Flexible and Low Power Driving of Solenoid Coils

In many microcontroller applications inductive loads, such as monostable or bistable relays, valves, or lifting solenoids must be operated from supply voltages that are above the output level. Specifically in industrial applications they can often be 12 to 24 V, which have to be controlled e.g. with a 3.3 V logic signal [1]. The control should be as flexible and energy-saving as possible and should not impair the microcontroller’s operation through feedback disturbances during the switching of inductive loads.

This White Paper shows which elements should be considered for the design and how space, power loss and logistics costs can be reduced through an intelligent control.

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1) Switching Characteristics of Electromagnets

Inductive loads in microcontroller applications are usually windings of a coil in electromagnets or motors. They serve as actuators to convert electric energy to mechanic energy and are hereinafter referred to as EM actuators. They consist of magnetic circuits with a core and a variable or fixed air gap. In this paper only electromagnets with variable air gaps will be considered. The inductivity of a coil can be calculated with the following formula 1:

Formula 1: \[ L \approx \frac{\mu_0 \times \mu_r \times A \times N^2}{sL} \] [H]

\( L \) ≡ inductivity, \( \mu_0 \) ≡ relative permeability, \( \mu_r \) ≡ permeability of the core, \( A \) ≡ coil surface, \( N \) ≡ number of windings and \( sL \) ≡ coil length

The formula above shows the alteration of inductivity if the air gap is reduced or closed at the activation of the actuator, e.g. valve or relay.

The generated mechanical force, in turn, is proportional to the strength of the magnetic field. This can be calculated with formula 2:

Formula 2: \[ B = \mu_0 \times \mu_r \times N \times I \] [T]

\( B \) ≡ magnetic field strength, \( I \) ≡ current flowing through coil

The result shows that the mechanical force increases when the magnetic circuit is closed. The current can be reduced after activation in order to save energy and to avoid an unnecessary heat generation.

A special characteristic of the coil is that the self-induction generated by a current flow counteracts this flow until the magnetic field is built up. A current change thus occurs after a voltage change with a 90° phase shift. This can be calculated with formula 3, neglecting the internal coil resistance:

Formula 3: \[ \frac{di}{dt} = \frac{U}{L} \] [A/s]

\( U \) ≡ voltage, \( di \) ≡ current change, \( dt \) ≡ time change

The current change and accordingly the activation speed increases proportionally to the voltage applied. The coil serves as energy storage system and becomes a current source when the current is switched off. Switching off the current abruptly results in a voltage increase. For the control switch’s safety this increase needs to be limited until the saved energy is depleted.

When applying a DC voltage to a coil/inductivity the current changes according to formula 4 considering the internal resistance:

Formula 4: \[ I(t) = (1 - e^{-t/\tau}) \times \frac{U}{Ri} \] mit \( \tau = \frac{L}{Ri} \)

\( t \) ≡ time, \( U \) ≡ voltage, \( Ri \) ≡ internal resistance, \( \tau \) ≡ time constant

The equivalent circuit diagram (see figure 1) of a coil results from the inductivity, the internal resistance of
the copper windings in series and the capacity of the windings. Losses through hysteresis and eddy currents can be neglected at normal switch on and off processes. The effect of the winding capacity is usually negligibly small, since only small switching frequencies are reached in the electro mechanical actuators.

![Equivalent Circuit Diagram of an Actuator Coil](image)

Figure 1: Equivalent Circuit Diagram of an Actuator Coil

The switching characteristics of coils in electromagnets can be summarized as follows:

1) The inductivity of the coil changes with the closing of the magnetic circuit:
   ➤ This can be used for a reduction of the control power!

2) The current change in the magnetic circuit is proportional to the applied voltage:
   ➤ This can be used for a speed-up of the activation process!

3) The coil is an energy storage system which releases its energy during switch off:
   ➤ This requires safety measures for the control circuit!

2) What needs to be considered for the Design?

This paragraph should provide an overview of what needs to be considered for the design and selection of the control circuit.

