DIPLOMA / ENGINEERING STUDY NOTES

ELECTRONICS DEVICES & CIRCUITS

Chapter 4

RECTIFIER AND POWER SUPPLY

Topics Covered

4.1 Half-wave and full-wave rectifier, average voltage, rms voltage, efficiency and ripple factor, percentage voltage regulation

4.2 Function of filter circuits: capacitor input filter, inductive filter, π filter – calculation of ripple factor and average output voltage

4.3 Series and shunt regulator using transistor, IC regulator

4.4 Concept of switch mode power supply (SMPS)

4.5 Block schematic description of uninterruptible power supply (UPS)

Extra: 15 Multiple Choice Questions with Answer Key and 10 Descriptive Questions

Notes in paragraph, list and table format with diagrams, designed for engineering students.

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4.0 DC Power Supply: Block Diagram and Basic Terms

4.0.1 Need for a DC power supply

Most electronic circuits (amplifiers, oscillators, digital ICs, microcontrollers) need a **steady DC voltage** to work, but the mains supply available at home is **AC (230 V, 50 Hz)**. A **DC power supply** converts this AC into a smooth, constant DC voltage. A battery can also supply DC, but it is costly to replace and supplies limited energy, so a mains-operated power supply is preferred wherever mains is available.

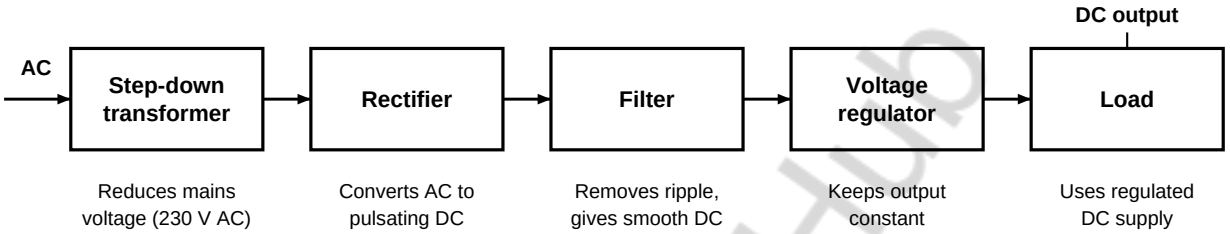


Fig. 4.1: Block diagram of a regulated DC power supply

Block	Function
Step-down transformer	Reduces the 230 V AC mains to the required lower AC voltage and also provides electrical isolation from the mains.
Rectifier	Converts the AC input into **unidirectional pulsating DC** using diodes (half-wave, full-wave or bridge).
Filter	Removes (smooths) the AC ripple contained in the pulsating DC, using capacitors and/or inductors.
Regulator	Keeps the output voltage **constant** in spite of changes in mains voltage (line) and load current (load).
Load	The electronic circuit which uses the DC voltage.

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4.0.2 Important terms used in rectifier analysis

Term	Meaning / formula
Average (DC) value	Mean value of the output over one cycle. $V_{dc} = I_{dc} R_L$. It is the reading of a DC voltmeter.
RMS value	Effective value of the output (heating effect). $V_{rms} = I_{rms} R_L$. It is the reading of an AC voltmeter.
Form factor	F = rms value / average value.
Peak factor	Peak value / rms value.
Ripple factor (γ)	Ratio of rms value of AC component to the DC value of output: $\gamma = V_{r(rms)} / V_{dc} = \sqrt{(F^2 - 1)}$. Smaller is better.
Rectification efficiency (η)	η = DC output power / AC input power = P_{dc} / P_{ac}.
PIV (Peak Inverse Voltage)	Maximum reverse voltage that appears across a diode when it is not conducting. The diode must be rated above it.
TUF (Transformer Utilisation Factor)	DC power delivered to load / AC power rating of the transformer secondary.
Voltage regulation	Change in output voltage from no-load to full-load: $\%VR = (V_{NL} - V_{FL}) / V_{FL} \times 100$. Smaller is better; ideal value is 0%.

Notation used: V_m = peak value of the secondary voltage, I_m = peak load current, R_f = forward (dynamic) resistance of a diode, R_L = load resistance, f = supply frequency (50 Hz).

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4.1 Half-wave and Full-wave Rectifiers

A **rectifier** is a circuit that converts alternating current into **unidirectional (pulsating DC)** current by allowing the current to flow in one direction only. A p-n junction diode is used because it conducts when forward biased and blocks when reverse biased. Rectifiers are of three types: **half-wave**, **full-wave (centre-tapped)** and **bridge** rectifiers.

4.1.1 Half-wave rectifier (HWR)

Circuit and working

A half-wave rectifier uses **one diode** in series with the load resistance R_L. The input is the secondary voltage $v_s = V_m \sin \omega t$ of the step-down transformer (shown here as the AC source).

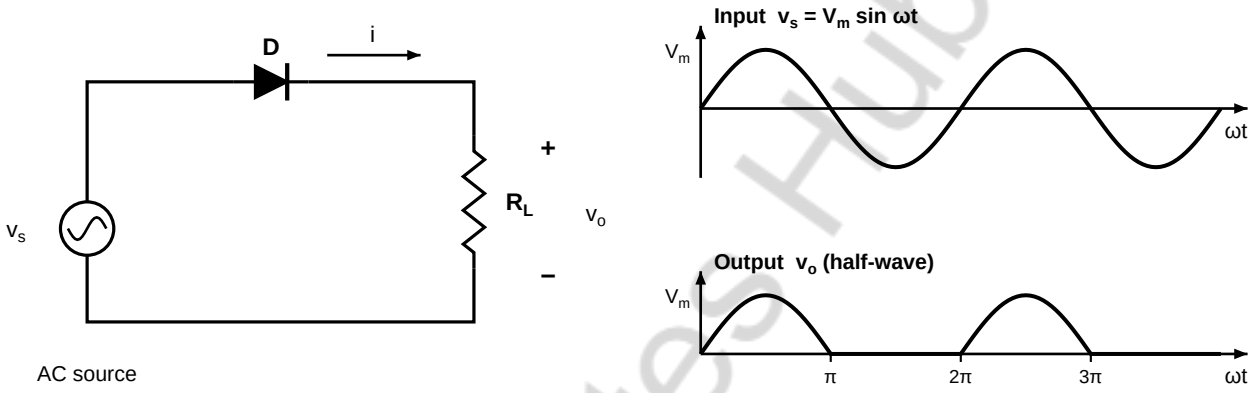


Fig. 4.2: Half-wave rectifier circuit with input and output waveforms

- **Positive half-cycle (0 to π):** The anode of the diode is positive with respect to the cathode, so the diode is forward biased and conducts. Current flows through R_L and the output follows the input.
- **Negative half-cycle (π to 2π):** The diode is reverse biased, does not conduct, and the output is zero. The whole input voltage (V_m) appears across the diode.
- The output is a series of positive half-sine pulses; it is unidirectional but **pulsating**. Output frequency = input frequency (50 Hz).

Analysis (ideal diode, R_f included)

Load current: $i = I_m \sin \omega t$ for $0 \le \omega t \le \pi$ and $i = 0$ for $\pi \le \omega t \le 2\pi$, where $I_m = V_m / (R_f + R_L)$.

(a) Average (DC) current and voltage

$$\mathbf{I_{dc} = (1/2\pi) \int_0^{\pi} I_m \sin\theta \, d\theta = I_m / \pi \qquad V_{dc} = I_{dc} R_L = I_m R_L / \pi}$$

If R_f is neglected, $V_{dc} = V_m / \pi = \mathbf{0.318\ V_m}$.

(b) RMS current and voltage

$$\mathbf{I_{rms} = \sqrt{[\ (1/2\pi) \int_0^{\pi} I_m^2 \sin^2\theta \, d\theta\ ]} = I_m / 2 \qquad V_{rms} = I_m R_L / 2 = V_m / 2}$$

(c) Efficiency

$$\mathbf{P_{dc} = I_{dc}^2 R_L = I_m^2 R_L / \pi^2; \quad P_{ac} = I_{rms}^2 (R_f + R_L) = I_m^2 (R_f + R_L) / 4}$$

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$$\eta = P_{dc} / P_{ac} = (4/\pi^2) \times R_L/(R_f + R_L) = 40.6\% / (1 + R_f/R_L)$$

The maximum efficiency of a half-wave rectifier is **40.6%** (when $R_f = 0$).

