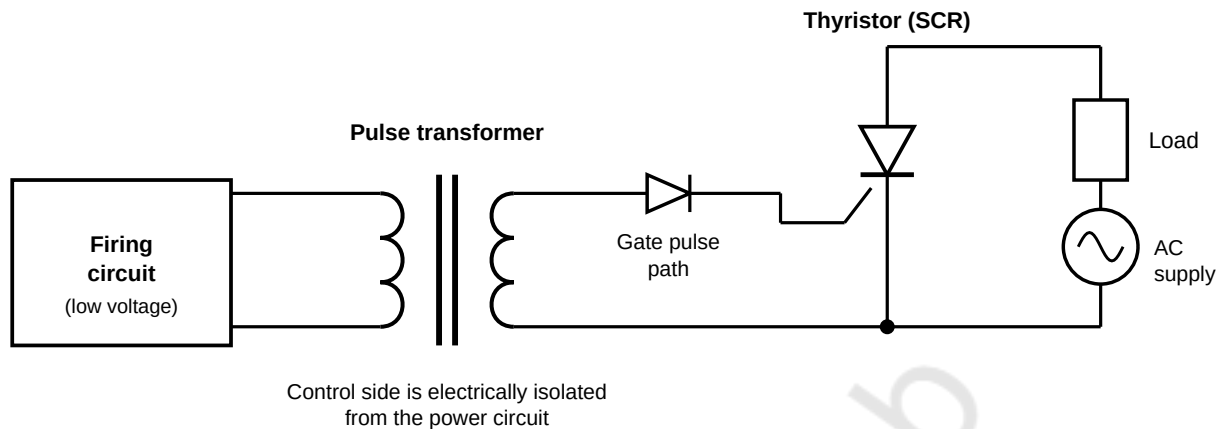


Fig. 6.6: Pulse transformer used for isolated triggering of a thyristor (SCR)

6.3.7 Pulse transformer compared with power transformer

Table 6.13: Pulse transformer vs power transformer

Parameter	Pulse transformer	Power transformer
Signal handled	Rectangular pulses (very wide bandwidth)	Sinusoidal at 50 Hz
Main purpose	Preserve pulse shape; isolate; match	Transfer power efficiently
Core	Ferrite or thin tape alloy, small	Laminated CRGO steel, large
Number of turns	Very few	Many
Leakage inductance and capacitance	Made as small as possible	Not critical
Winding style	Bifilar / interleaved	Concentric or sandwich
Power rating	Milliwatts to some kW (mean power)	VA to MVA
Key parameters	Rise time, droop, volt-second	Efficiency, regulation, losses

Key Points – Pulse Transformer

- Transmits rectangular pulses with minimum distortion and provides isolation.
- Low leakage inductance and low capacitance give fast rise time; high magnetising inductance gives low droop.
- Wound on ferrite or thin-tape cores with few turns, often bifilar or interleaved.
- Droop $\approx t_p R_L / L_m$; core must support the volt-second product $V \cdot t_p = N \cdot A \cdot \Delta B$.
- Used for SCR/TRIAC firing, MOSFET/IGBT gate drive, data isolation, radar modulators.

6.4 K-Factor of Transformers

6.4.1 Background: linear loads, non-linear loads and harmonics

A **linear load** (a heater, an incandescent lamp, an induction motor running on a sinusoidal supply) draws a current of the same sinusoidal shape as the voltage. A **non-linear load** draws current in short pulses or with a distorted wave shape, even when the supply voltage is sinusoidal. Such current can be represented by a fundamental component (50 Hz) plus **harmonics**, which are sinusoidal components at integer multiples of the fundamental: 3rd = 150 Hz, 5th = 250 Hz, 7th = 350 Hz and so on.

