Technical documentation for relay control

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1. Introduction

This technical documentation provides detailed insight into the control of monostable and bistable relays. It is aimed at developers, technicians, and interested beginners and covers the necessary driver circuits, protection mechanisms, and signal curves for designing a robust and reliable relay circuit.

The principles apply to both digital and analog control circuits. The information presented here is general in nature but does not replace careful study of the data sheet for the specific component used.

2. Monostable Relays

Monostable relays (non-latching) only change their contact state if the coil is energized. When the coil is no longer energized, the relay returns to its rest position by spring force. This type of relay is the most used and is suitable for general switching tasks.

Many monostable relays require a higher pull-in power (pull-in voltage/current) for a short time to ensure reliable pull-in. Continuous control with this pull-in power would thermally overload the coil and could destroy it. For this reason, after the pull-in pulse, the circuit is switched to a reduced holding current (e.g., PWM or current control) that remains above the holding threshold.

2.1 Signal curve for monostable relays

Figure 1 shows the typical time curve of the signals when controlling a monostable relay. The following variables are explained:

U_{Nom}/I_{Nom}: Nominal voltage/current of the coil

U_{Close}/I_{Close}: Pull-in voltage/current of the coil

U_{Hold}/I_{Hold}: Holding voltage/current of the coil

$U_{Drop-Out}/I_{Drop-Out}$: Voltage/current at which the contacts open again

t_{close}: Duration of the pull-in pulse at rated voltage/current so that the contacts close reliably

t_{on}: Pull-in delay (time from start of control to contact closing)

t_{off}: Drop-out delay (time from switch-off to contact opening)
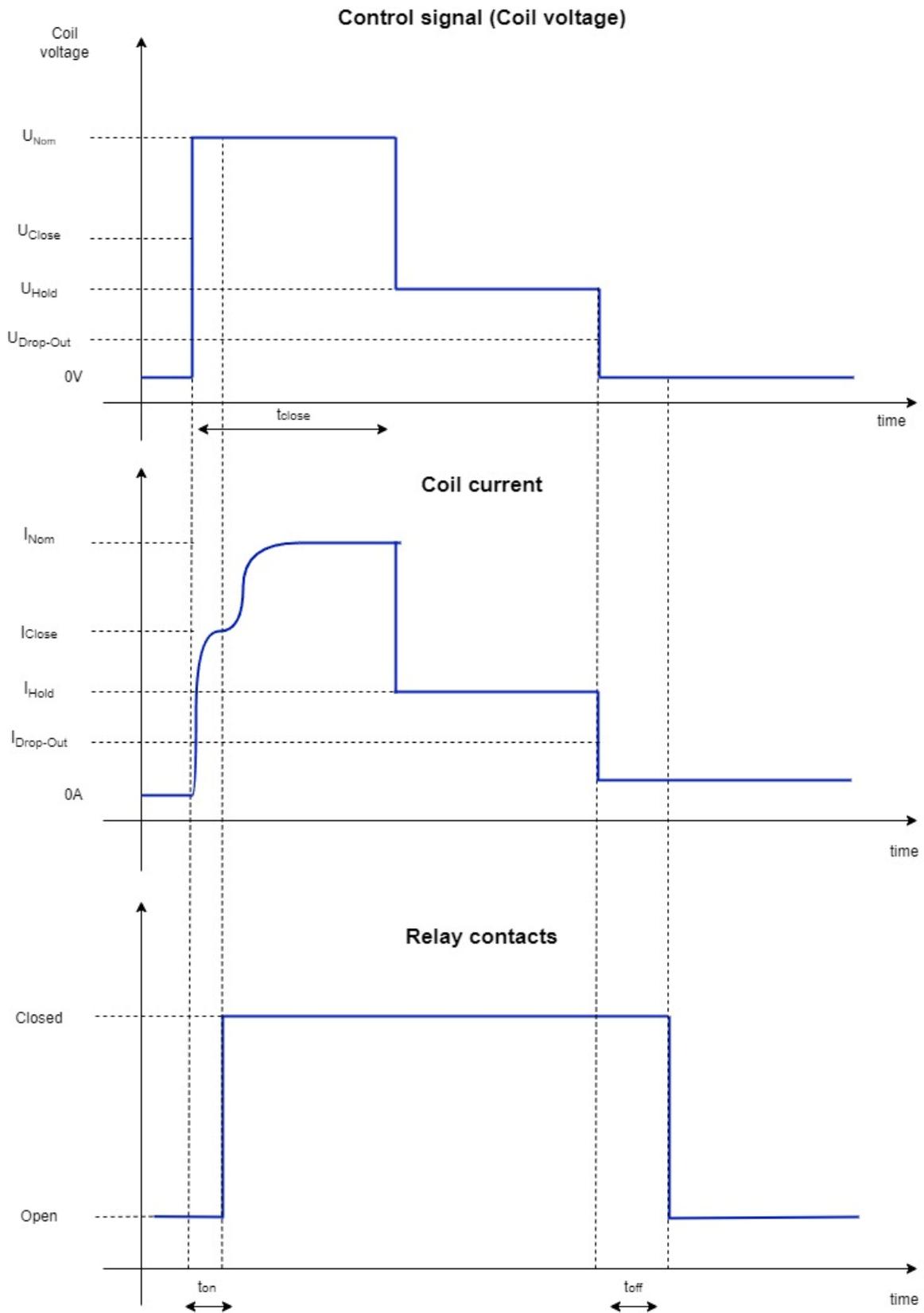
Note: The exact values depend on the data sheet.