(d) Ripple factor

$$\text{Form factor } F = I_{rms}/I_{dc} = (I_m/2)/(I_m/\pi) = \pi/2 = 1.57 \qquad \gamma = \sqrt{(F^2 - 1)} = 1.21$$

A ripple factor greater than 1 means the AC component is larger than the DC component, so heavy filtering is needed.

(e) PIV and other values: PIV = V_m; peak factor = I_m/I_{rms} = 2; ripple frequency = f; TUF = 0.287.

Advantages and disadvantages of HWR

Advantages	Disadvantages
• Simple circuit • Only one diode needed • Low cost	• Low efficiency (40.6%) • High ripple factor (1.21) • Low TUF (0.287); DC component flows through the transformer and may saturate its core • Ripple frequency equals f, so filtering is difficult

4.1.2 Full-wave rectifier (centre-tapped)

A full-wave rectifier utilises **both half-cycles** of the AC input. The centre-tapped type uses a transformer whose secondary winding has a centre tap (CT), and **two diodes** D_1 and D_2. The centre tap is the common (ground) point, and each half of the secondary delivers a voltage of peak value V_m with respect to CT.

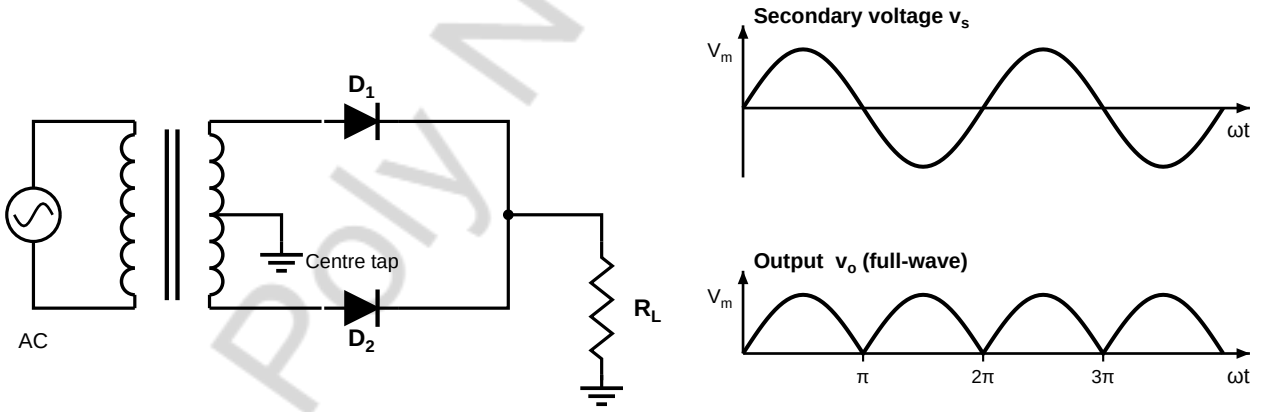


Fig. 4.3: Centre-tapped full-wave rectifier with input and output waveforms

- **Positive half-cycle:** The top end of the secondary is positive, so D_1 is forward biased (conducts) and D_2 is reverse biased (OFF). Current flows through R_L from top to bottom.
- **Negative half-cycle:** The bottom end becomes positive, so D_2 conducts and D_1 is OFF. **The current through R_L flows in the same direction** as before.
- Hence the output has pulses in both half-cycles; output frequency is **2f** (100 Hz).

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Analysis

Each diode conducts for half a cycle, giving a load current $i = I_m |\sin \omega t|$, where $I_m = V_m/(R_f + R_L)$. Averaging over one full period of the rectified wave (0 to π):

$$\mathbf{I_{dc} = (1/\pi) \int_0^{\pi} I_m \sin\theta \, d\theta = 2\, I_m / \pi \qquad V_{dc} = 2\, V_m / \pi = 0.636\, V_m}$$

$$\mathbf{I_{rms} = I_m / \sqrt{2} \qquad V_{rms} = V_m / \sqrt{2} = 0.707\, V_m}$$

$$\mathbf{\eta = P_{dc}/P_{ac} = (8/\pi^2) \times R_L/(R_f + R_L) = 81.2\% / (1 + R_f/R_L)}$$

$$\mathbf{F = I_{rms}/I_{dc} = \pi / (2\sqrt{2}) = 1.11 \qquad \gamma = \sqrt{(F^2 - 1)} = 0.482}$$

- **PIV = $2V_m$**: when D_1 conducts, D_2 sees the voltage of the two secondary halves in series ($V_m + V_m$).
- Peak factor = $\sqrt{2} = 1.414$; ripple frequency = 2f; TUF = 0.693 (taking the average of primary and secondary utilisation).
- Maximum efficiency is **81.2%**, exactly double that of the half-wave rectifier.

Advantages	Disadvantages
• Double the DC output and efficiency of HWR • Lower ripple (0.482); ripple frequency 2f is easier to filter • No DC saturation of the transformer core	• Needs a centre-tapped transformer (costly, bulky) • PIV rating of diodes must be $2V_m$ • Each half of the secondary is used only half the time

4.1.3 Bridge rectifier

The bridge rectifier uses **four diodes** connected as a bridge and does not require a centre-tapped transformer. The AC input is applied to two opposite corners of the bridge, and the load is connected across the other two corners.

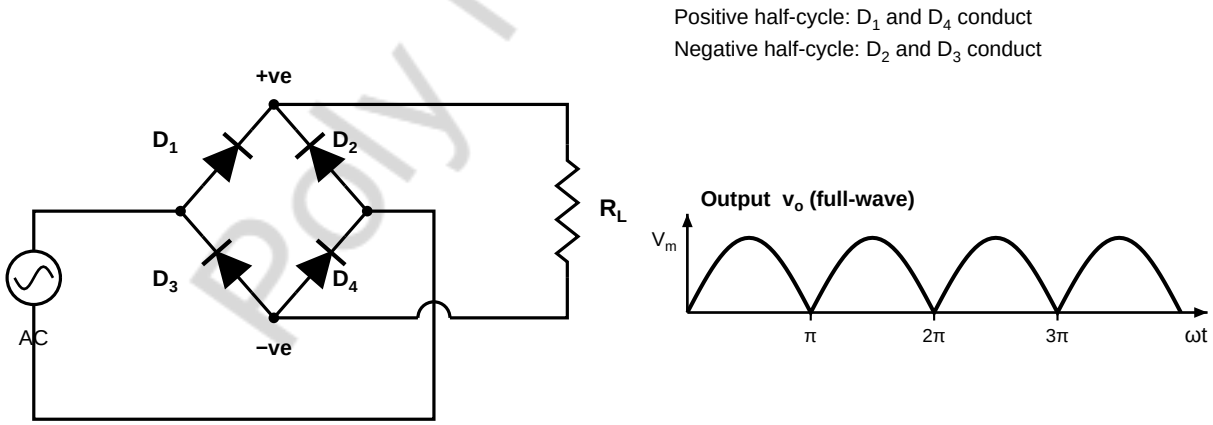


Fig. 4.4: Bridge rectifier circuit and output waveform

- **Positive half-cycle:** Diodes D_1 and D_4 are forward biased; D_2 and D_3 are reverse biased. Current flows through D_1, R_L (top to bottom) and D_4.
- **Negative half-cycle:** D_2 and D_3 conduct; D_1 and D_4 are OFF. The current again flows through R_L from top to bottom.
- At any instant **two diodes** are in series with the load, so $I_m = V_m / (2R_f + R_L)$. With silicon diodes, 2×0.7 V = 1.4 V is lost: $V_{dc} = 2(V_m - 1.4)/\pi$.

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The expressions for V_{dc}, V_{rms}, ripple factor (0.482), efficiency (81.2% maximum) and ripple frequency (2f) are the same as for the centre-tapped full-wave rectifier. The differences are: **PIV = V_m** only (each reverse-biased diode sees the peak secondary voltage), TUF = 0.812, and the efficiency with diode resistance is $\eta = 81.2\% / (1 + 2R_f/R_L)$.

