Application description AN1014
AM 462: processor interface circuit for the conversion of PWM signals into 4…20mA (current loop interface)

This article describes a simple interface circuit for the conversion of a PWM (pulse width modulation) signal into a standard current signal (4...20mA). It explains how a processor is connected up to the industrial analog network which then transmits the processor signals to the process control system (PLC).

The simple interface requires a processor PWM output signal, a low pass filter and a voltage-to-current converter.

Besides outlining the basic possibilities for D/A conversion the article will also explain how a digital processor output (PWM) is converted into a current signal using a simple low pass filter; suitable dimensions are suggested to this end.

The industrial current interface IC AM462 acts as a voltage-to-current converter whose use for the 4...20mA interface in a 3-wire version shall be exemplified herein.

NB: The following descriptions can be applied by analogy to all voltage-to-current converter ICs produced by Analog Microelectronics GmbH (AM400, AM402, AM422, AM442, AM460 and AM462) [1] and can also be adapted to suit the 2-wire current interface using the press release [2] and the applications not [3].

As a typical industrial application a basic configuration is first determined (*Figure 1*), in which a measurement signal is processed in a follow-on processor after signal conditioning. This is then to be transmitted to a receiver as analog information for a PLC or a DDC. When using such system many users ask the question:

How do I convert the digital processor signal into an adequate current signal of, for example, 4...20mA?

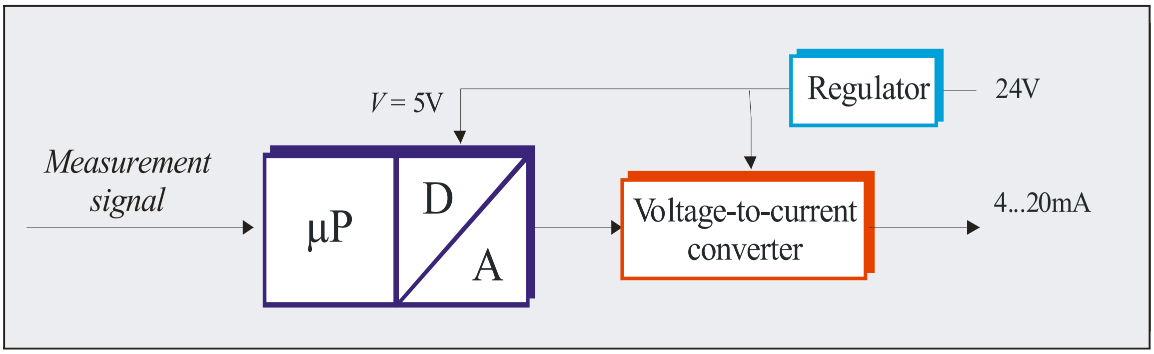

Figure 1: Typical industrial application: connecting up a microprocessor to the 4...20mA current loop signal for a PLC system

The following attempts to provide some answers, giving examples of a solution for the 4...20mA (life-zero) signal and assistance in the dimensioning of an interface circuit such as this.

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D/A conversion

Today there are suitable, inexpensive microprocessors available for almost all types of application. They are appropriate for signal compensation, for example, for linearization, for control and, where required, also for the identification of measurement channels or products identification. The internal routines and processes are all digital. In order to transmit signals in cost-sensitive industrial applications, their digital results (output signal) must be converted into analog values.

Should an analog current signal of 4...20mA be necessary for the PLC or DCD systems, for example, the conversion from measurement to current signal takes place in several consecutive stages. First the measurement signal has to be amplified, digitized (A/D conversion) and, after conditioning in the processor, converted back into an adequate voltage signal (D/A conversion). Following conversion and any filtering which may be necessary the analog voltage signal is to transform into a current and to calibrate to the desired current output values.

