Block 12 — Diode Applications

Student Group

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Table of Contents

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Learning objectives

After this 90-minute block, you can

- design a simple LED circuit with a series resistor.
- explain why LEDs and signal diodes need current limitation.
- use Z-diodes for simple voltage limitation and voltage stabilization.
- explain how a freewheeling diode protects a switching transistor or contact.
- explain diode clamp circuits for sensitive microcontroller inputs.
- distinguish half-wave, center-tap, and bridge rectifier circuits.
- calculate the ideal average value \(U_{\rm di}\) of rectified sinusoidal voltages.
- explain ripple voltage and ripple frequency.
- estimate a smoothing capacitor for a simple diode rectifier power supply.

90-minute plan

- **Warm-up (10 min):**
    - What happens if an LED is connected directly to \(24~{\rm V}\)?
    - Recall from Block 11: diode polarity, forward voltage, reverse blocking.
    - Recall from switching transients: inductor current cannot jump.
- **Core concepts (55 min):**
    - LED operation with a series resistor.
    - Z-diode voltage limitation and stabilization.
    - Freewheeling diode for inductive loads.
    - Clamp diodes for sensitive inputs.
    - Diode rectifiers: M1, M2, B2.
    - Capacitor smoothing and ripple.
- **Practice (20 min):**
    - Calculate an LED series resistor.
    - Check Z-diode current limits.
    - Estimate switching overvoltages in an inductive load.
    - Calculate average rectifier voltages and smoothing capacitors.
- **Wrap-up (5 min):**
    - Which diode application belongs to which engineering problem?
    - Preview: bipolar transistors as controlled switches and amplifiers.

Conceptual overview

- A diode is useful because it is **nonlinear**: it behaves differently for the two voltage polarities.
- In applications, a diode often has one of four jobs:

  - **conduct only one half-wave**: rectifier,
  - **limit a voltage**: Z-diode or clamp diode,
  - **provide a safe current path**: freewheeling diode,
  - **emit light**: LED.
- A diode does not magically limit its own current. The circuit around it must do that.
- Real diodes cause voltage drops and losses:

$$\begin{align*} P_{\rm D}=U_{\rm D}I_{\rm D}. \end{align*}$$

- In mechatronics, diode circuits appear in power supplies, relay drivers, sensor inputs, motor-driver protection, status LEDs, and emergency signal paths.

Scope of this block

This block uses the diode models from Block 11 and applies them to practical circuits.

The focus is on **basic engineering estimates**, not yet on detailed datasheet design.

Core content

Practical diode models for circuit calculation

For hand calculations we usually do not use the full exponential equation, because it is often too complex for a quick solution.
Instead the following is often used:

Model	Forward direction	Reverse direction	Use	Example
ideal diode	$u_{\rm AK}=0$	$i_{\rm D}=0$	switching logic, first estimate	Is the rectifier path conducting?
constant-voltage model	$u_{\rm AK}\approx U_{\rm TO}$	$i_{\rm D}\approx 0$	quick current calculations	Which current flows through an LED and its series resistor?
piecewise-linear model	$u_{\rm AK}\approx U_{\rm TO}+r_{\rm F}\cdot i_{\rm D}$	$i_{\rm D}\approx 0$	more accurate operating point	How does the diode voltage change when the current changes?

Tab. ##: Diode models for circuit calculations

The differential forward resistance is

$$\begin{align*} r_{\rm F} = \frac{\Delta U_{\rm F}}{\Delta I_{\rm F}}. \end{align*}$$

For large forward voltages compared with $U_{\rm T}$, the diode equation leads approximately to

$$\begin{align*} r_{\rm D} = \frac{{\rm d}u_{\rm D}}{{\rm d}i_{\rm D}} \approx \frac{mU_{\rm T}}{I_{\rm D}}. \end{align*}$$

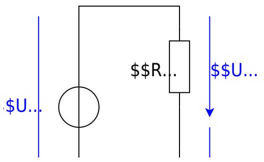
Unit check

$$\begin{align*} [r_{\rm D}] = \frac{[U_{\rm T}]}{[I_{\rm D}]} = \frac{{\rm V}}{{\rm A}} = \Omega. \end{align*}$$

Operating point with a series resistor

A diode must usually be operated with a current-limiting element.