Advantages	Disadvantages
• No centre-tapped transformer needed • PIV rating is only V_m • Highest TUF (0.812); good for high voltage output • Transformer can be smaller	• Four diodes required • Two diode drops (about 1.4 V), so poor for very low-voltage outputs • Slightly lower efficiency than CT type when R_f is considered

4.1.4 Comparison of HWR, centre-tapped FWR and bridge rectifier

Parameter	Half-wave	Full-wave (CT)	Bridge
Number of diodes	1	2	4
Transformer	Ordinary	Centre-tapped	Ordinary
I_{dc}	I_m/π	$2I_m/\pi$	$2I_m/\pi$
V_{dc}	0.318 V_m	0.636 V_m	0.636 V_m
I_{rms}	$I_m/2$	$I_m/\sqrt{2}$	$I_m/\sqrt{2}$
Form factor	1.57	1.11	1.11
Ripple factor	1.21	0.482	0.482
Maximum efficiency	40.6%	81.2%	81.2%
PIV	V_m	$2V_m$	V_m
Ripple frequency	f (50 Hz)	2f (100 Hz)	2f (100 Hz)
TUF	0.287	0.693	0.812
Peak factor	2	$\sqrt{2}$	$\sqrt{2}$
Diode drops in path	1	1	2

4.1.5 Percentage voltage regulation

When the load current increases, the DC output voltage of a rectifier **falls**, because of the voltage drops across the diode resistance R_f and the transformer winding resistance R_s. Voltage regulation measures this change.

$$\textbf{\% Regulation} = (V_{NL} - V_{FL}) / V_{FL} \times 100$$

- V_{NL} = DC output voltage at no load ($I_{dc} = 0$); V_{FL} = DC output voltage at full load.
- $V_{dc} = V_{NL} - I_{dc}(R_f + R_s)$ for a half-wave rectifier (and the same with the corresponding diode resistances for full-wave rectifiers), so the output drops **linearly** with load current.
- For an unfiltered rectifier $V_{NL} = V_m/\pi$ (HW) or $2V_m/\pi$ (FW). The smaller the diode and winding resistance, the better the regulation.
- An **ideal power supply has 0% regulation**; a good one has less than 1% (obtained using electronic regulators, see 4.3).

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Solved examples

Example 1. A half-wave rectifier is fed from a transformer secondary of 12 V rms. Load R_L = 1 kΩ. Assuming an ideal diode, find V_{dc}, I_{dc} and PIV.

Solution: $V_m = 12 \times \sqrt{2} = 16.97$ V. $V_{dc} = V_m/\pi = 16.97/3.1416 =$ **5.40 V**. $I_{dc} = 5.40 / 1000 =$ **5.4 mA**. PIV = V_m = **16.97 V**.

Example 2. A bridge rectifier is supplied with 20 V rms. R_L = 500 Ω, each silicon diode drops 0.7 V. Find V_{dc}, I_{dc} and PIV.

Solution: $V_m = 20 \times \sqrt{2} = 28.28$ V. Two diodes conduct, so effective peak = 28.28 − 1.4 = 26.88 V. $V_{dc} = 2 \times 26.88 / \pi =$ **17.11 V**. $I_{dc} = 17.11/500 =$ **34.2 mA**. PIV ≈ V_m = **28.28 V**.

Example 3. A half-wave rectifier has R_f = 50 Ω and R_L = 1 kΩ. Find its efficiency.

Solution: $\eta = 40.6\% / (1 + R_f/R_L) = 40.6 / (1 + 0.05) =$ **38.7%**.

Example 4. The DC output of a rectifier is 20 V at no load and 18 V at full load. Find the percentage regulation.

Solution: %VR = (20 − 18)/18 × 100 = **11.1%**.

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4.2 Filter Circuits

The output of a rectifier is pulsating DC, which contains a large AC (ripple) component. A **filter** is a circuit connected between the rectifier and the load that **removes the AC component and passes the DC component**, producing a smooth output. Filters work on the principle that a **capacitor** opposes sudden changes in *voltage* (it has a low reactance $X_C = 1/2\pi fC$ to ripple and is connected in **shunt**), whereas an **inductor** opposes changes in *current* (it has a high reactance $X_L = 2\pi fL$ to ripple and is connected in **series**).

Filter	Components	Connection	Best suited for
Capacitor (shunt C) filter	C	C in parallel with load	Light loads (high R_L), low current
Inductor (choke) filter	L	L in series with load	Heavy loads (low R_L), high current
LC (choke-input) filter	L, C	L series, C shunt	Medium to heavy loads, good regulation
π (CLC) filter	C_1, L, C_2	C, then L, then C	Light loads needing very low ripple and high voltage

4.2.1 Capacitor input filter (shunt capacitor filter)

A large capacitor C is connected **across the load** R_L, directly after the rectifier.

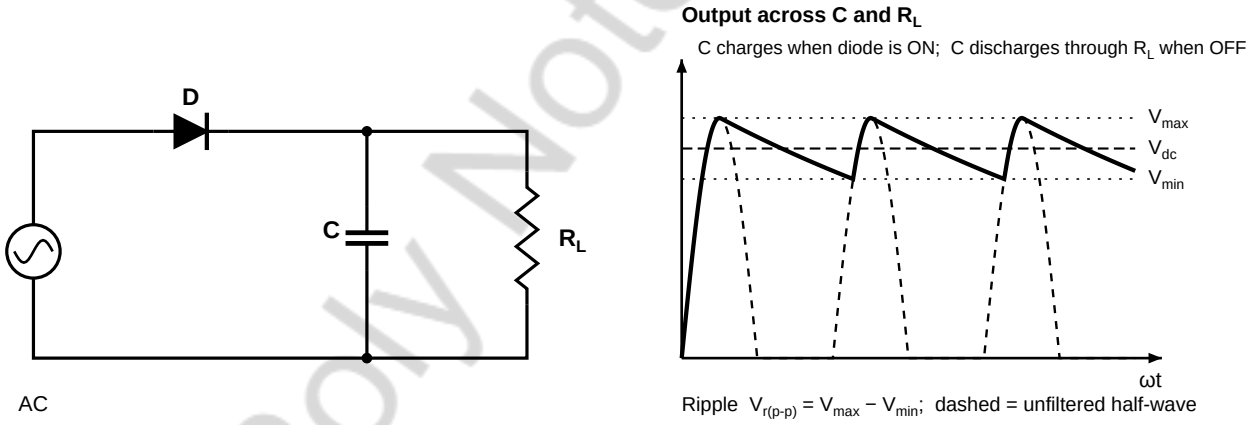


Fig. 4.5: Half-wave rectifier with capacitor filter and output waveform

- **Charging:** When the rectifier voltage rises, the diode conducts and the capacitor charges rapidly to the peak value V_m.
- **Discharging:** When the input falls below the capacitor voltage, the diode is reverse biased (OFF) and C discharges slowly through R_L. The output falls only slightly (the discharge time constant $R_L C$ is large).
- **Next peak:** The capacitor is recharged by the next peak. The output is therefore a nearly constant DC with small **saw-tooth ripple**.
- A larger C or larger R_L gives a longer time constant, hence smaller ripple and higher DC output (nearer to V_m).

Ripple factor and average output voltage

The ripple is approximated by a triangular wave. Let the capacitor discharge for time T_d at an almost constant current I_{dc}. $T_d \approx 1/f$ for half-wave and $1/2f$ for full-wave. The peak-to-peak ripple is $V_{r(p\text{-}p)} = I_{dc}\, T_d / C$, and for a triangular wave $V_{r(rms)} = V_{r(p\text{-}p)} / (2\sqrt{3})$.