Figure 1: Signal curve for monostable relay

2.2 Control philosophy: voltage vs. current control

The force that causes a relay to activate is defined by the ampere turns (AW), i.e., the product of the coil current and the number of windings. A defined minimum current must flow to ensure reliable switching and holding.

2.2.1 Voltage-controlled drive

A fixed holding voltage is applied to the coil. The current is calculated using Ohm's law ($I = U / R$). It should be noted that the coil resistance is temperature dependent. When heated (ambient temperature or self-heating), the coil resistance increases. As a result, the coil current decreases at constant voltage and increasing resistance. The voltage must therefore be designed so that the minimum current required for holding is reliably achieved under worst-case conditions. The disadvantage is that an unnecessarily high current flows when cold, which leads to increased power loss and significant self-heating.

2.2.2 Current-controlled actuation

A more elegant variant is current-controlled actuation. A constant current source or PWM control with current measurement can be used. Since the AW is decisive for the holding force (windings = constant, current = variable), a constant current is ideal for minimizing self-heating. The disadvantage of current-controlled drive is usually the higher circuitry complexity.

Conclusion: For highly reliable or energy-efficient applications, especially those with a wide operating temperature range, current-controlled drive is superior to the voltage-controlled method.

2.3 Control in the low-side configuration

A simple method is to control the coil in the low-side configuration using an N-channel MOSFET. The circuit is shown in Figure 2.

The relay coil is connected between the positive supply voltage and the drain terminal of the MOSFET. The control signal is applied to the gate of the MOSFET via a gate resistor. A pull-down resistor between the gate and source ensures that the MOSFET is reliably blocked when the control signal is de-energized. If the MOSFET is controlled with a fixed PWM after the pull-in pulse, this is referred to as voltage-controlled control. If a shunt is inserted between the MOSFET and ground and the PWM is regulated via the measured current, this is referred to as current-controlled control.

It is essential to provide a free-wheeling or clamping circuit for the induction voltage of the coil during switch-off. This is not shown in Figure 2 and will be dealt with separately later in this documentation.
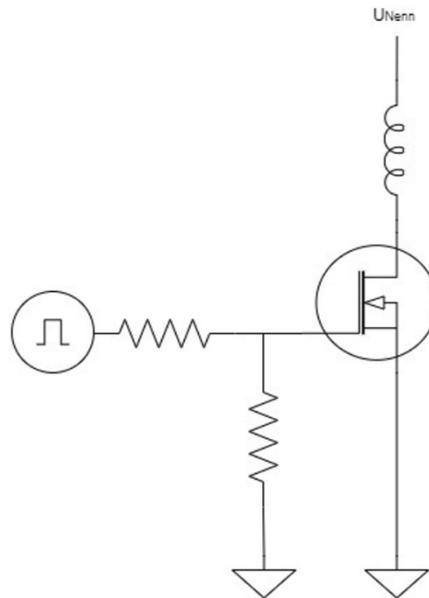

Figure 2: Low-side configuration

2.4 Control in the high-side configuration

Another method is high-side control of the coil with a P-channel MOSFET. The circuit for this is shown in Figure 3.