Fig. 1: Circuit of Diode with Shunt resistor.



For the circuit in figure 1 the loop equation is

$$\begin{align*} U_{\rm E} = U_R+U_{\rm D}. \end{align*}$$

With the constant-voltage model,

$$\begin{align*} U_{\rm D}\approx U_{\rm TO}. \end{align*}$$

Therefore

$$\begin{align*} I_{\rm D} \approx \frac{U_{\rm E}-U_{\rm TO}}{R}. \end{align*}$$

> Never connect a normal diode or LED directly to an ideal voltage source in forward direction.
> The diode current must be limited.
> The used resistor is often called **shunt resistor**.

Special Diodes

Z-Diodes

If the reverse voltage of a diode becomes too large, the diode enters **breakdown**. In this region, the reverse current rises strongly.

Two physical effects can cause breakdown:

- **avalanche breakdown:** charge carriers gain enough energy to free additional charge carriers by collisions.
- **Zener breakdown:** in strongly doped pn junctions, charge carriers can cross the barrier by a quantum-mechanical effect.

For ordinary diodes, breakdown is usually unwanted and can destroy the diode if the current is not limited.
Z-diodes are designed to operate safely in this reverse-breakdown region at a defined voltage $U_{\rm Z}$.

The current must still be limited by the surrounding circuit.
In its operating range, the diode voltage is approximately constant:

$$\begin{align*} u_{\rm Z}\approx U_{\rm Z}. \end{align*}$$

The piecewise-linear model is

$$\begin{align*} u_{\rm Z} \approx U_{\rm Z}+r_{\rm Z} \cdot i_{\rm Z}. \end{align*}$$

Z-diode preview

- Z-diodes are useful for voltage limitation and voltage stabilization.
- Z-diodes are still conventional diodes in the forward direction.

LEDs

An LED is a diode that emits light in forward direction. The required forward voltage depends on the semiconductor material and therefore on the color.

<tabcaption tab_led_forward_voltage|Typical LED forward voltages>

LED color	**Typical $U_{\rm TO}$**
infrared	$\approx 1.3~{\rm V}$
red	$\approx 1.6~{\rm V}$

LED color	Typical $U_{\rm TO}$
yellow	$\approx 1.7~{\rm V}$
green	$\approx 1.8~{\rm V}$
blue	$\approx 3.2~{\rm V}$

> LEDs usually tolerate only small reverse voltages. Do not operate an LED in reverse direction unless the datasheet explicitly allows it.

LED with series resistor

An LED is operated in forward direction. It converts part of the electrical energy into light.

Fig. ##: LED with current-limiting series resistor.

For a supply voltage $U_{\rm E}$, an LED forward voltage $U_{\rm F}$, and a desired LED current $I_{\rm F}$, the series resistor is

$$\begin{align*} \boxed{ R_{\rm V} = \frac{U_{\rm E}-U_{\rm F}}{I_{\rm F}} } \end{align*}$$

The resistor power is

$$\begin{align*} P_R = (U_{\rm E}-U_{\rm F})I_{\rm F} = R_{\rm V}I_{\rm F}^2. \end{align*}$$

The LED power is approximately

$$\begin{align*} P_{\rm LED} = U_{\rm F}I_{\rm F}. \end{align*}$$

> Do not connect an LED directly to an ideal voltage source. The current must be limited, usually with a resistor or a current source.

<tabcaption tab_led_values|Typical LED values for first estimates>

LED color	Typical forward voltage $U_{\rm F}$	Typical current
infrared	$\approx 1.3~{\rm V}$	$5\ldots 20~{\rm mA}$
red	$\approx 1.6~{\rm V}$	$5\ldots 20~{\rm mA}$
yellow	$\approx 1.7~{\rm V}$	$5\ldots 20~{\rm mA}$
green	$\approx 1.8~{\rm V}$	$5\ldots 20~{\rm mA}$
blue / white	$\approx 3.0\ldots 3.3~{\rm V}$	$5\ldots 20~{\rm mA}$

Engineering example

A robot controller often uses a \(24~{\rm V}\) supply, but a status LED may need only \(10~{\rm mA}\) at about \(2~{\rm V}\). Most of the voltage must therefore drop across the resistor, not across the LED.