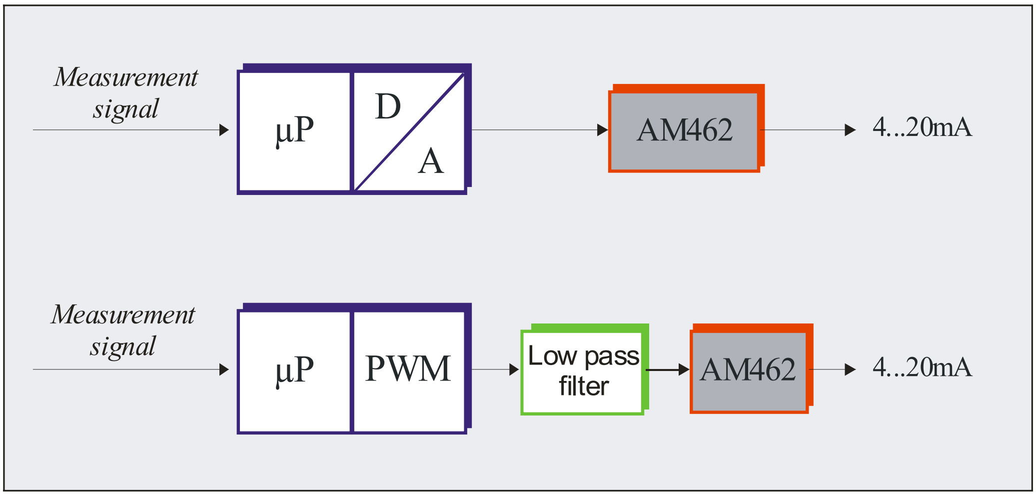

Figure 2: Possible interface configurations for signal conversion using AM462 for the 4...20mA network

If a D/A converter is integrated in the processor (*Figure 2*) and provided that the signal has been suitably filtered and the resolution is sufficient for the measurement accuracy, the analog DC voltage output signal has to be transformed into the required current. As this cannot usually be done using a passive resistor network due to the offset value of 4mA, then a voltage-controlled current source must then be assembled or a suitable IC (such as AM462) used which at best can be directly connected up to the D/A converter without much adjustment having to be made [2].

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If there is no D/A converter integrated in the processor and if no further component can be used for reasons of cost, the digital processor output signal has to be turned into a DC signal using other methods.

In many cases a PWM output installed as hardware in the processor can help, to convert the processor signal into the required current. In pulse width modulation part of the processor a square-wave voltage is generated in which the ratio of turn-on time to length of period T is varied according to the digital measurement.

If neither a D/A converter nor a hardware PWM output are available, as is often the case with low-cost RISC processors, the PWM signal can be generated using software together with a processor I/O output. Here, a timer-controlled interrupt routine can be used. To generate the PWM signal the output is switched on and off by software within a period T, where pulse width t_p is equivalent to the digitized measurement value.

PWM signal

As the I/O output of a processor normally produces discrete voltages (e.g. U_1 = 0/ 3.3V or 0/ 5V) with a clock frequency of $f = 1/t_{clk}$ in its output registers and as the I/O output is now equivalent to the PWM signal, the PWM signal has a pulse height or PWM amplitude of U_1.

The ratio of turn-on and period length tp/T is expressed as a duty cycle (see *Figure 3*). The temporal development of the duty cycle is equivalent to the measurement information processed in the processor. If this information is to be resolved with 10 bits, for example, then $T = 1024\ t_{clk.}$ must apply.

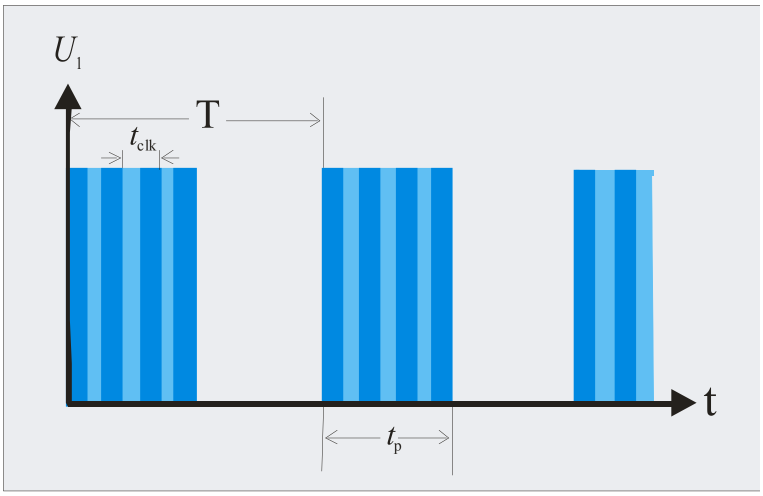

Figure 3: Definition of the designation "PWM pulse"