The relay coil is connected between ground and the source of the P-MOSFET. The special feature here is that the coil is disconnected from the supply voltage when switched off. The circuitry is more complex than in the low-side variant, but may be the better choice in many applications, e.g., if ground shifts or interference on the ground line are to be avoided. In principle, the combination of both control methods (high-side and low-side) is the best choice, as it allows complete separation of the load.

Note on gate control (practice): In a high-side control with a P-channel MOSFET, the gate must be securely at source potential (VGS ≈ 0 V) in the OFF state. To switch ON, the gate must be pulled down sufficiently (negative VGS) without exceeding the maximum permissible gate-source voltage. If the relay voltage (e.g., 12/24 V) is significantly higher than the microcontroller logic (3.3/5 V), direct control of the P-MOSFET gate by the microcontroller is often insufficient. In this case, a driver/level converter stage (e.g., NPN or N-channel MOSFET as gate puller) is required to switch the gate cleanly and quickly.
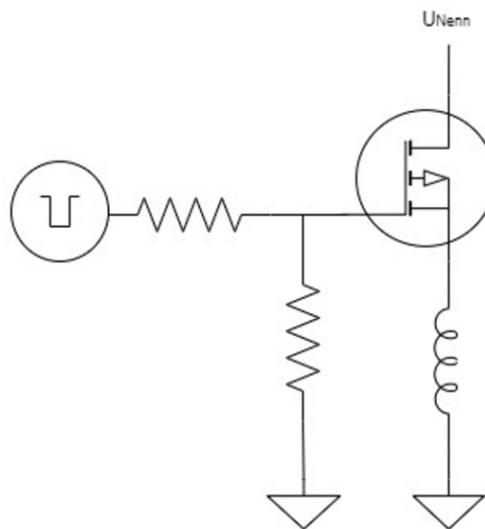
Figure 3: High-side configuration

3. Bistable relays (latching)

Bistable relays maintain their switching state after a short control pulse without further energy supply. This makes them particularly energy-efficient for applications in which the switching state must be maintained for long periods of time.

3.1 Bistable relay with one coil (single coil)

This variant has only one coil. The switching state is determined by the polarity of the control pulse.