Since the control of EM actuators mostly occurs through microcontrollers which increasingly have supply voltages of <5 V, level converters are required which are capable of operating the control circuit. Notes on the level conversion of 1.8 V/3.3 V signals to the industrial 24 V level are covered in a different White Paper [1]. If integrated actuator iCs are used, they are oftentimes directly controllable with 3.3 V logic signals.

The supply voltage of EM actuators is quite diverse and therefore ranges from +3 to +24 V and more. This means that the control circuits should have an electric strength which can cover a wide range and if possible contains protective circuits which can discharge the high switch-off voltages (e.g. through a freewheeling diode).

As previously described, a brief voltage and current excess results in a faster activation at switch on. This is often desirable in order to reach faster activation times and to safely overcome different static frictions from rest position. After closing the magnetic circuit a reduction to the normal supply voltage or
holding current can follow. The EM actuator’s min./max. value specified in the data sheet have to be considered even in absolute maximum conditions.

When switching off the EM actuator, the coil tries to maintain the current flow with its stored energy. Since this is not possible, the voltage abruptly increases and the output driver experiences an overvoltage load and needs to be protected, usually through a freewheeling diode. This freewheeling diode delays the switch off process and extends the time until the idle state is reached. For relay contacts with higher current loads this can possibly lead to switch arcs and increases the contact resistance, as well as the heat generation in the long run. A Z-diode can be helpful for faster depleting the stored energy.

The EM actuator’s winding wire typically consists of a copper wire and produces the coil’s ohmic internal resistance. The coil is heated up through the current flow inside the coil and the internal resistance is increased. This appears like an increased ambient temperature. The temperature coefficient of pure copper wire is about \( \alpha_{Cu} = 0.00393 \text{ per Kelvin}, \) i.e. per degree of temperature change the resistance changes about almost 0.4%. Thus, the internal resistance of e.g. a coil of 100 \( \Omega \) at 20 °C would increase to 134.7 \( \Omega \) at 80 °C operating temperature (~ 35%). At the same operating voltage the result is a lower current and a longer activation time (proportional to the resistance change), which should be considered for the driver circuit design in any case.

Especially for the control of relays, which switch alternating voltages, executing the activation in zero crossing is advantageous. This can be achieved by synchronizing the driver circuit with the voltage zero crossing. It boosts the lifespan of heavily loaded relay contacts and prevents current peaks. In paragraph 5 this topic is discussed in detail.

The most important questions for the driver circuit design in summary:

1) Is a level conversion from control signal to coil operating voltage necessary?
2) Are starting currents and switching times always sufficient to overcome the starting activation energy (under worst case and aging conditions)?
3) Is energy saving possible at reaching the active state (holding current)?
4) Is the electric strength of the driver and protective circuit sufficient?
5) Must the change of internal resistance be considered for the operating temperature?
6) Is a synchronization of the switching process with external processes necessary?

**3) Power Reduction through Intelligent Control**

EM actuators where a magnetic circuit is closing in the active state (air gap equals zero) then have a low energy requirement. This can be used to conduct a targeted control power reduction; e.g. for relays, solenoids or valves with iron core. The data sheet defines the minimal holding current in the activated state, which is oftentimes only 40 to 50% of the activation current. Following the maximum activation time at absolute maximum conditions, either the voltage can be reduced or the average current can be lowered by use of a pulse width modulation (PWM). With the simple PWM the current reduction is achieved through time-controlled voltage switch off. A lower average current, which is time-controlled via
the duty cycle, is set in the coil. The left-hand side of figure 2 shows this simple PWM control. It is easy to implement and can be conducted via software or integrated PWM controls. Transistor T1 switches the current path on and off. Freewheeling diode D1 protects T1 from overvoltage.

A more intelligent method is to measure and control the current through the coil. The diagram on the right-hand side in figure 2 illustrates this principle.