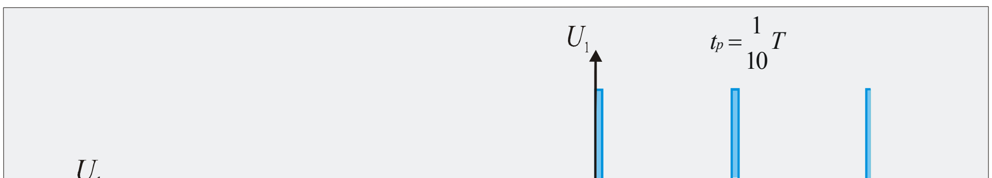

Figure 4: Various duty cycles with pulse width modulation

Example:
If the hexadecimal information in the processor is 006A, for example, and the clock rate of the processor t_{clk} = 1µsec, then the relevant PWM signal is generated with a pulse width of tp = 106µsec, provided that the internal processor prescalers are set to 1. With a 10-bit word in the processor the following duty cycle is obtained (see *Figure 4*):

$$\frac{t_p}{T} = \frac{106}{1024} \cong 0.10$$

Filtering

To convert the PWM signal into an analog voltage signal a mathematical average is usually calculated with the help of a low pass filter.

In the following description of the filtering and dimensioning of the necessary low pass filter components it is assumed that a PWM signal is present at the digital signal conditioning circuit (processor) output.

In doing so the pulse width modulated signal must fulfill the quasi-static condition $f_m << f_p$ (f_m = change in measurement value, $f_p = 1/tp$) to be able to be converted by the low pass filter into a DC value (see *Figure 5*).

The square-wave signal U_1 obtained from the processor (PWM signal) is filtered in a low pass, resulting in an averaged DC output signal (U2) which is proportional to the duty cycle tp/T. The following applies:

$$U_2 = \frac{1}{T} \int_{t_0}^{t_0+T} U_1(t)dt \longrightarrow U_2 = U_1 \frac{t_p}{T}$$

The filtered PWM signal is equivalent to the voltage U_2 which is then to be converted into the standard signal of 4...20mA. With a duty cycle of 0.5, for example, an output voltage of 2.5V is set in a 5-volt system (mathematical average).