Table 6.14: Common sources of harmonics

Non-linear load	Typical harmonics produced
Single-phase switch-mode power supplies (computers, TVs, chargers, LED drivers)	3rd, 5th, 7th, 9th ... (strong triplen content)
Electronic fluorescent ballasts, CFL and LED lamps	3rd, 5th, 7th
Six-pulse rectifiers, variable-frequency drives, UPS systems	5th, 7th, 11th, 13th
Thyristor controllers, dimmers, battery chargers	Low-order harmonics, depends on firing angle
Arc furnaces, arc welders	Wide spectrum, including interharmonics

The distortion of a current is measured by the **total harmonic distortion**:

$$THD_I = \sqrt{(I_2^2 + I_3^2 + I_4^2 + \dots)} / I_1 \times 100\%$$

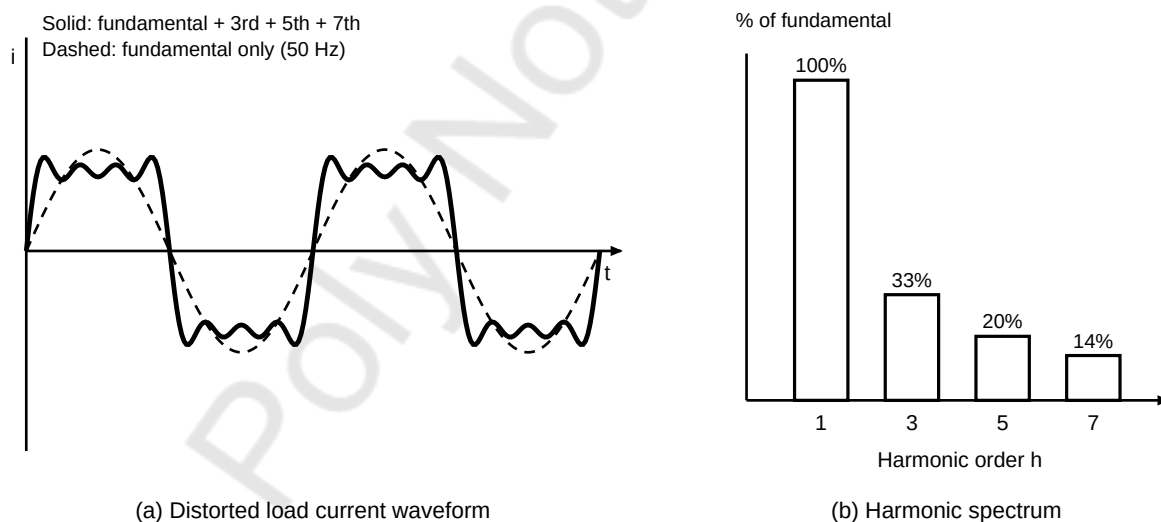


Fig. 6.7: (a) A distorted current waveform and its fundamental; (b) harmonic spectrum of a typical non-linear load

6.4.2 Overheating of transformers due to non-linear loads and harmonics

Transformers are designed for sinusoidal current at 50 Hz. When they supply harmonic currents the losses rise much more than the rms current alone would suggest, and the extra heat shortens the life of the insulation.