3.1.1 Signal curve

The coil voltage changes its polarity to switch between SET and RESET. A positive pulse switches the relay to one state, a negative pulse (reverse polarity) switches the relay to the other state. The pulse duration is typically between 50 and 100 ms and can be found in the data sheet. The relay state is maintained after the SET pulse, even if no current is flowing. Only the RESET pulse with reverse current direction switches back. Coils in bistable relays are not designed for continuous currents and can be thermally destroyed if the permissible pulse duration is exceeded. The signal waveform can be seen in Figure 4.
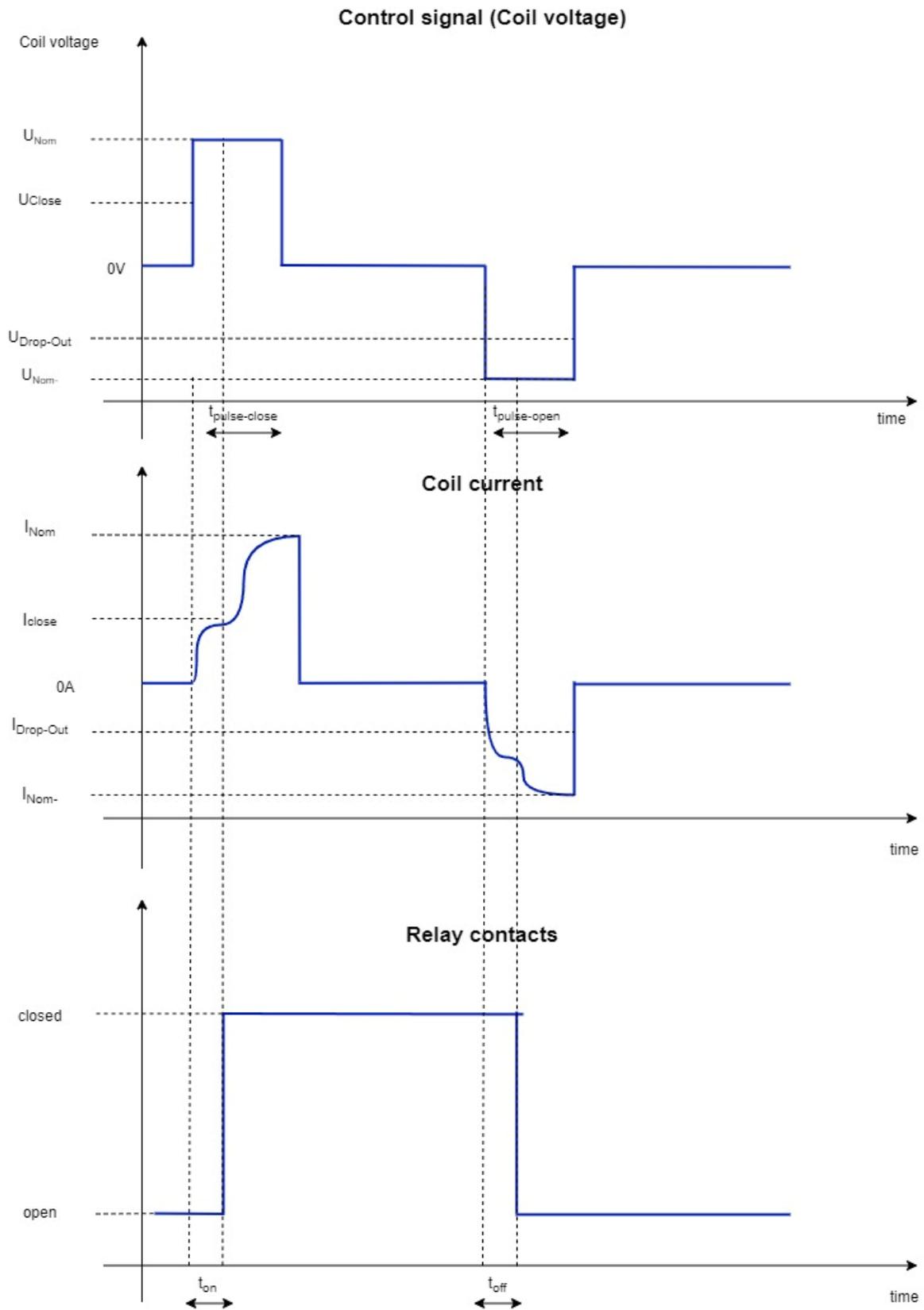
Figure 4: Signal curve for bistable relay with one coil