LED operation with AC voltage

LEDs tolerate only small reverse voltages. Therefore, operation directly at AC voltage needs protection.

Fig. ##: LED operation with AC voltage and reverse-voltage protection.

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A second diode can be placed antiparallel to the LED. Then, during the reverse half-wave, the normal diode conducts and limits the reverse voltage across the LED.

> For low-frequency indicator circuits, a visible flicker may occur if only one half-wave is used. For higher quality indicators, rectification or dedicated LED drivers are used.

Z-diode voltage limitation and stabilization

A Z-diode is operated in reverse breakdown. In its working range, the voltage is approximately constant:

\[\begin{align*} u_{\rm Z}\approx U_{\rm Z}. \end{align*} \]

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Fig. ##: Simple Z-diode voltage stabilizer with load resistor.

The input current through the series resistor is

\[\begin{align*} I_{\rm V} = \frac{U_{\rm E}-U_{\rm Z}}{R_{\rm V}}. \end{align*} \]

The load current is

$$\begin{align*} I_{\rm L} = \frac{U_{\rm Z}}{R_{\rm L}}. \end{align*}$$

The Z-diode current is

$$\begin{align*} \boxed{ I_{\rm Z} = I_{\rm V}-I_{\rm L} } \end{align*}$$

and must stay in the allowed operating range:

$$\begin{align*} I_{\rm Z,min} \leq I_{\rm Z} \leq I_{\rm Z,max}. \end{align*}$$

The power limit is

$$\begin{align*} P_{\rm Z} = U_{\rm Z}I_{\rm Z} \leq P_{\rm tot}. \end{align*}$$

Color scheme for the Z-diode stabilizer

$$\begin{align*} {\color{blue}{I_{\rm V}}} &= \frac{U_{\rm E}-U_{\rm Z}}{R_{\rm V}} &&\text{current supplied through the series resistor}, \\ {\color{green}{I_{\rm L}}} &= \frac{U_{\rm Z}}{R_{\rm L}} &&\text{useful load current}, \\ {\color{red}{I_{\rm Z}}} &= {\color{blue}{I_{\rm V}}} - {\color{green}{I_{\rm L}}} &&\text{remaining current through the Z-diode}. \end{align*}$$

The Z-diode can stabilize the voltage only if ${\color{red}{I_{\rm Z}}}$ remains inside the allowed range.

> A Z-diode stabilizer is simple, but not efficient for large load currents. It is useful for voltage limitation, small reference voltages, and robust simple circuits.

Simulation: Z-diode voltage reference

Use this simulation to observe how a Z-diode limits the output voltage.

Things to try:

- change the input voltage,
- change the load resistance,
- observe when the Z-diode current becomes too small for stabilization.

Freewheeling diode for inductive loads

Inductors resist a sudden change of current:

$$\begin{align*} u_L=L\frac{{\rm d}i_L}{{\rm d}t}. \end{align*}$$

If a relay coil, solenoid, or small motor is switched off, the current tries to continue flowing. Without a safe current path, the voltage can become very large.

Fig. ##: Switching an inductive load without freewheeling diode: dangerous overvoltage can occur.

Fig. ##: Switching an inductive load with freewheeling diode: the current has a safe path.

When the switch is opened, the freewheeling diode becomes forward-biased. The inductor current circulates through the diode and the coil.

Physical interpretation

The coil is like a flywheel for current.

- A mechanical flywheel cannot stop instantly.
- An inductor current cannot stop instantly.
- The freewheeling diode gives the current a safe path while the stored magnetic energy is dissipated.

The magnetic energy stored in the inductance is

$$\begin{align*} W_L = \frac{1}{2}LI_0^2. \end{align*}$$

With a freewheeling diode, the switch voltage is limited to a safe value. The disadvantage is that the current decays more slowly, so a relay or solenoid may release more slowly.