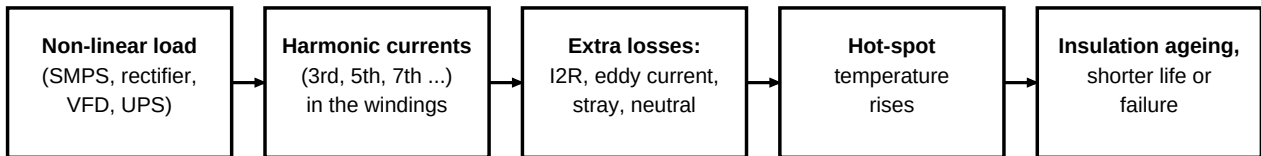


Fig. 6.8: Chain of events from non-linear load to transformer failure

Table 6.15: Harmonic effects on transformer losses

Loss component	Effect of harmonics
Winding I^2R loss	Depends on the rms value of the total current, which includes all harmonics, so it is larger than for a sinusoidal current of the same fundamental value.
Winding eddy-current loss	Eddy-current loss in the conductors rises with the square of frequency; for the h -th harmonic it is proportional to $(h I_h)^2$. High-order harmonics therefore cause much more heating than their small magnitude suggests. This is the dominant extra loss.
Other stray losses	Eddy currents in the tank walls, clamps, bolts and structural parts also rise with harmonic frequency, creating local hot spots.
Core loss	Voltage distortion and high-frequency components increase hysteresis and eddy-current loss in the core, usually a smaller effect than winding losses.
Triplen harmonics and neutral current	The 3rd, 9th, 15th ... harmonics of the three phases are in phase with each other, so they add in the neutral conductor of a 3-phase, 4-wire system (neutral current can approach about 1.7 times the phase current) and circulate in a delta winding, producing extra heating.

Additional consequences include increased audible noise, possible resonance with power-factor capacitors, saturation caused by high crest-factor currents and nuisance tripping of protective devices. As a rule of thumb, every rise of about 8–10 °C above the rated hot-spot temperature roughly **halves** the life of the insulation, so even a modest additional temperature rise matters a great deal.

6.4.3 K-factor

The **K-factor** is a number that rates a transformer's ability to supply non-sinusoidal load currents without exceeding its rated temperature rise (standards ANSI/IEEE C57.110 and UL 1561). It is a weighting of the harmonic load currents according to their *heating effect*. Mathematically, with I_h the rms value of the h -th harmonic current:

$$K = \Sigma (I_h^2 h^2) / \Sigma (I_h^2)$$

Since the denominator is the square of the total rms current, the same formula can be written as $K = \Sigma (I_{h(\text{pu})}^2 h^2)$ where $I_{h(\text{pu})}$ is each harmonic expressed as a fraction of the total rms current. This is the same as the harmonic loss factor F_{HL} of the IEEE standard.

- For a pure sinusoidal current only $h = 1$ exists, so **K = 1**. More harmonic content, especially at higher orders, gives a larger K.
- If the total rms load current equals the rated current, the winding eddy-current loss becomes K times its rated value.
- The standard UL K-ratings are **K-1, K-4, K-9, K-13, K-20, K-30, K-40 and K-50**. A transformer marked K-13 is built to carry a load whose calculated K-factor is 13 or less.

Table 6.16: K-factor calculation for the spectrum of Fig. 6.7(b)

h	I_h (% of fundamental)	I_h (per unit)	I_h^2	h^2	$I_h^2 h^2$
1	100	1.00	1.0000	1	1.0000
3	33	0.33	0.1089	9	0.9801
5	20	0.20	0.0400	25	1.0000
7	14	0.14	0.0196	49	0.9604
Total			1.1685		3.9405

Worked Example 6.5

A load draws a fundamental current with 3rd, 5th and 7th harmonics of 33%, 20% and 14% of the fundamental (Table 6.16). Find the THD and the K-factor, and select the K-rating.

Solution: THD = $\sqrt{(0.33^2 + 0.20^2 + 0.14^2)} = \sqrt{0.1685} = 41\%$.

$K = \Sigma(I_h^2 h^2) / \Sigma(I_h^2) = 3.9405 / 1.1685 = 3.37$.

The next standard rating above 3.37 is **K-4**, so a K-4 transformer is suitable.

Derating approach. Instead of buying a K-rated transformer, an ordinary transformer can be derated. According to the simplified method of IEEE C57.110, the maximum permissible rms current, in per unit of rated current, is

$$I_{max}(pu) = \sqrt{(1 + P_{EC-R}) / (1 + F_{HL} \cdot P_{EC-R})}$$

where P_{EC-R} is the rated eddy-current loss in per unit of the I^2R loss. For $P_{EC-R} = 0.10$ and $F_{HL} = K = 3.37$, $I_{max} = \sqrt{(1.10 / 1.337)} = 0.91$ pu: the ordinary transformer should not be loaded beyond about 91% of its nameplate current.