3.1.2 Control with an H-bridge

An H-bridge makes it possible to reverse the polarity of the voltage at the coil. It consists of four switches (typically MOSFETs) arranged in an H-shaped configuration. A circuit diagram for this can be seen in Figure 5.
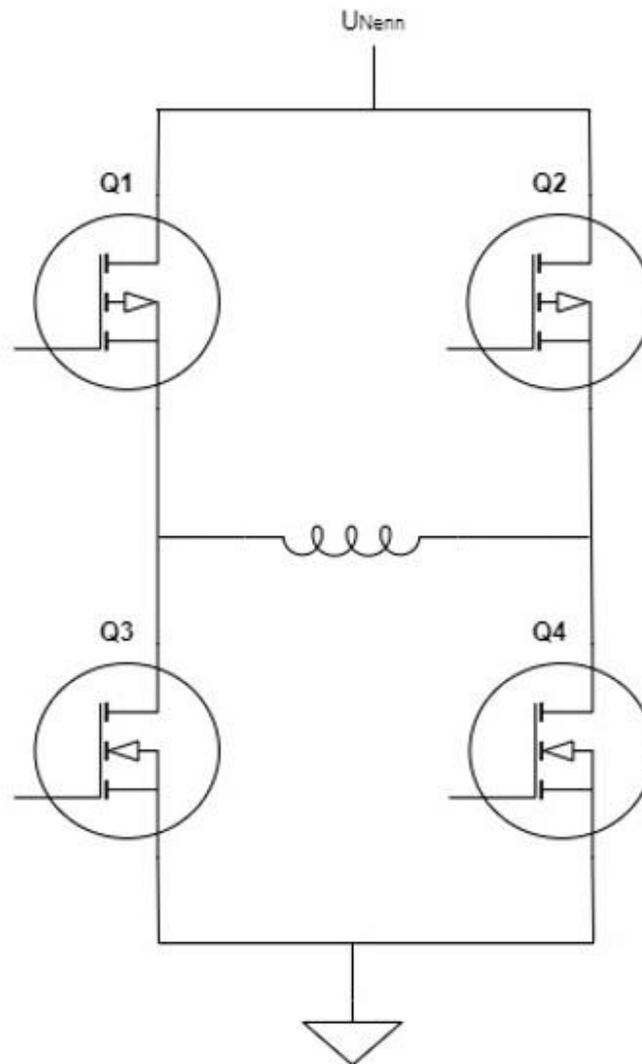
Figure 5: H-bridge for single coil

Important note (avoid shoot-through): In an H-bridge, the two switches of a half-branch must never be conductive at the same time (upper and lower transistor on the same side), as this would cause a short circuit between the supply and ground. A defined dead time must be provided when switching.

The body diodes of the MOSFETs already provides protection. For higher currents, additional external diodes can be connected in parallel to the MOSFETs.

The upper MOSFETs are P-channel MOSFETs (Q1 and Q2), the lower ones are N-channel MOSFETs (Q3 and Q4). Alternatively, all four can be designed as N-channel MOSFETs but then require a high-side gate driver.

3.2 Bistable relay with two coils (dual coil)

This variant is easier to control because it has separate coils for SET and RESET. Each coil can be controlled with its own driver circuit.