> For fast turn-off, additional components such as a Z-diode, TVS diode, or resistor-diode network can be used. The basic principle remains the same: provide a controlled path for the inductive current.

Simulation: inductive kickback protection

Use this simulation to observe the overvoltage when switching an inductive load, and how a diode limits it.

Things to try:

- open and close the switch,
- compare the circuit with and without the protection diode,
- observe the voltage across the switch.

Clamp diodes for sensitive inputs

Microcontroller and sensor inputs tolerate only a limited voltage range. Clamp diodes can conduct disturbances away from the sensitive input.

Fig. ##: Clamp diodes protecting a sensitive input against overvoltage and undervoltage.

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For a \(5~{\rm V}\) input, the input node is often clamped approximately to

\[\begin{align*} -0.7~{\rm V} \lesssim u_{\rm in} \lesssim 5.7~{\rm V}. \end{align*} \]

The resistor \(R_{\rm V}\) limits the clamp current:

\[\begin{align*} I_{\rm clamp} \approx \frac{U_{\rm disturb}-U_{\rm clamp}}{R_{\rm V}}. \end{align*} \]

> Clamp diodes are not a substitute for proper EMC design. For external connectors, use suitable protection components and check the datasheets.

Mechatronics example

A sensor cable near a motor cable can pick up short disturbance pulses. Clamp diodes can prevent the input voltage from exceeding the allowed range, while the series resistor limits the injected current.

Half-wave rectifier M1

A rectifier converts an AC voltage into a unidirectional voltage.

Fig. ##: Half-wave rectifier M1 with ideal diode and resistive load.

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Assumptions for the basic formulas:

- sinusoidal input voltage,
- RMS value $U_\sim$,
- ohmic load,
- ideal diode.

For a half-wave rectifier:

$$\begin{align*} \boxed{ U_{\rm di} = \frac{\sqrt{2}}{\pi}U_\sim } \end{align*}$$

The ripple frequency is

$$\begin{align*} f_\sigma=f. \end{align*}$$

The ripple factor for the ideal M1 circuit is

$$\begin{align*} w_U = \frac{U_\sigma}{U_{\rm di}} \approx 1.21. \end{align*}$$

> The half-wave rectifier is simple, but it uses only one half-wave. Therefore the ripple is large and the transformer is used poorly.

Simulation: half-wave rectifier

Use this simulation to observe how one half-wave is removed by a diode.

Things to try:

- reverse the diode direction,
- change the load resistance,
- compare input and output voltage.

Center-tap rectifier M2 and bridge rectifier B2

A full-wave rectifier uses both half-waves.

Fig. ##: Center-tap rectifier M2.

Fig. ##: Bridge rectifier B2.

For the center-tap rectifier M2:

$$\begin{align*} U_{\rm di} = \frac{2\sqrt{2}}{\pi}U_{1{\rm N}} = \frac{\sqrt{2}}{\pi}U_{\rm S}. \end{align*}$$

Here $U_{1{\rm N}}$ is the RMS voltage of one half of the secondary winding and $U_{\rm S}$ is the RMS voltage of the full secondary winding.

For the bridge rectifier B2:

$$\begin{align*} \boxed{ U_{\rm di} = \frac{2\sqrt{2}}{\pi}U_\sim } \end{align*}$$

The ripple frequency is

$$\begin{align*} f_\sigma=2f. \end{align*}$$

The ideal ripple factor is

$$\begin{align*} w_U\approx 0.48. \end{align*}$$

Real diode voltage drops

In a bridge rectifier, two diodes conduct at the same time. Therefore, for silicon diodes, the output voltage is roughly reduced by

$$\begin{align*} 2U_{\rm TO}\approx 1.4~{\rm V}. \end{align*}$$

This matters especially for low-voltage supplies.

<tabcaption tab_rectifier_summary|Comparison of simple rectifier circuits>

Circuit	**Uses half-waves**	**Ideal average voltage $U_{\rm di}$**	**Ripple frequency**
M1 half-wave	one half-wave	$\frac{\sqrt{2}}{\pi}U_\sim$	f
M2 center-tap	both half-waves	$\frac{2\sqrt{2}}{\pi}U_{1{\rm N}}$	$2f$
B2 bridge	both half-waves	$\frac{2\sqrt{2}}{\pi}U_\sim$	$2f$

Simulation: bridge rectifier

Use this simulation to compare half-wave and full-wave rectification.