6.4.4 Construction of K-factor (K-rated) transformers

A K-rated transformer is built to withstand the extra heating of harmonic currents rather than to remove the harmonics:

- **Reduced eddy-current loss in windings:** the winding is made of several thin, individually insulated parallel strands (or continuously transposed conductor) instead of one thick conductor, or of thin foil, so that the effective conductor depth is small at high frequency.
- **Lower flux density:** a larger core cross-section and low working flux density give margin against saturation by peaky currents and reduce core heating.
- **Oversized neutral:** the neutral busbar or conductor is rated at 200% of the phase current to carry the added triplen harmonic currents.
- **Delta primary:** a delta-connected primary traps and circulates the triplen harmonics instead of passing them to the supply.
- **Electrostatic shield** between windings to reduce noise coupling.
- **Better cooling and insulation:** wide ducts for airflow and a high-temperature insulation system (often class 220 °C) operated at a lower temperature rise, giving a reserve for hot spots.

Table 6.17: Ordinary vs K-rated transformer

Feature	Ordinary transformer	K-rated transformer
Designed for	Sinusoidal load current	Harmonic-rich non-linear current
Winding conductor	Single solid conductor	Multiple insulated strands / transposed / foil
Eddy-current loss	Higher under harmonics	Much reduced
Core flux density	Normal	Lower (more core steel)
Neutral rating	100%	Up to 200%
Size and cost	Smaller and cheaper	Larger and costlier (typically higher price)
Heating under harmonics	Hot spots, reduced life	Within rated temperature rise

6.4.5 Selection and mitigation

Table 6.18: Typical K-rating selection guide (actual selection should follow a harmonic survey)

K-rating	Typical load (indicative guideline only)
K-1	Linear loads: resistive heating, incandescent lighting, motors on sinusoidal supply.
K-4	Mixed loads with a modest non-linear share: welders, induction heating, fluorescent lighting, SCR drives.
K-9	Commercial buildings and offices with a significant proportion of electronic equipment.
K-13	Heavily non-linear loads: telecom equipment, hospitals, schools, computer-intensive offices.
K-20 and above	Predominantly non-linear loads: data centres, mainframes, UPS and drive installations.

Measures to limit harmonic heating:

- Use a **K-rated transformer** for the non-linear load, or **derate** a standard transformer.
- Install **passive tuned filters** or **active harmonic filters** near the non-linear loads.
- Use **12-pulse or 18-pulse** rectifiers and **phase-shifting (delta-star, zig-zag) transformers** to cancel low-order harmonics.
- Oversize the neutral conductor and feed non-linear loads from separate circuits.
- Measure the harmonics with a power-quality analyser and keep distortion within the limits of IEEE 519 or the applicable code.

Key Points – K-Factor

- $K = \Sigma(I_h^2 h^2) / \Sigma(I_h^2)$; $K = 1$ for a sinusoidal current.
- Harmonic currents raise I^2R , eddy-current and stray losses; eddy loss rises with h^2 .
- Triplen harmonics add in the neutral and circulate in delta windings.
- K-rated transformers use stranded windings, lower flux density and 200% neutral; ratings K-4, K-9, K-13, K-20, K-30, K-40, K-50.

Chapter Summary and Important Formulae

Table 6.19: Summary of special purpose transformers

Transformer	Key construction feature	Principle / key idea	Main applications
Isolation	Two separate windings, earthed Faraday shield, 1:1 ratio	Mutual induction; no conductive path; floating secondary	Medical, electronic servicing, instrumentation, site tools
Single phase welding	Step-down; few secondary turns of heavy conductor; large adjustable leakage reactance	Drooping V–I characteristic; high OCV to strike, low voltage to maintain the arc	Arc welding in workshops, repair, fabrication
Pulse	Ferrite or thin-tape core, few turns, bifilar / interleaved windings	Wide bandwidth; small L_p , C_d and large L_m	SCR / IGBT gate drive, data isolation, radar
K-factor (K-rated)	Stranded / transposed windings, low flux density, 200% neutral	Withstands extra heating from harmonics ($K = \Sigma I_h^2 h^2 / \Sigma I_1^2$)	Computers, UPS, drives, hospitals, data centres