![Figure 2: Comparison of PWM with and without current control](image)

Voltage +U is being switched on by transistor T1 until the set current is reached. T1 is then switched off and being switched on again at the end of the PWM cycle. The measuring of the coil current and the control to the set value \(i_{LSoll}\) results in the setting of an average current which flows through the coil, independent of the EM actuator coil’s normal operating voltage. This circuit has several advantages compared to the simple PWM control, such as:

1) Fluctuations of the supply voltage +U have no influence; since the current is being regulated and the size of the activation energy is proportional to the current (see formula 2).
2) The EM actuator’s nominal value can be smaller than +U and actuators with different nominal values can be controlled by the same driver, as the current is controlled.
3) A higher voltage +U than the nominal value reduces the activation time (see formula 3).
4) The deactivation time can be reduced as well, if a Zener diode instead of a simple diode is used for voltage limitation.
5) Temperature rises in operation with high internal resistance of the coil no longer have an influence on the activation energy and time (see paragraph 2).

Both circuitry principles can be used for a targeted reduction of the energy demand at activation. With the simple PWM the duty cycle is changed to shorter on times \((t_{Soll} \rightarrow t_{Min})\). With the current control the set point is reduced \((i_{LSoll} \rightarrow i_{LMin})\). The switching frequency usually does not change during the operation. However, they should be selected so that no interferences lie in the audible range or cause EMV problems.

Additional possibilities to reduce the power demand of EM actuators are the improvement of the magnet core or the use of bistable actuators. These have special requirements for the control and are discussed in paragraph 6.
4) Intelligent Control of Monostable Relays, Magnet Valves and Solenoids

In applications with electromechanical monostable relays, valves and solenoids the power consumption can be reduced independently of the voltage supply by using special ICs.

Solutions for a more flexible and energy-saving control range from simple circuits with a transistor and current reduction through RC circuitry to integrated circuits with PWM, or, as already described, using a current-regulated PWM.

With the simple PWM this means that both coil and PWM control (frequency, duty cycle) have to be adjusted to the supply voltage. In some integrated solutions it is tried to track the PWM control dependent on the supply voltage.

The decisive advantage of the current-regulated PWM is the coil current independent of the supply voltage. For adjusting to the EM actuator’s coil, only starting current and holding current have to be set. The PWM’s duty cycle is controlled automatically depending on the coil parameters, such as inductivity and internal resistance, as well as supply voltage. With this kind of control, e.g. a 6 V coil can be used in a wide voltage range (10 to 36 V), as the coil current is not dependent on the supply voltage anymore.

Figure 3 shows the practical implementation of such a current-controlled PWM control with the integrated circuit iC-GE for coils of 0.01 to 10 H and current ranging from 100 mA to 1 A. The activation current is set with the resistance RACT and is reduced to the hold current set with RHOLD after typ. 65 ms. Calculation is done according to the formulas:

Formula 5: \[ RACT = \frac{K_1}{I(SW)_{act}} \]

Formula 6: \[ RHOLD = \frac{K_2}{I(SW)_{hold}} \]

With capacitor CACT the length of the activation phase is being defined. Then the current control is reduced to the hold value. Calculation is based on:

Formula 7: \[ TpPWM = tpPMWlo + K3CACT \]

\[ K3CAT = 1 \text{ ms/nF (+/-20%)}; \quad tpPMWlo = 65 \text{ ms (+/-10 ms)} \]

The internal oscillator’s PWM frequency is 80 kHz and thus exceeds the audible range. For EMI emission reduction, the frequency is spread between 70 and 90 kHz. At a reduction of e.g. 2/3 of the activation current, the power dissipation is reduced by approx. 50%.
Input EN activates coil driver iC-GE with a high level. Logic levels are designed for 1.8, 2.5, 3.3, and 5 V microcontroller output stages. A hysteresis and a pull-down resistance prevent the activation of the coil driver by output ports, which are set to tri-state or input mode following switch on.

The PWM output stage is protected by a freewheeling diode (D1). The Zener diode (Z1) is activated at the driver switch off and allows a fast demagnetization of the coil through a higher freewheel voltage.