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Quantity	Half-wave	Full-wave
Peak-to-peak ripple $V_{r(p\text{-}p)}$	$I_{dc} / (f\,C)$	$I_{dc} / (2\,f\,C)$
RMS ripple $V_{r(rms)}$	$I_{dc} / (2\sqrt{3}\,f\,C)$	$I_{dc} / (4\sqrt{3}\,f\,C)$
Average output V_{dc}	$V_m - I_{dc} / (2\,f\,C)$	$V_m - I_{dc} / (4\,f\,C)$
Ripple factor γ	$1 / (2\sqrt{3}\,f\,C\,R_L)$	$1 / (4\sqrt{3}\,f\,C\,R_L)$

The expression for γ is obtained by dividing $V_{r(rms)}$ by $V_{dc} = I_{dc}\,R_L$. It shows that ripple is **inversely proportional to C, R_L and f**. Since $V_{dc} = I_{dc}\,R_L$, substituting gives $V_{dc} = V_m / [1 + 1/(4\,f\,C\,R_L)]$ for full-wave.

Characteristics and drawbacks

- Output voltage **falls as load current increases** (poor regulation) because $I_{dc}/(4fC)$ increases.
- Diode conducts only for a short time near each peak, so the **peak (surge) current** through the diode and transformer is large; diodes must have a high repetitive and surge current rating.
- Suitable for low-current loads; very simple and cheap; gives output close to V_m.

Example 5. A full-wave rectifier (f = 50 Hz) with V_m = 15 V uses a 1000 µF capacitor across R_L = 100 Ω. Find the ripple factor and V_{dc}.

Solution: $\gamma = 1/(4\sqrt{3} \times 50 \times 1000\times10^{-6} \times 100) = 1/34.64 =$ **0.0289 (2.9%)**. $V_{dc} = 15 / [1 + 1/(4 \times 50 \times 10^{-3} \times 100)] = 15 / 1.05 =$ **14.29 V**.

4.2.2 Inductor (choke) filter

An inductor (choke) L is connected in **series** between the rectifier and the load. It offers **very high reactance to the AC ripple** ($X_L = 2\pi fL$) and almost **zero resistance to DC**. By Lenz's law the inductor opposes any change in current; it stores energy when the current rises and releases it when the current falls, so the load current stays nearly constant.

- The DC component passes to the load with only a small drop in the winding resistance of the choke.
- Since the rectified wave contains the second harmonic (frequency 2f) as the dominant ripple, the choke reduces it.
- Ripple is smaller for **smaller R_L** (heavy load) – the opposite of a capacitor filter.

Ripple factor and output voltage (full-wave, with L only)

The full-wave output is $V_{dc} = 2V_m/\pi$ plus a series of harmonics, of which the strongest is the second harmonic of amplitude $4V_m/(3\pi)$ at angular frequency 2ω (ω = 2πf of the supply). The ripple current through L and R_L (taking 2ωL much larger than R_L) is $I_{ac(rms)} = [4V_m/(3\pi\sqrt{2})] / (2\omega L)$. Dividing by $I_{dc} = 2V_m/(\pi R_L)$:

$$\gamma = R_L / (3\sqrt{2}\,\omega L) \quad \text{and} \quad V_{dc} = 2V_m/\pi - I_{dc}\,R_c \quad (R_c = \text{choke resistance})$$

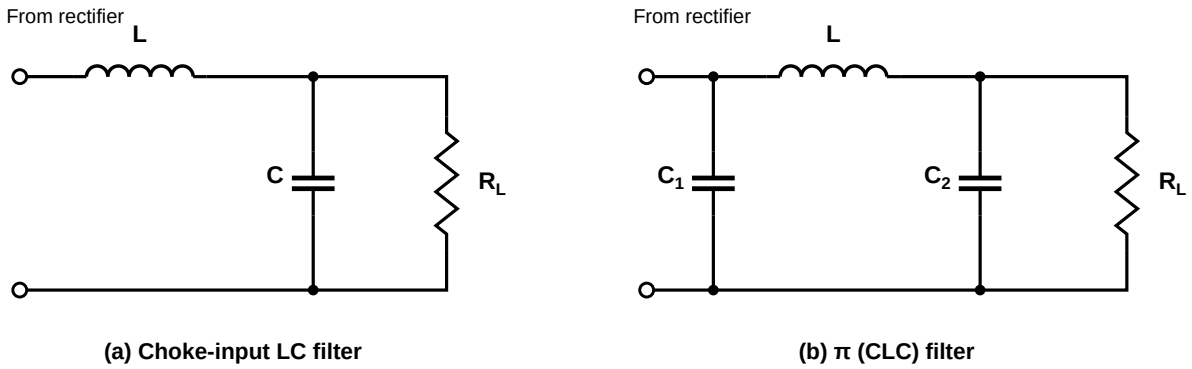
- γ is **directly proportional to R_L** and inversely proportional to L and f.
- V_{dc} does not depend on L; it equals the average of the rectified wave, so **regulation is good**.
- **Critical inductance:** for the choke current to be continuous, L must be above $L_c = R_L/(3\omega)$. For R_L = 1 kΩ at 50 Hz, $L_c \approx 1$ H.
- **Drawbacks:** bulky, heavy, costly; gives magnetic interference; poor for light loads.

Example 6. A full-wave rectifier (f = 50 Hz) has a series choke L = 10 H and R_L = 1 kΩ. Find the ripple factor.

Solution: $\omega = 2\pi \times 50 = 314.16$ rad/s. $\gamma = 1000 / (3\sqrt{2} \times 314.16 \times 10) = 1000/13329 =$ **0.075 (7.5%)**.

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4.2.3 LC filter (choke-input filter) and π filter



(a) Choke-input LC filter **(b) π (CLC) filter**

Fig. 4.6: (a) Choke-input LC filter and (b) π (CLC) filter

LC (L-section) filter

It combines a series inductor L and a shunt capacitor C. The inductor blocks the ripple, and the capacitor bypasses what remains. The attenuation of the ripple by the L-C section is $X_C/X_L = 1/(4\omega^2 LC)$ for the second harmonic. For a full-wave rectifier:

$$\boldsymbol{\gamma = 1 / (6\sqrt{2}\,\omega^2 L C) \approx 1.2 / (L C) \quad (50\ \text{Hz, L in henry, C in } \mu\text{F})}$$

The DC output is $V_{dc} = 2V_m/\pi - I_{dc}R_c$. The ripple is **independent of the load** as long as L is greater than the critical inductance, and the regulation is good. **Example 7:** L = 5 H, C = 10 μF, 50 Hz: γ = 1.2/(5 × 10) = **0.024 (2.4%)**.

π (CLC) filter

It consists of an input capacitor C_1, a series choke L and an output capacitor C_2, forming the Greek letter π. C_1 acts as a capacitor input filter and gives a high peak output; the L-C_2 section then removes most of the remaining ripple.

- Ripple factor is the product of the ripple of C_1 and the attenuation of the L-C_2 section: $\gamma = \gamma_{C1} \times X_{C2}/X_L$.
- For a full-wave rectifier: $\gamma_{C1} = 1/(4\sqrt{3}\, f\, C_1\, R_L)$, and $X_{C2}/X_L = 1/(\omega_r^2\, L\, C_2)$ where $\omega_r = 2\pi(2f)$ is the ripple angular frequency.
- Average output voltage $V_{dc} \approx V_m - I_{dc}/(4fC_1) - I_{dc}R_c$ (a little lower than that of a capacitor filter, but with far smaller ripple).

$$\boldsymbol{\gamma = [\,1 / (4\sqrt{3}\, f\, C_1\, R_L)\,] \times [\,1 / (\omega_r^2\, L\, C_2)\,]}$$

Example 8. A full-wave π filter has $C_1 = C_2 = 100$ μF, L = 5 H, $R_L = 1$ kΩ, f = 50 Hz. Find γ.

Solution: $\gamma_{C1} = 1/(4\sqrt{3} \times 50 \times 100\times10^{-6} \times 1000) = 1/34.64 = 0.0289$. $\omega_r = 2\pi \times 100 = 628.3$ rad/s, so $\omega_r^2 = 3.948\times10^5$; $X_{C2}/X_L = 1/(3.948\times10^5 \times 5 \times 100\times10^{-6}) = 1/197.4 = 0.00507$. γ = 0.0289 × 0.00507 = $\mathbf{1.46 \times 10^{-4}}$ **(0.0146%)**.

Note: A resistor R is sometimes used in place of L (RC π filter) in low-current supplies, but it drops DC voltage and reduces efficiency.

