Block 12 — Diode Applications

Student Group

First Name	Surname	Matrikel Nr.

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Learning objectives

After this 90-minute block, you can

- identify basic diode types such as universal diodes, Z-diodes, and LEDs.
- calculate simple diode operating points with a series resistor.
- 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, 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.

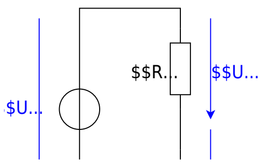
The focus is on **basic engineering estimates**, not yet on detailed datasheet design.

Core content

Operating point with a series resistor

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

Fig. 1: Circuit of Diode with resistor.



For the circuit in figure 1 the loop equation is

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

With the constant-voltage model,

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

Therefore

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

> Never connect a normal diode or LED directly to an ideal voltage source in forward direction.
> The diode current must be limited.

LED (with series resistor)

An LED is operated in forward direction. It converts part of the electrical energy into light via electron-hole recombination.
The required forward voltage depends on the semiconductor material and therefore on the color.

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

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

For circuit design it is important the check the real resistor power with the absolute maximum ratings of the resistors

$$\begin{align*} P_R = (U_{\rm I}-U_{\rm F})I_{\rm F} = R_{\rm V}I_{\rm F}^2 \quad \overset{!}{<} \quad P_{R, \rm max} \end{align*}$$

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.

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	$\approx 3.0\ldots 3.3~{\rm V}$	$5\ldots 20~{\rm mA}$

Tab. 1: Typical LED values for first estimates

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.

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

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

- Z-diodes are useful for voltage limitation and voltage stabilization.
- Z-diodes have a huge variety of breakdown voltages: $U_{\rm Z} \approx 1.0 ~\rm V... 400 ~ V$
  Z-diodes allow to get “knee voltages” above $0.7 ~\rm V$
- Z-diodes are still conventional diodes in the forward direction.

A typical application is a **Z-diode stabilizer**

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.

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

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

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

The power limit is

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

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.

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.

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 like a motor, 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.

Half-wave rectifier (M1)

A rectifier converts an AC voltage into a unidirectional voltage.

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,
- change capacitor,
- compare input and output voltage.

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 output voltage can be split into an average DC value and an AC ripple component:

$$\begin{align*} u_{\rm out}(t) = U_{\rm di} + u_\sigma(t). \end{align*}$$

Here

- $U_{\rm di}$ is the average value, i.e. the DC component,
- $u_\sigma(t)$ is the time-dependent ripple component,
- U_σ is the RMS value of this ripple component.

$$\begin{align*} U_\sigma = \sqrt{ \frac{1}{T} \int_0^T u_\sigma^2(t)\,{\rm d}t }. \end{align*}$$

The ripple factor for the ideal 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.
> Damping capacitors must be relatively large.

Bridge rectifier B2

A full-wave rectifier uses both half-waves.

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.

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.

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
B2 bridge	both half-waves	$\frac{2\sqrt{2}}{\pi}U_\sim$	$2f$

Tab. 2: Comparison of simple rectifier circuits

Capacitor smoothing

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

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.

Exercises

Exercise E1.1 Circuit with multiple diodes: which lamps light up?

The following simulation includes multiple diodes and several lamps. A lamp lights brightly when a voltage of approximately

\[\begin{align*} U_{\rm lamp}\geq 5~{\rm V} \end{align*} \]

drops across it.

Close the switch in the simulation.

- Which lamps light up brightly?
- Which lamps remain dark?
- Explain the result using the idea of diode bypass paths.

1. Determine which lamps light up brightly.

SolutionResult

Number the lamps from left to right:

\[\begin{align*} L_1,\;L_2,\;L_3,\;L_4,\;L_5. \end{align*} \]

After closing the switch, check the voltage across each lamp in the simulation.

A lamp is assumed to light brightly if

\[\begin{align*} U_{\rm lamp}\geq 5~{\rm V}. \end{align*} \]

The simulation shows that the outer lamps have a sufficiently large voltage across them, while the inner lamps are bypassed by conducting diodes.