3.2.1 Signal sequence

The SET coil receives a short pulse (50-100 ms) to close the relay. The RESET coil receives a separate pulse to reopen the relay. Both coils are never controlled simultaneously. After the SET pulse, the relay remains closed without requiring any further energy until the RESET pulse is applied. The signal waveform for this is shown in Figure 6.
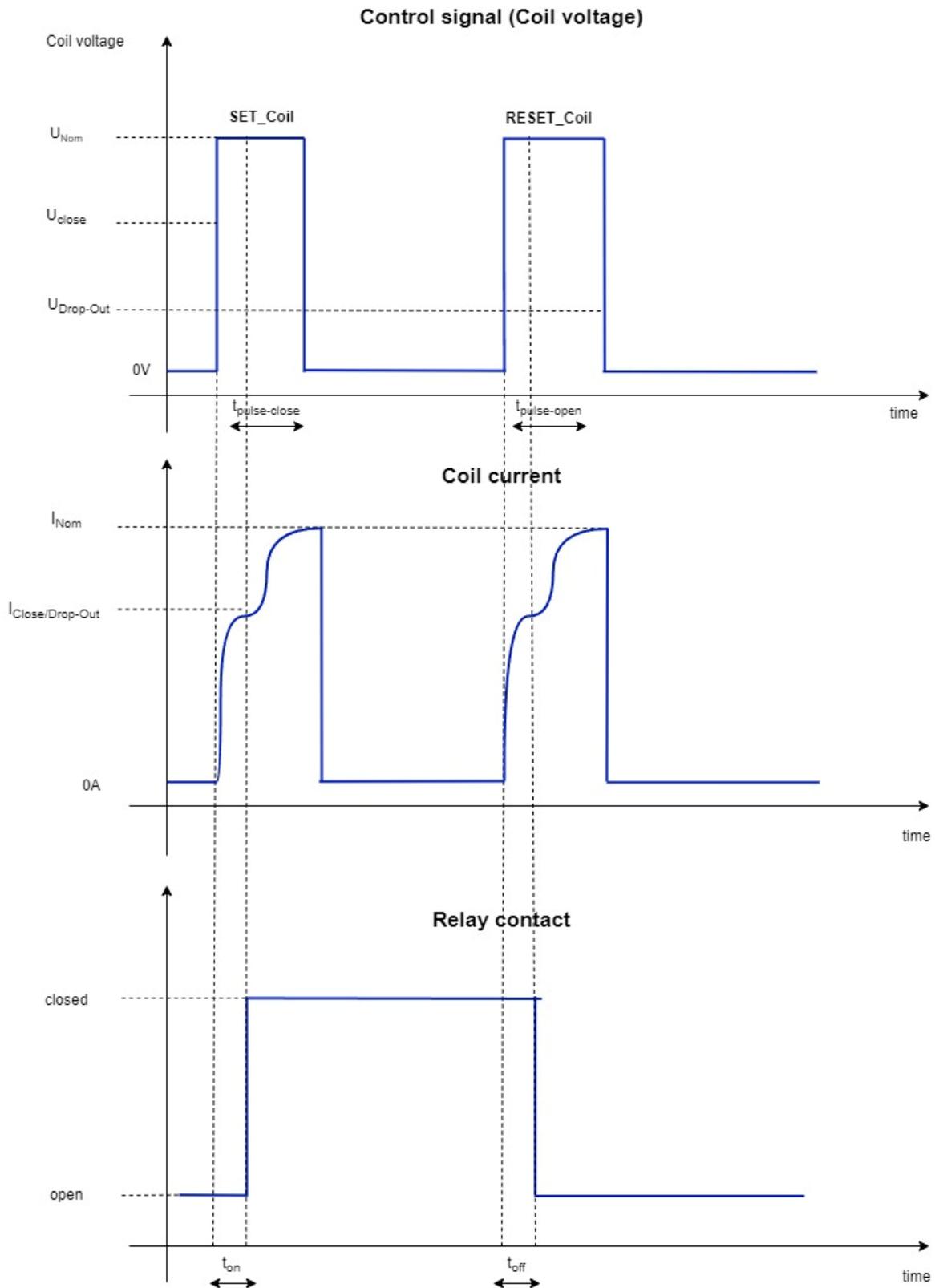
Figure 6: Signal curve for bistable relay with two coils

3.2.2 Control with two separate driver stages

Each coil is controlled by its own N-channel MOSFET, see Figure 7.
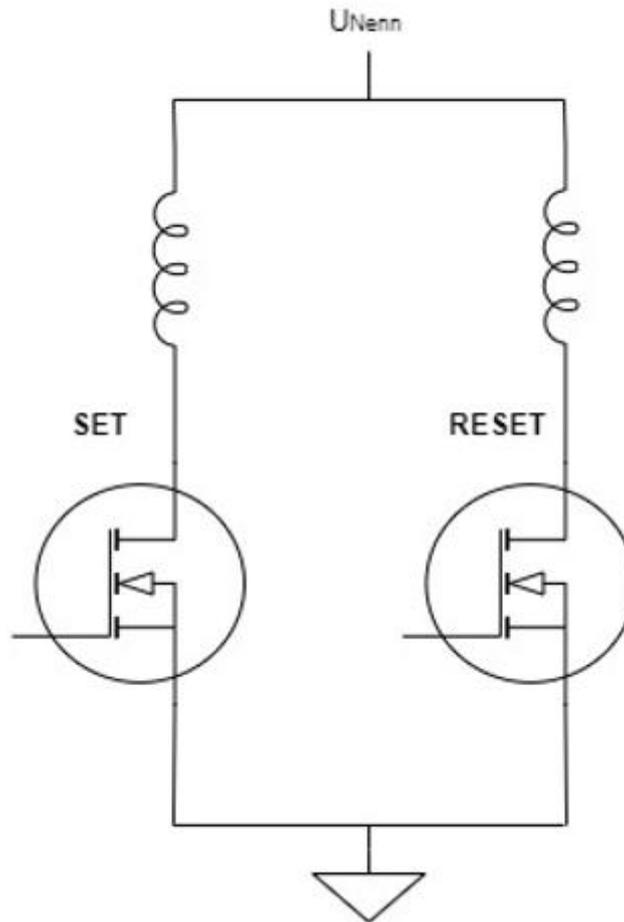
Figure 7: Circuit diagram of a bistable relay with two coils

4. Protection of control electronics against induction voltage

When an inductive load such as a relay coil is switched off, the magnetic field collapses. According to the law of induction, this creates a voltage spike with reverse polarity, which—depending on the current, inductance, and switch-off speed—can be very high and damage the control electronics. Therefore, a suitable protective circuit is necessary. Common protective circuits and their advantages and disadvantages are described below.