Things to try:

- observe which two diodes conduct in each half-wave,
- compare input and output voltage,
- add or remove smoothing if available in the simulation.

Capacitor smoothing

A rectifier output is not constant. A smoothing capacitor stores charge near the voltage maximum and supplies the load between maxima.

Fig. ##: Bridge rectifier with smoothing capacitor.

For a bridge rectifier with a sufficiently large smoothing capacitor, the DC voltage is approximately

$$\begin{align*} U_{\rm di} \approx \sqrt{2}U_\sim \end{align*}$$

for ideal diodes and small ripple.

With real silicon diodes in a bridge rectifier:

$$\begin{align*} U_{\rm di} \approx \sqrt{2}U_\sim - 2U_{\rm TO} - \frac{\Delta U}{2}. \end{align*}$$

Here ΔU is the approximate peak-to-peak ripple voltage.

A simple estimate for the smoothing capacitor is

$$\begin{align*} \boxed{ C \approx \frac{I_{\rm d}}{f_\sigma\Delta U} } \end{align*}$$

with

- $I_{\rm d}$: load current,
- f_σ: ripple frequency,
- ΔU: allowed peak-to-peak ripple voltage.

Course approximation with RMS ripple

If U_σ is used as the RMS value of the ripple voltage, a practical estimate is

$$\begin{align*} C \approx k\frac{I_{\rm d}}{f_\sigma U_\sigma}. \end{align*}$$

Typical factors:

$$\begin{align*} k&=0.25 &&\text{for one-pulse rectification},\\ k&=0.20 &&\text{for two-pulse rectification}. \end{align*}$$

> A larger capacitor reduces ripple, but it also creates short high charging-current pulses through the diodes and transformer. For power supplies, check diode peak current, transformer rating, capacitor ripple current, and inrush current.

Application overview

<tabcaption tab_diode_applications|Typical diode applications in mechatronics and robotics>

Problem	Diode application	Main design question
Status indication	LED with resistor	Which current and resistor value?
Small reference voltage	Z-diode stabilizer	Is $I_{\rm Z}$ inside the allowed range?
Relay or solenoid switch-off	freewheeling diode	Where can the inductor current flow?
Sensor input disturbance	clamp diodes	Is the clamp current limited?
AC to DC conversion	rectifier	M1, M2, or B2?
DC supply with lower ripple	smoothing capacitor	Which ripple voltage is acceptable?

Exercises

Exercise E1.1 Quick check: LED series resistor for a robot status LED

A robot controller provides

$$\begin{align*} U_{\rm E}=24~{\rm V}. \end{align*}$$

A green LED shall operate at

$$\begin{align*} U_{\rm F}=1.8~{\rm V}, \qquad I_{\rm F}=10~{\rm mA}. \end{align*}$$

- Calculate the required series resistor $R_{\rm V}$.
- Choose a nearby standard value.
- Calculate the resistor power for your calculated value.

Result

> The resistor value is
>
> $$\begin{align*} R_{\rm V} &= \frac{U_{\rm E}-U_{\rm F}}{I_{\rm F}} \\ &= \frac{24~{\rm V}-1.8~{\rm V}}{10~{\rm mA}} \\ &= 2.22~{\rm k}\Omega. \end{align*}$$
>
> A suitable standard value is, for example,
>
> $$\begin{align*} R_{\rm V}=2.2~{\rm k}\Omega. \end{align*}$$
>
> The resistor power is approximately
>
> $$\begin{align*} P_R &= (U_{\rm E}-U_{\rm F})I_{\rm F} \\ &= 22.2~{\rm V}\cdot 10~{\rm mA} \\ &= 222~{\rm mW}. \end{align*}$$
>
> A $0.25~{\rm W}$ resistor is very close to the limit. A $0.5~{\rm W}$ resistor gives

> more margin.