The lamps

\[\begin{align*} L_1 \quad \text{and} \quad L_5 \end{align*} \]

light up brightly.

2. Determine which lamps remain dark.

SolutionResult

The inner lamps are connected in parts of the circuit that are bypassed by forward-biased diodes.

A forward-biased diode has only a small voltage drop. Therefore, a lamp in parallel with such a diode path receives only a small voltage.

If

\[\begin{align*} U_{\rm lamp}<5~{\rm V}, \end{align*} \]

the lamp does not light brightly.

The lamps

\[\begin{align*} L_2,\;L_3,\;L_4 \end{align*} \]

remain dark or almost dark.

Exercise E2.1 Circuit with multiple diodes II: current calculation

The following simulation includes two diodes and two resistors.

Assume a simple constant-voltage diode model:

\[\begin{align*} U_{\rm F}=0.6~{\rm V}. \end{align*} \]

The source voltage is

\[\begin{align*} U_0=4.0~{\rm V}. \end{align*} \]

The resistors are

\[\begin{align*} R_1=200~\Omega, \qquad R_2=100~\Omega. \end{align*} \]

Calculate the currents through

- \(D_1\),
- \(R_1\),

- R_2.

1. Calculate the current through R_1.

SolutionResult

The current through R_1 passes through one forward-biased diode.

Therefore the voltage across R_1 is

$$\begin{align*} U_{R1} = U_0-U_{\rm F}. \end{align*}$$

Insert the values:

$$\begin{align*} U_{R1} &= 4.0~{\rm V}-0.6~{\rm V} \\ &= 3.4~{\rm V}. \end{align*}$$

Now apply Ohm's law:

$$\begin{align*} I_{R1} = \frac{U_{R1}}{R_1} = \frac{3.4~{\rm V}}{200~\Omega} = 17~{\rm mA}. \end{align*}$$

$$\begin{align*} I_{R1}=17~{\rm mA} \end{align*}$$

2. Calculate the current through R_2.

SolutionResult

The current through R_2 passes through two forward-biased diodes.

Therefore the voltage across R_2 is

$$\begin{align*} U_{R2} = U_0-2U_{\rm F}. \end{align*}$$

$$\begin{align*} I_{R2}=28~{\rm mA} \end{align*}$$

Insert the values:

$$\begin{align*} U_{R2} &= 4.0~{\rm V}-2\cdot 0.6~{\rm V} \\ &= 2.8~{\rm V}. \end{align*}$$

Now apply Ohm's law:

$$\begin{align*} I_{R2} = \frac{U_{R2}}{R_2} = \frac{2.8~{\rm V}}{100~\Omega} = 28~{\rm mA}. \end{align*}$$

3. Calculate the current through D_1.

SolutionResult

The diode D_1 supplies both current paths.

Therefore, by Kirchhoff's current law,

$$\begin{align*} I_{D1} = I_{R1}+I_{R2}. \end{align*}$$

Insert the values:

$$\begin{align*} I_{D1} &= 17~{\rm mA}+28~{\rm mA} \\ &= 45~{\rm mA}. \end{align*}$$

$$\begin{align*} I_{D1}=45~{\rm mA} \end{align*}$$

Exercise E3.1 Circuit with multiple diodes III: switch-dependent currents

The following simulation includes two diodes and a switch.

Assume a simple constant-voltage diode model:

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

The source voltage is

$$\begin{align*} U_0=5.0~{\rm V}. \end{align*}$$

The resistor is

$$\begin{align*} R_1=1.0~{\rm k}\Omega. \end{align*}$$

Calculate the currents through

- R_1,
- D_1,
- D_2,

depending on the switch state S.

1. Calculate the currents for open switch S.

SolutionResult

With the switch open, only D_1 is connected to the resistor path.