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4.2.4 Comparison of filters

Parameter	Capacitor	Choke (L)	LC	π (CLC)
Ripple factor (FW)	$1/(4\sqrt{3}\, fCR_L)$	$R_L/(3\sqrt{2}\, \omega L)$	$1/(6\sqrt{2}\, \omega^2 LC)$	Very small (product of two stages)
V_{dc}	Near V_m, falls with load	$2V_m/\pi$, constant	$2V_m/\pi$, constant	Slightly below V_m
Regulation	Poor	Good	Good	Poor
Diode surge current	High	Low	Low	High
Ripple vs load	Decreases as R_L increases	Increases as R_L increases	Independent of load	Decreases as R_L increases
Cost and size	Low, small	High, bulky	High	Medium to high
Application	Low-current supplies	High-current supplies	Medium-power supplies	Radio, instruments

Bleeder resistor: A high-value resistor connected across the filter capacitor to discharge it when the supply is switched off (a safety measure) and to improve regulation by drawing a minimum load current.

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4.3 Voltage Regulators

4.3.1 Need for regulation

The output of a rectifier-filter combination changes when the **mains voltage varies** (line variation) or the **load current changes** (load variation), and also with temperature. Sensitive circuits need a constant voltage. A **voltage regulator** is a circuit that maintains an almost constant output voltage irrespective of these changes. A **Zener diode** operating in breakdown gives a stable reference voltage V_Z, which is used in most regulators.

Term	Definition
Line regulation	Change in output voltage for a change in input voltage at constant load: $\Delta V_o/\Delta V_{in}$ (or % per volt). Smaller is better.
Load regulation	Change in output voltage from no-load to full-load: $(V_{NL} - V_{FL})/V_{FL} \times 100\%$.
Output resistance	$R_o = \Delta V_o/\Delta I_L$. Smaller means better regulation.
Ripple rejection	Ability of the regulator to suppress the ripple at the input.

Zener shunt regulator (basic): A Zener diode connected across the load with a series resistor R_s holds $V_o = V_Z$. If V_{in} or the load changes, the Zener current changes and the drop across R_s compensates. It is simple, but gives only small load currents (limited by the Zener power rating) and poor regulation. Transistor regulators extend this principle to higher currents.

4.3.2 Series voltage regulator using transistor

In a series regulator, a **control (pass) transistor Q_1 is connected in series** with the load. The Zener diode provides a fixed reference at the base, and the transistor works as an **emitter follower**, so the output follows the base voltage.

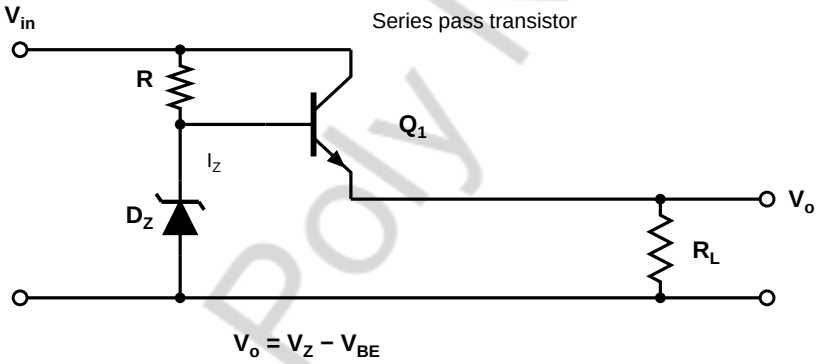


Fig. 4.7: Series voltage regulator using transistor and Zener diode

Working

1. Resistor R supplies the biasing current to the base of Q_1 and to the Zener diode D_Z, which holds the base at V_Z.
2. The output voltage is $\mathbf{V_o = V_Z - V_{BE}}$ (about $V_Z - 0.7$ V), which is constant.
3. **If V_o tends to rise** (due to increased input or reduced load): $V_{BE} = V_Z - V_o$ decreases → base current decreases → Q_1 conducts less → V_{CE} increases → V_o falls back to its set value.
4. **If V_o tends to fall** (heavier load): V_{BE} increases → Q_1 conducts more → V_{CE} decreases → V_o rises back.
5. The excess input voltage $(V_{in} - V_o)$ is dropped across the transistor, which therefore dissipates $P = (V_{in} - V_o) I_L$.

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Design: $R = (V_{in} - V_Z) / (I_Z + I_B)$, where $I_B = I_L/\beta$. Because the load current is supplied by the transistor and the Zener carries only $I_B + I_Z$, the series regulator supplies a load current **β times larger** than a plain Zener regulator.

- **Advantages:** better regulation and higher load current than Zener alone; simple; output current is not drawn from the Zener; efficient at heavy loads.
- **Disadvantages:** output is fixed and depends on V_Z and V_{BE} (temperature dependent); the pass transistor dissipates power and needs a heat sink; no protection against short circuit unless a limiting circuit is added.
- **Improvement:** a comparator (error amplifier, e.g. op-amp) compares a sample of V_o with V_Z and drives the pass transistor. Then $V_o = V_Z (1 + R_1/R_2)$ and the output is adjustable.

4.3.3 Shunt voltage regulator using transistor

In a shunt regulator, a **control transistor Q_1 is connected in parallel (shunt) with the load**, and a resistor R_s is connected in series with the supply. The transistor diverts the extra current away from the load so that the voltage across the load stays constant.

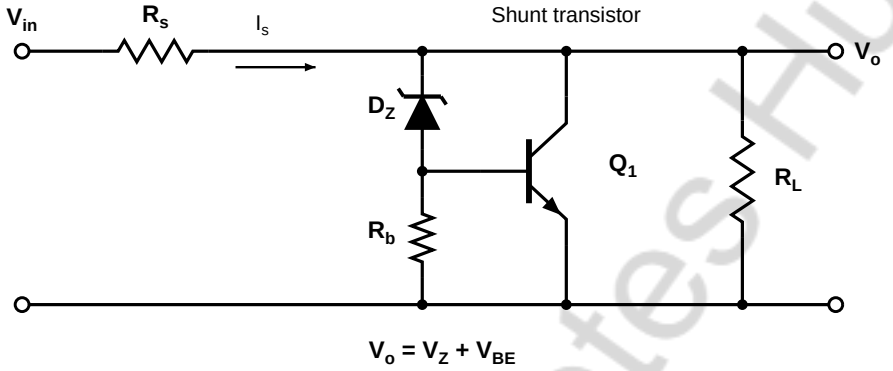


Fig. 4.8: Shunt voltage regulator using transistor

Working

1. Total current drawn from the supply is $I_s = I_L + I_Q$, where I_Q is the shunt-transistor current. The drop across R_s is $I_s R_s$, so $V_o = V_{in} - I_s R_s$.
2. The output voltage is $\mathbf{V_o = V_Z + V_{BE}}$, because the Zener (breaking down) and the base-emitter junction are across the output.
3. **If V_o tends to rise:** the Zener current and base current of Q_1 increase → Q_1 shunts more current → larger drop across R_s → V_o falls back.
4. **If the load current I_L increases:** Q_1 automatically passes less current so I_s remains nearly constant, and V_o stays constant.

Design: $R_s = (V_{in} - V_o) / I_s$, with I_s chosen ≥ maximum load current.

- **Advantages:** very simple; inherently **protected against short circuit** (current limited by R_s).
- **Disadvantages:** low efficiency because I_s flows continuously, even at no load (constant power drawn); R_s and Q_1 waste power; unsuitable for large or varying high loads.

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Comparison: series and shunt regulators

Parameter	Series regulator	Shunt regulator
Position of control element	In series with the load	In parallel with the load
Output voltage	$V_Z - V_{BE}$	$V_Z + V_{BE}$
Efficiency	Higher (especially at heavy loads)	Lower (constant current drawn)
Power wasted	In pass transistor, depends on load	In R_s and Q_1, nearly constant
Short-circuit protection	Not inherent; needs a limiter	Inherent (limited by R_s)
Load current capability	High	Low
Regulation	Better	Less good
Used for	General supplies, high current	Low-power, reference supplies

Example 9. A series regulator uses a 10 V Zener and a silicon transistor. Find the output voltage. *Solution:* $V_o = V_Z - V_{BE} = 10 - 0.7 =$ **9.3 V**.