Additionally, iC-GE and iC-GE100 have diagnostic functions \[2\], which indicate coil defects, such as not reaching the set current (isolation defect or wire breakage), undervoltage, and overtemperature at error output DIAG (active LOW) through blinking (typ. 2.4 Hz). The DIAG pin can either serve as an interrupt for the microcontroller or can directly drive an LED as visible error message for the service.

Another interesting device characteristic is that the switch on of the EM actuator can occur with external incidents synchronized via the SYNC input. The switching contact protection allows relays, which e.g. control an alternating voltage, to switch in zero crossing of the load current. These applications are discussed in paragraph 5.

Since the adjustable current control range should be as flexible and as precise as possible, as an alternative to iC-GE with 0.1 to 1 A, iC-GE100 has been designed for a current range of 10 to 100 mA. Figure 4 shows the timing diagram of the current flow during the phase startup, hold, and switch off.
Following switch on of the driver stage, the current rises linearly to the set activation current $I_{(SW)\text{act}}$. Then the regulated PWM operation begins, which automatically switches to the lower hold current after expiry of the activation time $t_{act}$. At switch off the Z diode is activated for a higher countervoltage in order to faster de-energize the coil.

Figure 4: Signal flow in the intelligent current-controlled PWM
5) Network-Synchronous Switching Prevents High Input Currents

If the switching of high capacitive or resistive loads at alternating voltages does not occur synchronously in zero crossing, it represents a high current load for the switching contacts. The circuit in figure 5 shows the usage and wiring of the SYNC input of [IC-GE](http://www.ichaus.com). The live contact’s alternating voltage is launched via CSN and CSP and through the low pass of RSG and CSG it is delayed in the phase to max. -90°. CSN/CSP and CSG is a capacitive voltage divider which reduces the alternating voltage at the SYNC input in relation to its magnitude. If the EN input receives a high signal, at the next zero crossing SYNC switches on the SW output with a hysteresis of +/-40 mV (figure 6).

The switch on time TRelon of the relay must correspond with the phase shift (through RSG and CSG). It has a maximum of -90°, or at a frequency of max. 50 Hz TRelon can have a maximum of 5 ms. For the dimensioning example shown in figure 5 where RSG = 2 MΩ and CSG = 1 nF, the phase shift is 3 ms.
6) Intelligent Control of Bistable Relays, Magnet Valves and Solenoids

The primary advantage of bistable relays, magnet valves and solenoids is the reduced power consumption. In order to switch from the on mode to the off mode and vice versa, simply a defined current pulse is required. This can be implemented with a coil and current reversal, or with two coils (one for each switching direction). Thus, two push/pull output stages are required for the control, as shown in figure 7. With one coil, driver 1 is switched to $V_{BB}$ and driver 2 is switched to ground. The current reversal takes place for switch off, as driver 2 is switched to $V_{BB}$ and driver 1 is switched to ground. The right-hand side of figure 7 shows the control for the two-coil type. Driver 1 is responsible for switch on and driver 2 for switch off.

![Control of bistable relays with two push/pull output drivers](image)

Figure 7: Control of bistable relays with two push/pull output drivers

The driver effort and the control pulses are identical in both cases. The increased driver effort of the bistable control only pays off with long activation times and a high amount of relays, magnet valves and solenoids which need to be controlled, e.g. a control of a switch matrix for wire and board tests or pneumatic control systems.

For this application, output port iC-DY6818 is especially useful, since it is controlled via a serial SPI interface and has 32 push/pull output driver. Figure 8 shows the block diagram of iC-DY6818 with the separately supplied push/pull outputs. They can control bistable relays, magnet valves or solenoids with a supply voltage of 8 to 36 V. The driver current of the push/pull outputs is designed symmetrically and amounts to $+/-25$ mA.