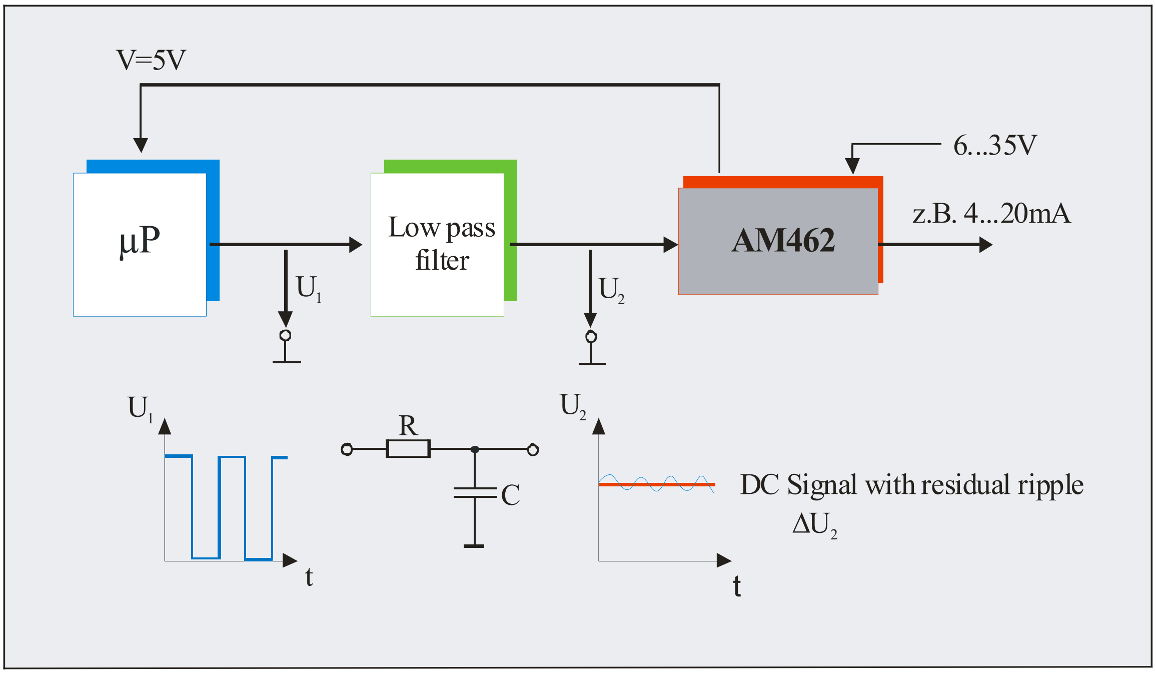

Figure 5: Connecting up a processor with a PWM output to the 4...20mA supply with the help of a voltage-controlled current source (AM462)

The above formulae provide no information as to the dimensioning of the low pass circuitry or its behavior regarding the errors in the current signal. The question thus remains:

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How do I dimension the low pass filter subject to the resulting errors in the current output signal? Or: what must be done so that the effect of the PWM on the current output signal error is negligible and which disturbance variables play a role in the dimensioning of the setup?

Dimensioning

In principle it is assumed that the low pass filter has little or no effect on the overall error of the output current. This means that the disturbances resulting from the filtering of the low pass (residual ripple) should be as minimal as possible.

The PWM amplitude is expressed by U_1 and the residual ripple at U_2 by ΔU_2. With a suitable analysis and given condition of:

$$\Delta U_2 \ll U_1 ,$$

it can be shown that ΔU_2 is at its greatest ($\max\Delta U_2$) when:

$$tp = \frac{1}{2} T \qquad (1)$$

It then follows for $\max\Delta U_2$ that: $\max \Delta U_2 = \frac{U_1 \cdot T}{4 \cdot R \cdot C}$ (2)

This means that besides PWM amplitude U_1 the residual ripple is dependent on PWM period length T and on the dimensioning of the low pass components R and C.

If a low pass resistor R is present, an offset U_{Off} is determined by the input bias current (I_{INPUT}) of the voltage-controlled current source (e.g. voltage-to-current converter AM462) at the IC input. This offset also has an error percentage of ΔI_{out} in the output current:

$$U_{Off} = I_{INPUT} \cdot R \qquad (3)$$

It can be deduced that with regard to resistor R the offset (3) and the residual ripple (2) exhibit a contradirectional behavior which in calculating R and C is tantamount to an optimization problem. One practically relevant, given condition for the calculation is that both error percentages in the output current have the same value.

Based on equations (2) and (3) the search for a local minimum regarding the offset and residual ripple results in the following equation for resistor R:

$$R = \frac{\max \Delta U_2}{I_{INPUT}} \qquad (4)$$

Capacitance C is calculated as:

$$C = \frac{I_{INPUT} \cdot T \cdot U_1}{4 \cdot \max \Delta U_2{}^2} . \qquad (5)$$

With R and C determined the low pass filter is now set under the condition that the error percentages resulting from the offset and residual ripple are the same (ΔI_{OUT}). Regardless of the concrete dimensioning the dissipation factor of capacitance C (tanδ) and the temperature coefficient must possibly be taken into account as conditions governing practical implementation; together with the size and cost of the capacitors to be used, the temperature coefficient can also influence the characteristics of the system.