Example 10. A shunt regulator has V_{in} = 15 V, V_o = 10 V and I_s = 100 mA. Find R_s and its power rating. *Solution:* $R_s = (15 - 10)/0.1 =$ **50 Ω**; $P = I_s^2 R_s = 0.01 \times 50 =$ **0.5 W**.

4.3.4 IC voltage regulators

An **IC regulator** contains the complete regulator circuit – reference voltage source, error amplifier, series pass transistor and protection circuits – in a single chip. The most common are the **three-terminal fixed regulators**: the **78XX series** (positive output) and the **79XX series** (negative output). The last two digits give the output voltage; for example, 7805 = +5 V, 7912 = −12 V.

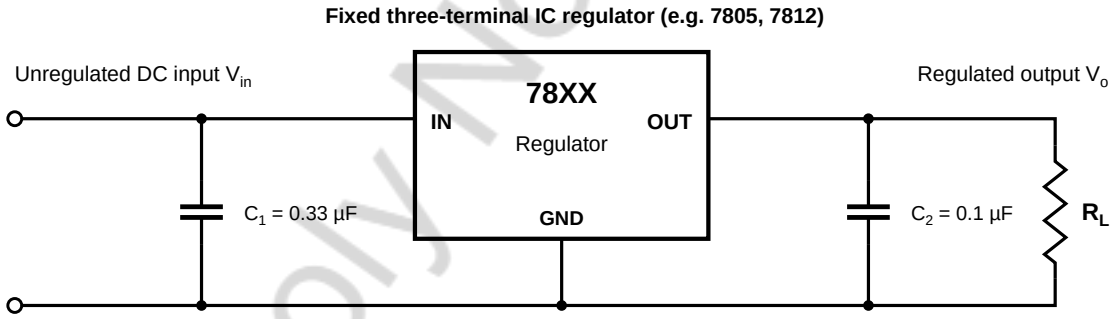


Fig. 4.9: Connection of a 78XX three-terminal fixed voltage regulator

IC	7805	7806	7808	7809	7810	7812	7815	7818	7824
V_o (V)	+5	+6	+8	+9	+10	+12	+15	+18	+24

Features of 78XX / 79XX regulators

- Output current up to **1 A** (78XX); 100 mA (78LXX) and 500 mA (78MXX) versions are available.
- Built-in **thermal shutdown**, **current limiting** and **safe operating area protection**: the IC is practically indestructible.
- Input voltage must be at least about **2 V above** the output (dropout voltage), e.g. $V_{in} \geq 7$ V for 7805, and within the maximum rating (about 35 V).

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- Needs few external components: C_1 (0.33 µF) is needed if the IC is far from the filter capacitor; C_2 (0.1 µF) improves transient response.
- Line and load regulation are very good (a few mV); the IC requires a heat sink at high currents. Power dissipated: $P = (V_{in} - V_o)\, I_L$.
- A **dual supply (±12 V)** is obtained using a 7812 and a 7912 with a centre-tapped transformer.

Adjustable regulators

- **LM317** (positive adjustable, 1.25 V to 37 V, 1.5 A) and **LM337** (negative adjustable): $V_o = 1.25\,(1 + R_2/R_1) + I_{adj}\,R_2$, where R_1 (about 240 Ω) is connected between OUT and ADJ and R_2 between ADJ and ground.
- **IC 723** is a general-purpose adjustable regulator (2 V to 37 V, 150 mA) which can be extended to higher current with an external pass transistor.

Advantages of IC regulators	**Limitations**
• Very few components, small size, low cost • Excellent regulation and ripple rejection • Built-in protection • Easy to design and use	• Dropout of about 2 V reduces efficiency • Dissipates heat (linear regulator) • Fixed types give only fixed voltages • Limited current (1 A)

Example 11. A 7805 operates with V_{in} = 12 V and I_L = 500 mA. Find the power dissipated in the IC. *Solution:* $P = (12 - 5) \times 0.5 =$ **3.5 W** (a heat sink is required).

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4.4 Switch Mode Power Supply (SMPS)

4.4.1 Concept

A **linear** power supply (transformer + rectifier + filter + series regulator) wastes much power as heat in the pass transistor and needs a large, heavy 50 Hz transformer. A **Switch Mode Power Supply (SMPS)** overcomes this: the transistor (MOSFET or BJT) is used as a **high-speed switch**, which is either fully ON (low voltage across it) or fully OFF (no current), so very little power is lost in it. The mains is first rectified directly, then **chopped at a high frequency (20 kHz to several hundred kHz)**, passed through a small high-frequency transformer, and rectified and filtered again. The output voltage is regulated by controlling the **duty cycle** (the ON-time fraction) of the switch.

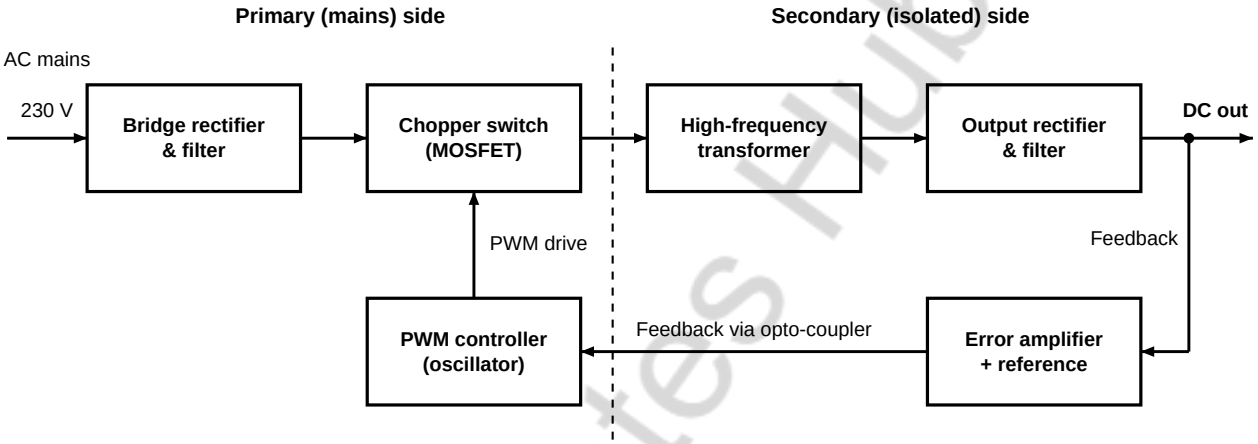


Fig. 4.10: Block diagram of an off-line SMPS

Working of each block

1. **Input rectifier and filter:** The 230 V AC mains is rectified directly by a bridge rectifier (no 50 Hz transformer) and filtered by a large capacitor to give about 310 V DC (unregulated).
2. **Chopper (switching transistor):** A power MOSFET switches the DC ON and OFF at a high frequency, converting it into a high-frequency pulsed waveform.
3. **High-frequency transformer:** Steps the voltage down and provides **isolation** from the mains. As core size is inversely related to frequency, it is very small and light.
4. **Output rectifier and filter:** Fast-recovery or Schottky diodes rectify the secondary voltage; a small LC filter smooths it, since the ripple frequency is high.
5. **Feedback and control:** An error amplifier compares the output voltage with a reference. The error signal, through an opto-coupler (for isolation), controls the **PWM controller**, which varies the pulse width (duty cycle) of the switch to hold the output constant.

Regulation principle: If the output voltage rises, the PWM controller reduces the ON-time of the switch (smaller duty cycle D), and if it falls the ON-time is increased. For a forward-type converter $V_o \approx D \times V_{in} \times (N_s/N_p)$ where $D = t_{on}/T$.

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Basic converter topologies (non-isolated)

Converter	Function	Output voltage (ideal)
Buck	Step-down	$V_o = D \times V_{in}$
Boost	Step-up	$V_o = V_{in} / (1 - D)$
Buck-boost	Step-up or step-down, inverted polarity	$V_o = -V_{in} \times D / (1 - D)$

Examples: buck with V_{in} = 24 V and D = 0.5 gives 12 V; boost with V_{in} = 12 V and D = 0.5 gives 24 V. Isolated types include the **flyback** (low power, e.g. mobile chargers) and **forward** converters (medium power).