Already integrated as well are the freewheeling diodes for a bistable control of inductive loads. At the serial transmission of new output data they are first inserted into a 32-bit shift register. With the activation of the ST input the data is stored in a 32-bit output register which controls the output stages. Via a BLNK input (active HIGH) all outputs can be set to active LOW. This serves e.g. for the generation of a defined pulse for the bistable control, which is either generated through a monoflop or through the micromicrocontroller controller via software routine.
**Figure 8:** Block diagram of the 32-bit shift register with 8 to 36 V output driver

*iC-DY6818* monitors the VBB and VDD voltage and detects an undervoltage as well as the device’s chip temperature. If a temperature above 125° C is reached or an undervoltage is detected, the outputs are deactivated and a low signal for the microcontroller as error message is output at NERR.

The shift register of *iC-DY6818* allows a daisy-chaining for a multiple of the 32 outputs. Figure 9 shows the daisy-chaining of three *iC-DY6818*. For this, serial outputs SDO and CKLO are connected to inputs SDI and CKLI and all ST and BLNK inputs are controlled collectively by the microcontroller. The NERR outputs are open drain outputs, and combined they can drive the microcontroller’s interrupt input. All inputs have a Schmitt-Trigger characteristic with a 600 mV hysteresis and are controllable with 3 to 5 V logic signals.

**Figure 9:** Cascading of three *iC-DY6818* with 32 output drivers each
7) Notes on the Layout of Control Circuits

At the inductance’s switch off, fast voltage changes occur which need to be considered for the PCB layout of the control circuit. The most important goal is to keep away the fast voltage changes from the sensitive analog or logic parts, as well as from the microcontroller. The recommended layout provisions are:

- The lines from the driver IC to the control coils should be as short as possible and separated from the control and clock lines, in order to minimize cross talk.
- The placement of the backup capacitors should be as close as possible to the supply line connections of the driver IC (separately for iC-DY6818).
- Separate supply lines for the coil drivers with higher voltages.
- Separate ground levels for signal and driver outputs (only connected to a central ground point).
- Usage of the thermal pad for the cooling of the QFN package.
- Unused control inputs should be connected to defined ground or voltage levels.

8) Design Checklist

Finally, for the layout of control circuits it is recommended to check the following points:

- Have the layout provisions of paragraph 7 been considered?
- Have the worst case conditions been considered for the dimensioning of the coil current (voltage, temperature, tolerances, aging)?
- Do the heat dissipation capabilities from the driver to the ambiance suffice for high switching frequencies and all drivers that can simultaneously be active (possibly cooling necessary)?

9) Summary

As described in the different paragraphs, the control of inductive loads, which can be found in relays, valves, solenoids and other electromagnetic actuators, can occur through special drivers in an efficient and energy-saving mode. With monostable EM actuators, a current-controlled PWM reaches shorter activation times and the application of different voltage versions at the same driver circuit. This reduces the storage and logistics costs. Bistable actuators that are used in a variety of applications in a system allow drivers with 32 push/pull outputs to control up to 16 actuators in a single iC package. The power dissipation reduction through the intelligent control can easily amount to several tens of kWh in the course of active operation and can more than compensate for the intelligent control’s increased effort.
10) Literature

[1] Interfacing Microcontrollers to the Industrial World, White Paper iC-Haus
[2] E/A Error Monitoring in Industrial Machine Controls, Dr. David Lin

About iC-Haus

iC-Haus GmbH is a leading, independent German manufacturer of standard iCs (ASSP) and customized ASIC semiconductor solutions with worldwide representation. For more than 25 years the company has been active in the design, production, and sales of application-specific iCs for industrial, automotive, and medical applications.

The iC-Haus cell libraries in CMOS, bipolar, and BCD technologies are specifically suited to realize the design of sensor, laser/opto, and actuator ASiCs, amongst others. The iCs are assembled in standard plastic packages or using the iC-Haus chip-on-board technology to manufacture complete microsystems, multichip modules, and optoBGA/QFN in conjunction with sensors. Further information is available at http://www.ichaus.com.