The low pass cutoff frequency f_g (the 3dB point of the RC filter), which can be used to transmit any alteration in the PWM signal (f_m), is:

$$f_g = \frac{1}{2 \cdot \pi \cdot R \cdot C} \tag{6}$$

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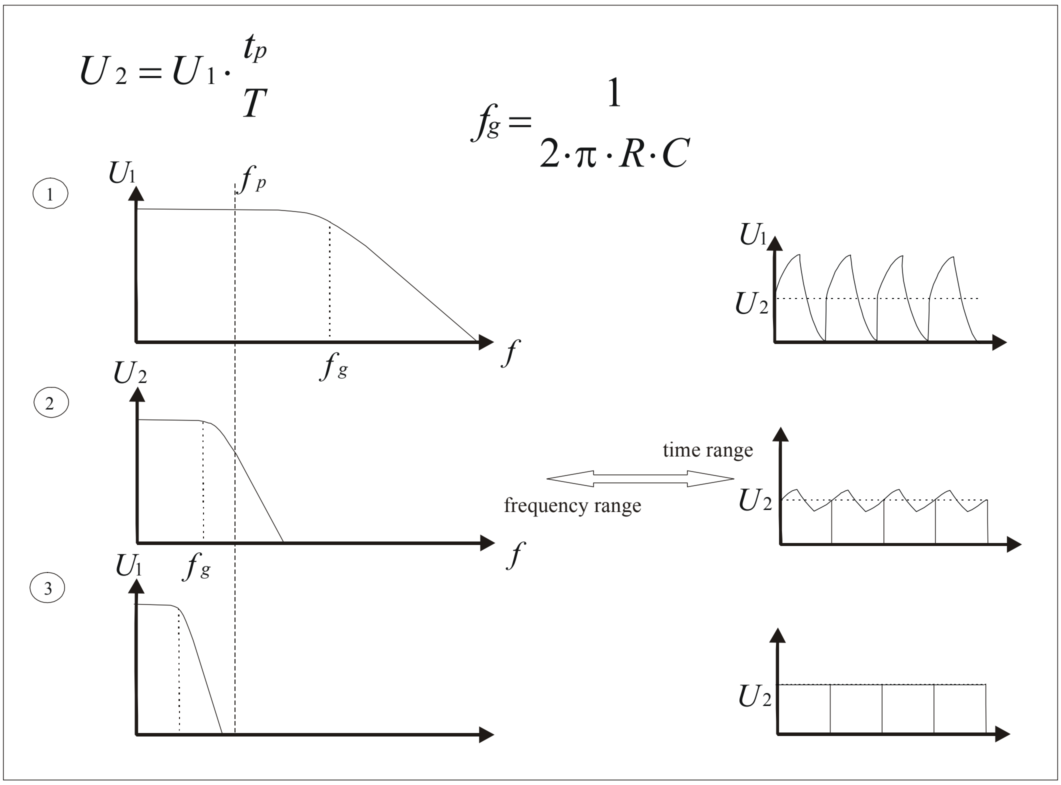

Figure 6: Residual ripple depending on the low pass cutoff frequency

Theoretically it is clear from *Figure 6* that the residual ripple and low pass cutoff frequency are coupled variables. The smaller the residual ripple, the smaller the cutoff frequency.

It follows from equations (4) and (5) that:

$$f_g = \frac{2 \cdot \max \Delta U_2}{U_1 \cdot T \cdot \pi} \qquad (7)$$

where it is obvious that with a given $\max\Delta U_2$ the cutoff frequency f_g is also determined.

Example: t_{clk} = 1µsec, T = 1024 t_{clk}, residual ripple $\max\Delta U_2$ (filtering error percentage at the output signal) and the offset percentage should both be 0.1%, signal at the PWM output = 5V, output signal at AM462 is I_{out} = 4…20mA.

As a general rule the input bias current is $I_{Input} \approx$ 10nA for all voltage-to-current converter ICs by Analog Microelectronics (AM400, AM402, AM422, AM442, AM460 and AM462) in accordance with [2].

Using the data given above and equations (4) and (5):

$$R = \frac{5mV}{10 \cdot 10^{-9} A} = 500k\Omega \text{ and } C = \frac{10 \cdot 10^{-9} A \cdot 5V \cdot 1024 \cdot 10^{-6} \sec}{4 \cdot 25 \cdot 10^{-6} V} = 512nF$$

Applying the values in equation (7), the low pass cutoff frequency is calculated as:

$$f_g = \frac{2 \cdot 5mV}{5V \cdot \pi \cdot 1024 \mu \sec} = 0.62Hz$$

It should be taken into account that the following also applies: low pass cutoff frequency f_g < f_{it}. Here f_{it} is the transmission frequency of the follow-on IC which in the case of AM462 is given as ca. 50kHz.