4.4.2 Linear power supply vs SMPS

Parameter	Linear (series regulated) supply	SMPS
Operation of pass element	Works in active region (continuous)	Works as a switch (ON/OFF)
Efficiency	30% to 60%	70% to 95%
Size and weight	Large and heavy (50 Hz transformer)	Small and light (HF transformer)
Heat produced	High; large heat sinks	Low
Output noise / EMI	Very low	High switching noise; needs shielding and filters
Circuit complexity	Simple	Complex
Cost	Low for small power; high for large power	Lower at medium/high power
Input voltage range	Narrow	Wide (90 V to 270 V universal input)
Applications	Audio, test equipment, low-noise analog	Computers (ATX), TVs, chargers, LED drivers, telecom

- **Advantages of SMPS:** high efficiency, small size and weight, wide input range, low heat, can give multiple outputs and step-up as well as step-down operation.
- **Disadvantages:** complex design, electromagnetic and high-frequency noise, output ripple (switching spikes), costly for very low power, repairs are difficult.

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4.5 Uninterruptible Power Supply (UPS)

4.5.1 Concept

An **Uninterruptible Power Supply (UPS)** is a device that supplies **continuous AC power to the load** even when the mains fails, using stored battery energy. It also protects the load from voltage sags, surges and spikes. It is essential for computers, servers, medical equipment, telecom systems, ATMs and industrial controls where sudden power loss would cause data loss or damage. A UPS is basically a battery-backed combination of **charger (rectifier), battery, inverter and a static switch**.

4.5.2 Block schematic of an on-line (double conversion) UPS

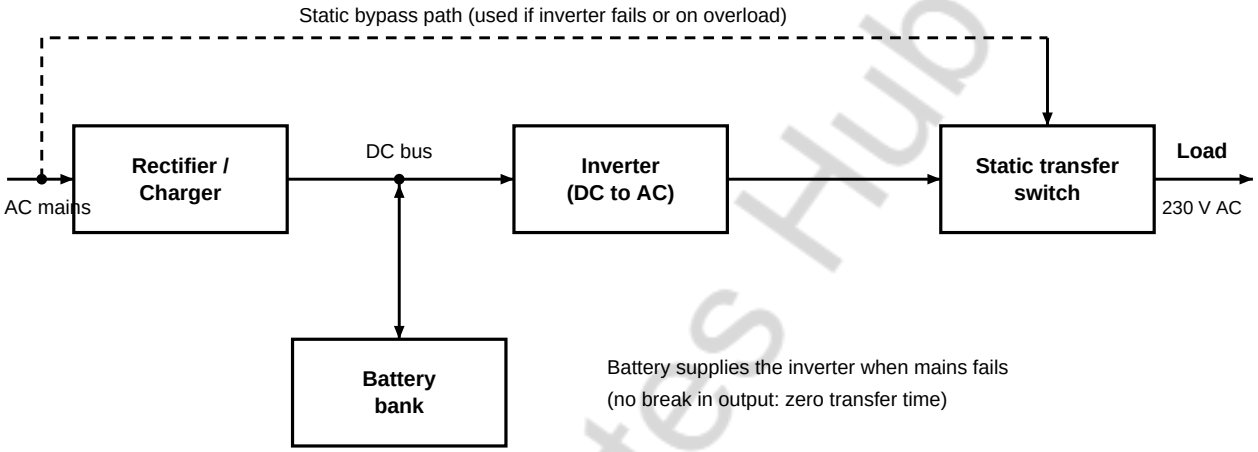


Fig. 4.11: Block schematic of an on-line UPS

Block	Function
Rectifier / charger	Converts AC mains to DC. This DC charges the battery and also feeds the inverter.
Battery bank	Stores energy (sealed maintenance-free lead-acid, SMF, or lithium-ion). Supplies the inverter when the mains fails.
Inverter	Converts the DC into AC (230 V, 50 Hz) using switching devices (MOSFET/IGBT) with PWM and a filter, giving a sine or modified-sine output.
Static transfer switch	Electronic switch (SCR/IGBT) that selects the inverter output or the bypass path without any break (a few ms or zero).
Bypass path	Passes the mains directly to the load if the UPS faults or is overloaded.
Control and monitoring	Controls inverter frequency and voltage, monitors battery, gives alarms and overload protection.

Operation

- **Normal mode (mains present):** The rectifier converts the AC to DC; the DC charges the battery and feeds the inverter, which supplies the load with **clean, regulated AC**.
- **Battery mode (mains failure):** The rectifier stops, but the battery supplies the inverter at once. Because the load is always fed by the inverter, there is **no transfer time**.
- **Bypass mode:** On inverter failure or overload, the static switch transfers the load to the mains through the bypass path.

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- When the mains returns, the rectifier recharges the battery and the system returns to normal mode.

4.5.3 Off-line (standby) UPS

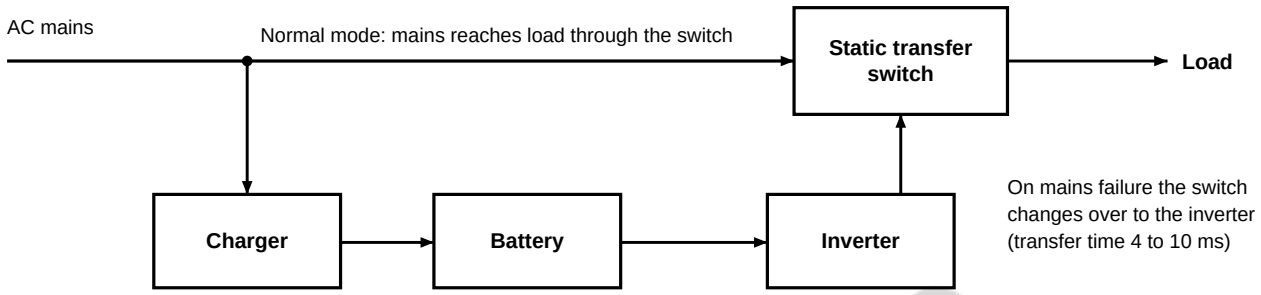


Fig. 4.12: Block schematic of an off-line (standby) UPS

In an off-line UPS the load is normally supplied **directly from the mains** through the static switch; the charger only keeps the battery charged. When the mains fails or goes out of limits, the switch changes over to the inverter, which runs from the battery. It is cheap and efficient, but the output is unregulated and there is a short transfer time.

4.5.4 Types of UPS compared

Parameter	Off-line (standby)	Line-interactive	On-line (double conversion)
Normal supply to load	Mains directly	Mains via autotransformer (AVR)	Inverter always
Transfer time	4 to 10 ms	2 to 4 ms	0 ms
Voltage regulation	Poor	Good (tap changing)	Excellent
Efficiency	Highest (about 95%)	High	Lower (85% to 92%)
Cost	Lowest	Medium	Highest
Use	Home PCs, small office	Small servers, network	Data centres, hospitals, industry

Specifications and backup time

- **Rating:** in VA (volt-ampere). Real power (W) = VA × power factor (typically 0.6 to 0.8 for offline UPS; 0.9 to 1 for online).
- **Backup time:** T (hours) = (Battery voltage × Ah rating × efficiency) / Load power (W).
- **Example:** A 12 V, 7 Ah battery feeds a 100 W load with 80% efficiency: T = 12 × 7 × 0.8 / 100 = 0.67 h ≈ **40 minutes**.
- **Inverter output waveform:** square wave (cheap, may harm motors), modified sine wave, or pure sine wave (best, used in online UPS).
- **Advantages:** continuous power, protection against surges, sags and blackouts, protects data and hardware.
- **Disadvantages:** costly, batteries need replacement every 3 to 5 years, limited backup time, heat and noise from inverter and fan, needs maintenance.