4.1 Simple free-wheeling diode

A diode connected in anti-parallel to the coil (cathode at the rated voltage) is a very common method of protective circuitry. It limits the voltage spike to about 0.7 V (forward voltage of the diode). Figure 8 shows the circuit diagram for this.
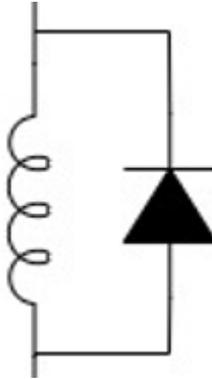

Figure 8: Protective circuit diode

Disadvantages for the relay:

Slow decay: The coil current decays very slowly via the diode. The magnetic field collapses slowly.

Longer arc: Due to the slow decay, the relay contacts also open slowly. When switching loads (especially DC, inductive, or capacitive), an arc is created that burns longer due to the slow contact opening.

Increased contact wear: The longer arc duration leads to increased burn-off and material migration at the contacts, which drastically reduces their service life and can lead to premature failure of the relay.

Conclusion: A simple free-wheeling diode is only suitable for non-critical applications with low loads and low switching frequencies.

4.2 Free-wheeling diode with Z-diode in series

A Z-diode in series with the free-wheeling diode is a good compromise. The voltage peak is limited to U_nom + Vz, and the coil current decays much faster than with a simple free-wheeling diode. The circuit diagram is shown in Figure 9.
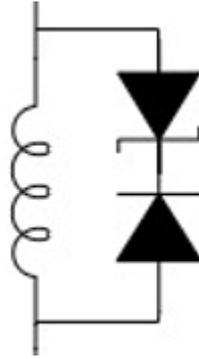
Figure 9: Free-wheeling circuit with Z-diode

Advantage: Fast, defined switch-off; significantly reduced arc duration; good protection for electronics.

Disadvantages: MOSFET must withstand the higher voltage VDS > UNenn + Vz. The Z-diode must be able to absorb the energy from the coil decay.

Recommendation: Vz should be approximately 0.5x to 1.0x the rated voltage of the relay.

4.3 TVS diode (transient voltage suppressor)

A TVS diode is essentially a very fast Z diode that has been specially developed to absorb transient overvoltages. It is connected in parallel to the coil. The circuit for this is shown in Figure 10.
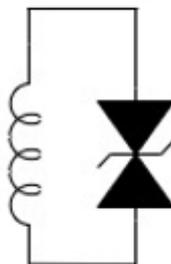

Figure 10: TVS diode

Advantage: Very fast response time; high energy absorption; simple wiring.

Disadvantage: Somewhat more expensive than a Zener diode.

4.4 Comparison of free-running methods

Method	Voltage limit	Shutdown speed	Protection of contacts	Protection of electronics	Complexity
Simple diode	Very good (~0.7V)	Very slowly	Poor	Very good	Very low
Diode + Z-Diode	Good (VCC + Vz)	Fast	Very good	Good	Low
TVS-Diode	Good (Vclamp)	Very fast	Very good	Very good	Low

4.5 Dimensioning the protective circuit

Calculating the energy stored in the coil is crucial for correctly dimensioning the protective circuit. This is calculated using the following formula:

$E = 0.5 \times L \times I^2$

Where E is the energy in joules, L is the inductance of the coil in henries, and I is the coil current in amperes. The protective circuit (Z-diode or TVS diode) must be able to absorb this energy without being destroyed.

When selecting a Z-diode or TVS diode, it is important to ensure that the maximum pulse current rating (specified in the data sheet) is greater than the calculated energy. Typical values for relay coils range from a few millijoules to several hundred millijoules.