Exercise E2.1 Quick check: Z-diode stabilizer

A simple Z-diode stabilizer shall generate approximately

$$\begin{align*} U_{\rm Z}=5.1~{\rm V} \end{align*}$$

from

$$\begin{align*} U_{\rm E}=12~{\rm V}. \end{align*}$$

The series resistor is

$$\begin{align*} R_{\rm V}=470~\Omega. \end{align*}$$

The load resistor is

$$\begin{align*} R_{\rm L}=1.0~{\rm k}\Omega. \end{align*}$$

- Calculate $I_{\rm V}$.
- Calculate $I_{\rm L}$.
- Calculate $I_{\rm Z}$.
- Calculate the Z-diode power $P_{\rm Z}$.

Result

> The current through the series resistor is
>
> $$\begin{align*} I_{\rm V} &= \frac{U_{\rm E}-U_{\rm Z}}{R_{\rm V}} \\ &= \frac{12~{\rm V}-5.1~{\rm V}}{470~\Omega} \\ &= 14.7~{\rm mA}. \end{align*}$$
>
> The load current is
>
> $$\begin{align*} I_{\rm L} = \frac{U_{\rm Z}}{R_{\rm L}} = \frac{5.1~{\rm V}}{1.0~{\rm k}\Omega} = 5.1~{\rm mA}. \end{align*}$$
>
> The Z-diode current is
>
> $$\begin{align*} I_{\rm Z} = I_{\rm V}-I_{\rm L} = 14.7~{\rm mA}-5.1~{\rm mA} = 9.6~{\rm mA}. \end{align*}$$
>
> The Z-diode power is

> $$\begin{align*} P_{\rm Z} = U_{\rm Z}I_{\rm Z} = 5.1~{\rm V}\cdot 9.6~{\rm mA} = 49~{\rm mW}. \end{align*}$$
>
> This is acceptable only if the datasheet permits this current and power.

Exercise E3.1 Quick check: freewheeling diode energy

A relay coil has

$$\begin{align*} L=80~{\rm mH} \end{align*}$$

and carries

$$\begin{align*} I_0=200~{\rm mA} \end{align*}$$

just before switch-off.

- Calculate the magnetic energy stored in the coil.
- Explain why a freewheeling diode is useful.
- State one disadvantage of a simple freewheeling diode.

Result

> The stored magnetic energy is
>
> $$\begin{align*} W_L = \frac{1}{2}LI_0^2 = \frac{1}{2}\cdot 80~{\rm mH}\cdot (200~{\rm mA})^2. \end{align*}$$
>
> Insert SI units:
>
> $$\begin{align*} W_L = 0.5\cdot 0.080~{\rm H}\cdot (0.200~{\rm A})^2 = 1.6~{\rm mJ}. \end{align*}$$
>
> When the switch opens, this energy must go somewhere. The freewheeling diode provides a safe path for the coil current and limits the overvoltage.
>
> A disadvantage is that the coil current decays more slowly. Therefore, a relay or solenoid may release more slowly.

Exercise E4.1 Quick check: bridge rectifier average voltage

A bridge rectifier B2 is supplied by a sinusoidal AC voltage with

$$\begin{align*} U_\sim=12~{\rm V} \end{align*}$$

at

$$\begin{align*} f=50~{\rm Hz}. \end{align*}$$

Assume an ohmic load and ideal diodes.

- Calculate the ideal average rectified voltage $U_{\rm di}$.
- State the ripple frequency f_σ.
- Compare this with a half-wave rectifier M1 using the same $U_\sim$.

Result

For the bridge rectifier:

$$\begin{align*} U_{\rm di,B2} = \frac{2\sqrt{2}}{\pi}U_\sim = \frac{2\sqrt{2}}{\pi}\cdot 12~{\rm V} = 10.8~{\rm V}. \end{align*}$$

The ripple frequency is

$$\begin{align*} f_\sigma=2f=100~{\rm Hz}. \end{align*}$$

For the half-wave rectifier:

$$\begin{align*} U_{\rm di,M1} = \frac{\sqrt{2}}{\pi}U_\sim = \frac{\sqrt{2}}{\pi}\cdot 12~{\rm V} = 5.4~{\rm V}. \end{align*}$$

The bridge rectifier uses both half-waves. Therefore, the average voltage is twice as large and the ripple frequency is doubled.