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Quick Revision: Important Formulas and Points

Quantity	Half-wave	Full-wave (CT / bridge)
V_{dc}	$V_m/\pi = 0.318\ V_m$	$2V_m/\pi = 0.636\ V_m$
I_{rms}	$I_m/2$	$I_m/\sqrt{2}$
Ripple factor	1.21	0.482
Maximum efficiency	40.6%	81.2%
PIV	V_m	$2V_m$ (CT); V_m (bridge)
Ripple frequency	f	2f
TUF	0.287	0.693 (CT); 0.812 (bridge)
% Regulation	$(V_{NL} - V_{FL})/V_{FL} \times 100$	same

Filter / regulator	Key formula
Capacitor filter, full-wave	$\gamma = 1/(4\sqrt{3}\, f\, C\, R_L)$; $V_{dc} = V_m - I_{dc}/(4fC)$
Capacitor filter, half-wave	$\gamma = 1/(2\sqrt{3}\, f\, C\, R_L)$; $V_{dc} = V_m - I_{dc}/(2fC)$
Choke filter, full-wave	$\gamma = R_L/(3\sqrt{2}\,\omega L)$
LC filter, full-wave	$\gamma = 1/(6\sqrt{2}\,\omega^2 LC) \approx 1.2/(LC)$ at 50 Hz (L in H, C in μF)
π filter	$\gamma = [1/(4\sqrt{3}\, f\, C_1 R_L)] \times [1/(\omega_r^2 LC_2)]$
Series regulator	$V_o = V_Z - V_{BE}$
Shunt regulator	$V_o = V_Z + V_{BE}$; $R_s = (V_{in} - V_o)/I_s$
LM317	$V_o = 1.25\ (1 + R_2/R_1)$
Buck / Boost converter	$V_o = D\, V_{in}$; $V_o = V_{in}/(1 - D)$
UPS backup time	$T = V_{bat} \times Ah \times \eta\ /\ P_{load}$

Points to remember

- A rectifier changes AC into pulsating DC; a filter smooths it; a regulator keeps it constant.
- Full-wave rectifiers have double the DC voltage, double the efficiency and lower ripple than half-wave.
- A bridge rectifier needs no centre tap and its PIV is only V_m, but it has two diode drops.
- Capacitor filter: ripple $1/(C\, R_L)$; choke filter: ripple R_L/L.
- Series regulator: $V_o = V_Z - V_{BE}$; shunt regulator: $V_o = V_Z + V_{BE}$.
- 78XX gives positive and 79XX gives negative regulated voltage; dropout is about 2 V.
- SMPS = high efficiency, small size, high-frequency switching with PWM feedback.
- UPS = charger + battery + inverter + static switch; on-line UPS has zero transfer time.

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Multiple Choice Questions (15)

Choose the correct answer. The answer key follows the questions.

Q1. The ripple frequency of a half-wave rectifier fed from a 50 Hz supply is

(A) 50 Hz (B) 100 Hz
(C) 25 Hz (D) 200 Hz

Q2. The maximum rectification efficiency of a full-wave rectifier is

(A) 40.6% (B) 50%
(C) 81.2% (D) 100%

Q3. The PIV of each diode in a centre-tapped full-wave rectifier (V_m = peak of half secondary) is

(A) V_m (B) $2V_m$
(C) $V_m/2$ (D) V_m/π

Q4. An ideal half-wave rectifier has V_m = 10 V. The DC output voltage is about

(A) 3.18 V (B) 6.37 V
(C) 5 V (D) 10 V

Q5. The ripple factor of a half-wave rectifier is

(A) 0.482 (B) 1.21
(C) 0.121 (D) 0.0482

Q6. Which rectifier does NOT require a centre-tapped transformer for full-wave rectification?

(A) Bridge rectifier (B) Half-wave rectifier
(C) Centre-tap rectifier (D) Clamper

Q7. The ripple factor of a capacitor filter is

(A) directly proportional to C (B) independent of load resistance
(C) inversely proportional to both C and R_L (D) inversely proportional to L

Q8. An inductor (choke) filter is preferred for

(A) very light loads (B) no-load condition
(C) high-resistance loads (D) heavy load currents (small R_L)

Q9. A π filter consists of

(A) L-C-L (B) C-L-C
(C) R-L only (D) C only

Q10. In a series transistor regulator using a Zener diode, the output voltage is approximately

(A) $V_Z - V_{BE}$ (B) $V_Z + V_{BE}$
(C) V_Z only (D) V_{in}

Q11. In a shunt regulator, the control transistor is connected

(A) in series with the load (B) in series with the supply only
(C) in parallel with the load (D) across the transformer

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Q12. The IC 7812 gives an output of

(A) +5 V
(B) −12 V
(C) +15 V
(D) +12 V

Q13. The IC LM317 is a

(A) fixed positive regulator
(B) adjustable positive regulator
(C) fixed negative regulator
(D) adjustable negative regulator

Q14. The main advantage of an SMPS over a linear power supply is

(A) high efficiency and small size
(B) very low noise
(C) very simple circuit
(D) no need for feedback

Q15. In an on-line (double conversion) UPS, the load is always supplied by

(A) the mains directly
(B) the battery directly
(C) the inverter
(D) the bypass line only

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Answer Key for MCQs

Q.No.	Answer	Explanation
1	(A)	HWR output has one pulse per cycle, so its frequency equals f.
2	(C)	$\eta_{max} = 8/\pi^2 = 81.2\%$.
3	(B)	The reverse voltage is the sum of the two half-windings: $2V_m$.
4	(A)	$V_{dc} = V_m/\pi = 10/3.1416 = 3.18$ V.
5	(B)	$\gamma = \sqrt{(1.57^2 - 1)} = 1.21$.
6	(A)	The bridge rectifier uses four diodes and an ordinary transformer.
7	(C)	$\gamma = 1/(4\sqrt{3}\, f\, C\, R_L)$ for full-wave.
8	(D)	Choke filter ripple R_L/L, so it works best with small R_L.
9	(B)	Input capacitor, series choke, output capacitor.
10	(A)	The pass transistor acts as an emitter follower.
11	(C)	Shunt means in parallel with the load.
12	(D)	78XX is positive; XX = 12 V.
13	(B)	LM317 gives 1.25 V to 37 V; LM337 is the negative one.
14	(A)	The switching transistor dissipates little power and the transformer is small.
15	(C)	Mains → rectifier → inverter → load, so there is no transfer time.

Quick answer grid

Q1	Q2	Q3	Q4	Q5
A	C	B	A	B
Q6	**Q7**	**Q8**	**Q9**	**Q10**
A	C	D	B	A
Q11	**Q12**	**Q13**	**Q14**	**Q15**
C	D	B	A	C

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Descriptive (Broad) Questions (10)

Q1. Explain the working of a half-wave rectifier with a neat circuit diagram and waveforms. Derive expressions for average (DC) output voltage, rms voltage, efficiency and ripple factor.

Q2. Explain the working of a centre-tapped full-wave rectifier with a neat diagram. Derive its V_{dc}, V_{rms}, efficiency, ripple factor and PIV.

Q3. Explain the working of a bridge rectifier. Compare half-wave, centre-tapped full-wave and bridge rectifiers in tabular form (any eight points).

Q4. Define percentage voltage regulation, ripple factor, rectification efficiency, PIV and TUF. A bridge rectifier is fed with 24 V rms, R_L = 600 Ω, and each diode drops 0.7 V. Calculate V_{dc}, I_{dc} and PIV.

Q5. Describe the capacitor input filter with circuit and waveforms. Derive the expressions for ripple factor and average output voltage for a full-wave rectifier.

Q6. Explain the inductor (choke) filter and the LC filter. Derive the ripple factor of the choke filter for a full-wave rectifier and state why the choke filter suits heavy loads.

Q7. Draw and explain the π filter. For a full-wave rectifier with $C_1 = C_2$ = 100 μF, L = 10 H and R_L = 2 kΩ at 50 Hz, calculate the ripple factor.

Q8. Explain the working of the series and shunt voltage regulators using transistors with neat circuit diagrams. Compare them.

Q9. Explain the construction of a fixed three-terminal IC regulator (78XX) with a connection diagram, its features and applications. How can the LM317 provide an adjustable output?

Q10. With the help of block diagrams, explain the concept of SMPS and the working of an on-line UPS. Compare an SMPS with a linear power supply.

— End of Chapter 4 —

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