As AM462 is a purely analog IC, the output signal resolution which can be achieved is wholly dependent on the temporal behavior of the PWM signal and thus chiefly on the clock frequency of the processor.

If higher demands are made of the residual ripple, filters with other transmission characteristics, such as Chebyshev, Bessel or Butterworth filters, can be deployed.

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AM462: An industrial voltage-to-current converter IC

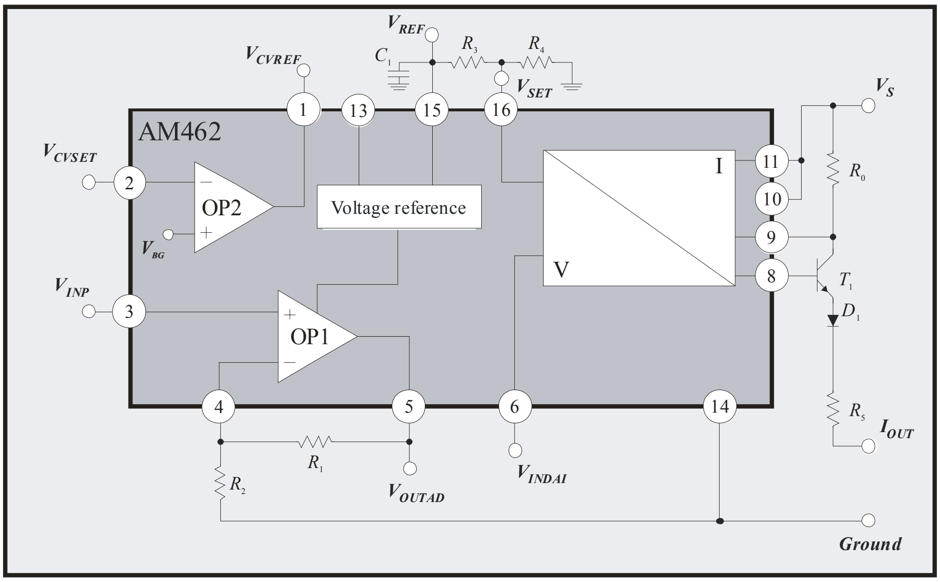

***Figure** 7:* 3-wire application using AM462 as a voltage-to-current converter IC with a 4...20mA current output

AM462 (*Figure 7*) is a voltage-to-current converter IC designed as a multistage amplifier with a number of additional and protective functions which can be used optionally, providing a high degree of flexibility and functionality. The IC is modular throughout. All function blocks can be individually accessed via the relevant pins and connected up externally or operated separately.

AM462 contains the following functional units:

1. An *operational amplifier stage*
This *amplifier stage* (OP1) is suitable for ground-referenced input signals of 0 to VCC 5V. Amplification is set using two external resistors. The operational amplifier stage output has been designed so that it can be set right down to zero if the load requires. OP1 is voltage limited, protecting follow-on stages even when overvoltage occurs at the front end of the device.

2. A *voltage/current converter stage*
At the back end of the device the *voltage/current converter stage* translates the input voltage into a freely selectable output current of between 0 and 20mA. In doing so the converter output stage activates an external resistor (*Figure 6*) which ensures that power is dissipated outside the IC. The output current range for the current offset and final current value can be easily set using two external voltage dividers.

3. A *bandgap reference*

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The *reference voltage source* included in AM462 enables external components, such as sensors and microprocessors etc., to be supplied with voltage. Reference voltage V_{REF} can be set via pin *VSET* to V_{REF} = 5V/10V. Using two external resistors (inserted between pins *VREF* and *VSET* and pins *VSET* and *GND*) intermediate values can also be set.

4. An *operational amplifier*
A second *operational amplifier* (OP2) can be used as a current or voltage source to power external components. OP2's positive input is connected internally to voltage V_{BG}, enabling the output current or voltage to be set within a wide range using one or two external resistors.