Exercise E5.1 Longer exercise: small DC supply with bridge rectifier and smoothing capacitor

A $12~{\rm V}$ RMS transformer secondary feeds a bridge rectifier with a smoothing capacitor. The mains frequency is

$$\begin{align*} f=50~{\rm Hz}. \end{align*}$$

The load current is

$$\begin{align*} I_{\rm d}=250~{\rm mA}. \end{align*}$$

The allowed peak-to-peak ripple voltage is

$$\begin{align*} \Delta U=1.0~{\rm V}. \end{align*}$$

Assume silicon diodes with

$$\begin{align*} U_{\rm TO}=0.7~{\rm V}. \end{align*}$$

- Calculate the peak value of the transformer secondary voltage.
- Estimate the ripple frequency f_σ.
- Estimate the required capacitor C.
- Estimate the average DC output voltage with ripple and diode drops.
- Explain why the transformer and diodes must tolerate current pulses.

Result

The peak value of the secondary voltage is

$$\begin{align*} \hat{U}_\sim = \sqrt{2}U_\sim = \sqrt{2}\cdot 12~{\rm V} = 17.0~{\rm V}. \end{align*}$$

For a bridge rectifier,

$$\begin{align*} f_\sigma=2f=100~{\rm Hz}. \end{align*}$$

Using

$$\begin{align*} C\approx \frac{I_{\rm d}}{f_\sigma\Delta U}, \end{align*}$$

we get

$$\begin{align*} C &\approx \frac{250~{\rm mA}}{100~{\rm Hz}\cdot 1.0~{\rm V}} \\ &= \frac{0.250~{\rm A}}{100~{\rm s}^{-1}\cdot 1.0~{\rm V}} \\ &= 2.5\cdot 10^{-3}~{\rm F} = 2500~\mu{\rm F}. \end{align*}$$

A nearby practical value would be, for example,

$$\begin{align*} C=2200~\mu{\rm F} \quad \text{or} \quad C=3300~\mu{\rm F}, \end{align*}$$

depending on the allowed ripple.

In a bridge rectifier, two diodes conduct at the same time, so the diode drop is approximately

$$\begin{align*} 2U_{\rm TO}=1.4~{\rm V}. \end{align*}$$

The average DC output voltage can be estimated as

$$\begin{align*} U_{\rm d} &\approx \hat{U}_\sim - 2U_{\rm TO} - \frac{\Delta U}{2} \\ &= 17.0~{\rm V} - 1.4~{\rm V} - 0.5~{\rm V} \\ &= 15.1~{\rm V}. \end{align*}$$

The capacitor is recharged only near the peaks of the AC voltage. Therefore the diode current is not a smooth $250~{\rm mA}$, but occurs in short charging pulses. The diodes, transformer, and capacitor must tolerate these pulse currents.

Common pitfalls

- **Connecting LEDs without current limitation:** The LED current can become destructive.
- **Forgetting resistor power:** In $24~{\rm V}$ control cabinets, LED resistors can dissipate noticeable heat.
- **Using a Z-diode without load-current check:** The Z-current must remain between $I_{\rm Z,min}$ and $I_{\rm Z,max}$.
- **Using clamp diodes without a series resistor:** The clamp current must be limited.
- **Thinking the freewheeling diode removes energy instantly:** It gives the current a safe path, but turn-off may become slower.
- **Ignoring diode drops in bridge rectifiers:** Two diodes conduct at the same time.
- **Confusing RMS and peak values:** A $12~{\rm V}$ RMS sine has a peak value of about $17~{\rm V}$.
- **Assuming a smoothing capacitor creates perfect DC:** The output still has ripple and charging-current pulses.
- **Using capacitor formulas without checking ratings:** Check voltage rating, ripple current, polarity, and inrush current.

Embedded resources

The Falstad simulations are embedded directly in the relevant chapters above.

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