Table 6.20: Important formulae

Quantity	Formula
EMF equation	$E = 4.44 f N \Phi_m$
Voltage ratio of ideal transformer	$V_2/V_1 = N_2/N_1$
Rated current from kVA	$I = S / V$
Welding source terminal voltage	$V_t \approx \sqrt{E_2^2 - (IX)^2}$; $I_{sc} \approx E_2/X$
Arc voltage (empirical)	$V_{arc} \approx 20 + 0.04 I$
Duty cycle	$D = (\text{arc-on time} / \text{cycle time}) \times 100\%$
Equivalent current at another duty cycle	$I_x = I_{rated} \sqrt{(D_{rated}/D_x)}$
Pulse droop	$\text{Droop} \approx t_p R_L / L_m$
Volt-second product	$V t_p = N A \Delta B$
Natural frequency (ringing)	$f_0 = 1 / (2\pi\sqrt{L_1 C_d})$
Total harmonic distortion	$\text{THD} = \sqrt{(\Sigma_{h \geq 2} I_h^2) / I_1^2} \times 100\%$
K-factor	$K = \Sigma(I_h^2 h^2) / \Sigma(I_h^2)$

Multiple Choice Questions

Choose the correct alternative. The answer key and short explanations are given at the end of this section.

1. Which of the following is the main purpose of an isolation transformer?
 - (A) Increase the supply frequency
 - (B) Provide electrical isolation between supply and load
 - (C) Improve the power factor of the load
 - (D) Convert AC supply into DC supply
2. The electrostatic (Faraday) shield between the windings of an isolation transformer is connected to:
 - (A) The primary live terminal
 - (B) The secondary live terminal
 - (C) Earth
 - (D) It is left unconnected
3. Isolation transformers are preferred for patient-connected medical equipment because:
 - (A) They increase the supply voltage
 - (B) They improve the power factor
 - (C) They reduce the frequency
 - (D) The floating secondary prevents a single earth fault from sending shock current through the patient
4. A welding transformer has a drooping voltage–current characteristic mainly to:
 - (A) Increase arc voltage as current rises
 - (B) Improve its power factor
 - (C) Reduce core loss
 - (D) Limit the short-circuit current when the electrode touches the job
5. A large leakage reactance in a welding transformer is obtained by:
 - (A) Tightly interleaving the windings
 - (B) Using a very small core
 - (C) Separating the windings and/or using a magnetic shunt
 - (D) Using a single winding
6. The typical open-circuit voltage of a single-phase arc welding transformer is about:
 - (A) 5 – 10 V
 - (B) 55 – 100 V
 - (C) 230 – 415 V
 - (D) about 1000 V
7. A welding transformer is rated 300 A at 60% duty cycle. This means it can deliver 300 A for:
 - (A) 6 minutes in every 10 minutes
 - (B) continuously without limit
 - (C) 60 minutes at a stretch
 - (D) only when efficiency is 60%
8. Which of the following is commonly used to control the welding current smoothly?
 - (A) Frequency variation
 - (B) Field rheostat
 - (C) Movable magnetic shunt or tapped reactor
 - (D) Capacitor bank on the primary