The conducting diode clamps the node voltage to approximately

$$\begin{align*} U_{\rm node}\approx U_{\rm F}=0.7~{\rm V}. \end{align*}$$

The resistor current is therefore

$$\begin{align*} I_{R1} &= \frac{U_0-U_{\rm F}}{R_1} \\ &= \frac{5.0~{\rm V}-0.7~{\rm V}}{1.0~{\rm k}\Omega} \\ &= 4.3~{\rm mA}. \end{align*}$$

Since only D_1 conducts,

$$\begin{align*} I_{D1}=I_{R1}, \qquad I_{D2}=0. \end{align*}$$

For open switch:

$$\begin{align*} I_{R1}&=4.3~{\rm mA}, \\ I_{D1}&=4.3~{\rm mA}, \\ I_{D2}&=0. \end{align*}$$

2. Calculate the currents for closed switch S.

SolutionResult

With the switch closed, D_1 and D_2 are connected in parallel.

The resistor current is still determined by the source voltage, the forward diode voltage, and R_1:

$$\begin{align*} I_{R1} &= \frac{U_0-U_{\rm F}}{R_1} \\ &= \frac{5.0~{\rm V}-0.7~{\rm V}}{1.0~{\rm k}\Omega} \\ &= 4.3~{\rm mA}. \end{align*}$$

Kirchhoff's current law gives

$$\begin{align*} I_{D1}+I_{D2}=I_{R1}. \end{align*}$$

With the ideal constant-voltage diode model, the individual currents through two parallel diodes are not uniquely determined.

If both real diodes are approximately identical, the current splits approximately equally:

$$\begin{align*} I_{D1} \approx I_{D2} \approx \frac{4.3~{\rm mA}}{2} = 2.15~{\rm mA}. \end{align*}$$

For closed switch:

$$\begin{align*} I_{R1}=4.3~{\rm mA} \end{align*}$$

and

$$\begin{align*} I_{D1}+I_{D2}=4.3~{\rm mA}. \end{align*}$$

For approximately identical real diodes:

$$\begin{align*} I_{D1} \approx I_{D2} \approx 2.15~{\rm mA}. \end{align*}$$

3. Explain why the current sharing is not unique in the simple model.

SolutionResult

The constant-voltage diode model assumes that each conducting diode has exactly the same voltage drop:

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

For two parallel diodes, this condition is true for many possible current distributions.

Therefore, the model only determines the sum

$$\begin{align*} I_{D1}+I_{D2}, \end{align*}$$

not the individual diode currents.

The constant-voltage diode model determines only

$$\begin{align*} I_{D1}+I_{D2}=4.3~{\rm mA}. \end{align*}$$

It does not uniquely determine I_{D1} and I_{D2} separately.

Parallel diodes are sensitive to small differences in real diode characteristics. Current sharing should not be assumed to be perfect without checking the design.

Exercise E4.1 Quick check: LED series resistor for a robot status LED

A robot controller provides

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

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

$$\begin{align*} R_{\rm V} &= \frac{U_{\rm I}-U_{\rm F}}{I_{\rm F}} \\ &= \frac{24~{\rm V}-1.8~{\rm V}}{10~{\rm mA}} \\ &= 2.22~{\rm k}\Omega. \end{align*}$$

A suitable standard value is, for example,

$$\begin{align*} R_{\rm V}=2.2~{\rm k}\Omega. \end{align*}$$

The resistor power is approximately

$$\begin{align*} P_R &= (U_{\rm I}-U_{\rm F})I_{\rm F} \\ &= 22.2~{\rm V}\cdot 10~{\rm mA} \\ &= 222~{\rm mW}. \end{align*}$$

A $0.25~{\rm W}$ resistor is very close to the limit. A $0.5~{\rm W}$ resistor gives more margin.

Exercise E5.1 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

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

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

$$\begin{align*} I_{\rm V} &= \frac{U_{\rm I}-U_{\rm Z}}{R_{\rm V}} \\ &=$$

$$\begin{aligned} &\frac{12~{\rm V}-5.1~{\rm V}}{470~\Omega} \\ &= 14.7~{\rm mA}. \end{aligned}$$

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 E6.1 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 E7.1 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 E8.1 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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