The IC also includes internal circuitry protecting the amplifier stage OP1 against overvoltage, integrated protection against reverse polarity with regard to the output stage (V/I converter) across the entire voltage range and an output current limiter which protects the IC against destruction. Using just a minimum of external circuitry an industrial output stage can be realized which is fully protected.

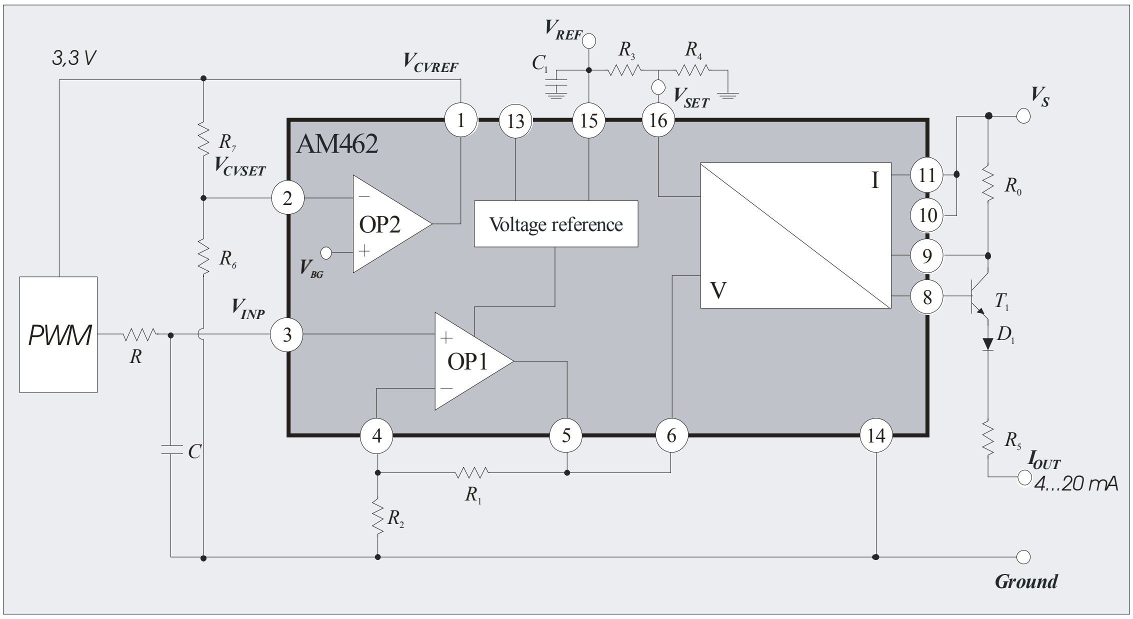

***Figure** 7:* Interface circuit: PWM – to the 4..20mA output signal in 3-wire operation

Conclusion

The digital output signal of a processor whose clock rate and I/O output voltage are given with respect to the PWM output can be converted fairly easily into a 4...20mA current signal using a simple low pass filter and a voltage-controlled current source (taking AM462 as an example). The dimensioning of the low pass circuitry, described herein in detail, illustrates how the PWM signal is transformed into a 4...20mA current signal.

With the help of the derived equations the interface circuit can be easily adapted to suit the conditions the user requires.

In the description of this particular application the dimensioning of the low pass filter is demonstrated using a 3-wire circuit by way of example. With reference to the relevant data sheets [1] these dimensions can be easily applied to 2-wire variants as – with the exception of a domestic current supply limit (max. 4mA) in 2-wire operation – the output circuitry in 2- or 3-wire operation has no further effect on the interface circuitry.

Further reading:

All information is available at www.analogmicro.de

[1] Data sheets for the voltage-to-current converter ICs AM400, AM402, AM422, AM442, AM460 and AM462

[2] Data sheet AM462: see *Applications*

[3] Press release PR1012: Voltage-to-current converter IC for 2-wire current loop applications

[4] Application note AN1010: Current loop output (4...20mA) for a 0.5...4.5V pressure transmitter