9. A pulse transformer is designed mainly to:
- (A) Deliver large continuous power at 50 Hz
 - (B) Transmit rectangular pulses with minimum distortion
 - (C) Step up a DC voltage
 - (D) Improve the efficiency of a motor
10. The droop (sag) of the flat top of a pulse is mainly determined by:
- (A) Magnetising inductance
 - (B) Leakage inductance
 - (C) Distributed capacitance
 - (D) Core window area
11. The rise time of a pulse transformer output is mainly affected by:
- (A) Magnetising inductance and core area
 - (B) Supply frequency and number of poles
 - (C) Load power factor
 - (D) Leakage inductance and distributed capacitance
12. Bifilar or interleaved windings are used in pulse transformers to:
- (A) Increase leakage inductance
 - (B) Increase eddy-current loss
 - (C) Reduce leakage inductance and improve coupling
 - (D) Increase core size
13. The K-factor of a transformer indicates its ability to:
- (A) Supply non-linear (harmonic-rich) loads without excessive heating
 - (B) Regulate voltage at no load
 - (C) Withstand a short circuit
 - (D) Step up the voltage ratio
14. The K-factor of a purely sinusoidal load current is:
- (A) 0
 - (B) 4
 - (C) 13
 - (D) 1
15. Which harmonics are called triplen harmonics and add up in the neutral of a 3-phase 4-wire system?
- (A) 2nd, 4th, 6th
 - (B) 3rd, 9th, 15th
 - (C) 5th, 7th, 11th
 - (D) Only the fundamental

Answer Key

Q.	Ans.	Q.	Ans.	Q.	Ans.
1	B	6	B	11	D
2	C	7	A	12	C
3	D	8	C	13	A
4	D	9	B	14	D
5	C	10	A	15	B

Brief explanations

1. **(B)** Primary and secondary are linked only magnetically, giving galvanic isolation.
2. **(C)** The earthed shield diverts common-mode noise current to earth.
3. **(D)** A floating (ungrounded) secondary gives no return path for shock current on a first fault.
4. **(D)** Large leakage reactance limits the current at the moment of arc striking.
5. **(C)** Leakage flux is increased by winding separation and shunts.
6. **(B)** OCV must be high enough to strike the arc but low enough to be safe.
7. **(A)** Duty cycle is the percentage of a 10-minute period for which rated current may be supplied.
8. **(C)** Varying leakage reactance with a movable shunt changes the output current.
9. **(B)** Its core, turns and winding style preserve the pulse shape.
10. **(A)** Droop $\approx t_p R_L / L_m$; a larger magnetising inductance gives less droop.
11. **(D)** L_l and C_d form the network that slows the leading edge.
12. **(C)** Close coupling gives low leakage inductance, faster rise time and less ringing.
13. **(A)** K weights the harmonic currents by their heating effect.
14. **(D)** Only $h = 1$ exists, so $K = I_1^2 \cdot 1 / I_1^2 = 1$.
15. **(B)** Triplen harmonics of the three phases are in phase, so their currents add in the neutral.

Broad Questions

Answer in detail with neat, labelled diagrams wherever required.

1. With a neat diagram, explain the construction and working principle of an isolation transformer. State its applications.
2. Explain the function of the electrostatic shield in an isolation transformer. How does an isolation transformer protect against electric shock and ground loops? Compare it with an autotransformer.
3. Describe the construction of a single phase welding transformer with a neat sketch. Explain any two methods of controlling the welding current.
4. Explain the working principle of a welding transformer. Why is a drooping V-I characteristic required? Draw the characteristic and explain how the operating point is obtained.
5. Define duty cycle of a welding transformer. A welding transformer is rated 250 A at 60% duty cycle. Calculate the current it can supply continuously. List the advantages, limitations and applications of welding transformers.
6. Explain the construction and working of a pulse transformer. Draw and explain its equivalent circuit.
7. Define the following pulse parameters and state what affects each of them: rise time, pulse width, overshoot, ringing, droop and backswing.
8. Compare a pulse transformer with a power transformer. Explain how a pulse transformer is used to trigger a thyristor with a neat circuit diagram.
9. Define K-factor of a transformer. Explain with the help of harmonics why non-linear loads cause overheating of transformers. State the construction features of a K-rated transformer.
10. A non-linear load current has a 3rd, 5th and 7th harmonic of 40%, 25% and 15% of the fundamental respectively. Calculate the K-factor and select a suitable standard K-rated transformer. [Ans: $K \approx 4.1$; select the next higher standard rating, K-9]

End of Chapter 6

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