Sample calculation: With a coil inductance of 100 mH and a current of 50 mA, the stored energy is $E = 0.5 \times 0.1 \text{ H} \times (0.05 \text{ A})^2 = 0.125 \text{ mJ}$. A standard TVS diode can easily absorb this energy.

4.6 Influence of cable length

When laying cables between the control electronics and the relay coil, there are a few important aspects to consider:

• Additional inductance: Long cables add additional inductance to the circuit, which influences the switching behavior and increases the induction voltage when switching off.

• Cable resistance: The ohmic resistance of the cable reduces the effective voltage at the coil and must be taken into account when dimensioning.

• Electromagnetic interference (EMI): Long cables can act as antennas and emit or capture electromagnetic interference. Twisting the forward and return cables and shielding them can minimize these effects.

Recommendation: The protective circuit (free-wheeling diode, Z-diode, or TVS diode) should be placed as close as possible to the relay coil to maximize effectiveness and reduce interference.

5. Troubleshooting tips

If you encounter problems with relay circuits, the following test steps may be helpful:

- Measure coil voltage: Use a multimeter or oscilloscope to check the voltage at the coil during the switching process. The voltage should reach the nominal value.
- Check coil current: Measure the current through the coil and compare it with the data sheet. Too low a current may indicate line losses or a defective control.
- Observe induction voltage: Use an oscilloscope to observe the voltage at the MOSFET drain during shutdown. Excessive voltage peaks indicate a missing or defective protective circuit.
- Check switching times: Measure the pick-up and drop-out delay with an oscilloscope and compare it with the data sheet specifications. Deviations may indicate problems with the control circuit or the protective circuit.
- Test temperature behavior: Test the relay under different temperature conditions to ensure that it operates reliably throughout its entire operating range.

6. Summary

The choice between monostable and bistable relays depends on the requirements of the application. Monostable relays are easy to control and are suitable for applications where the switching state must be kept active. Bistable relays are more energy-efficient and are suitable for applications where the switching state is to be maintained for long periods without energy supply.

When controlling with MOSFETs, particular attention must be paid to the use of pull-down resistors and suitable free-wheeling circuits. The choice of free-wheeling circuit has a direct influence on the service life of the relay contacts: a simple free-wheeling diode provides optimum protection for the electronics but leads to slower switching off and increased contact wear. For critical applications, a Z-diode in series or a TVS diode is therefore recommended.

For applications with a wide temperature range or high reliability requirements, current-controlled control (constant current source or PWM with current measurement) is preferable to voltage-controlled control, as it ensures constant amperage and lower power dissipation.

For bistable relays with two coils, check whether integrated protection diodes are already present to avoid double wiring.

The same principles apply to analog circuits as to digital circuits. The control signals can come from operational amplifiers, comparators, or other analog circuits, if the required voltage levels and currents are maintained.

7. Disclaimer

This documentation has been compiled with the utmost care but is intended for general information purposes only. The information contained herein does not constitute professional technical advice. For correct and safe application, the parameters and circuits specified in the respective manufacturer's data sheet are decisive. We accept no liability for damage resulting from the application of the information described here.

8. Glossary

Ampere turns (AW): The product of coil current and number of turns. Determines the magnetic force of a relay.

Bistable relay: A relay that maintains its switching state without a continuous power supply.

Free-wheeling diode: A diode connected in parallel to the inductive load to dissipate induction voltages during shutdown.

H-bridge: A circuit consisting of four transistors that allows the polarity of the voltage at a load to be reversed.

High-side circuit: A configuration in which the switch is located between the supply voltage and the load.

Induction voltage: The voltage generated by the collapsing magnetic field when an inductive load is switched off.

Low-side circuit: A configuration in which the switch is located between the load and ground.

Monostable relay: A relay that returns to its rest position by spring force as soon as the control signal is terminated.

PWM (pulse width modulation): A technique for controlling the effective voltage by rapidly switching it on and off with a variable duty cycle.

TVS diode (transient voltage suppressor): A special diode for rapid absorption of transient over voltages.

Z diode (Zener diode): A diode that becomes conductive at a defined reverse voltage (Zener voltage) and is used for voltage limiting.