APEX MICROTECHNOLOGY
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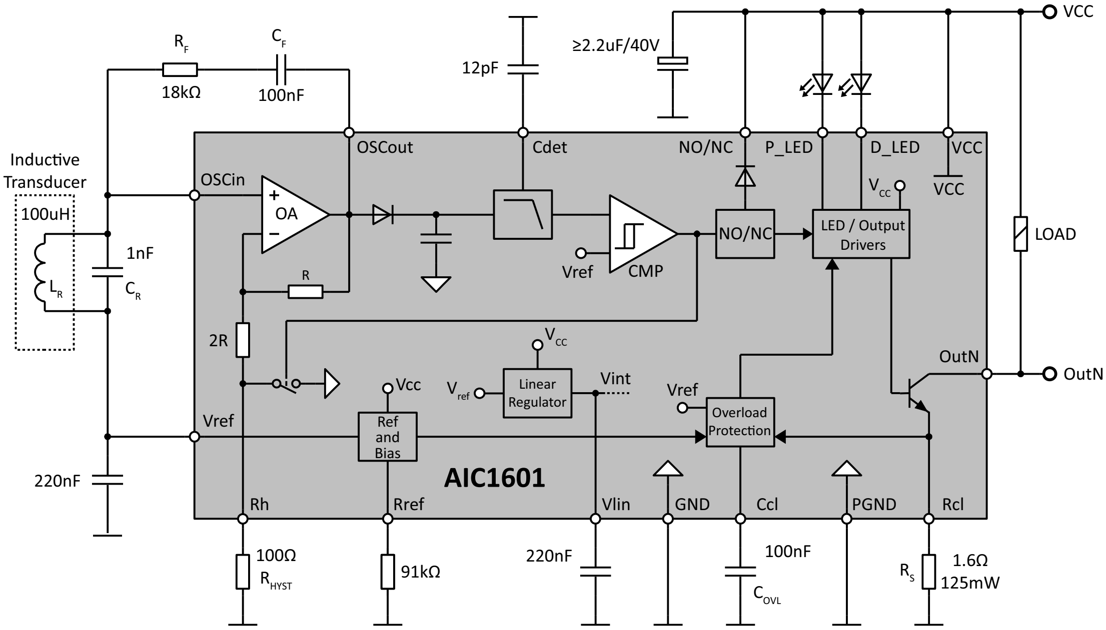
AN67

AIC1601 Inductive Proximity Sensor IC

EXAMPLE APPLICATION CIRCUIT

Figure 1: Example Application Circuit



PRINCIPLE OF OPERATION

The operation of the AIC1601 integrated proximity detector is based on reduction of the Q-factor of a parallel LC resonant circuit (LC tank) caused by a conductive (metal) object invading the inductor’s stray field.

Figure 2: Simplified Equivalent Circuit Diagram of LC Tank

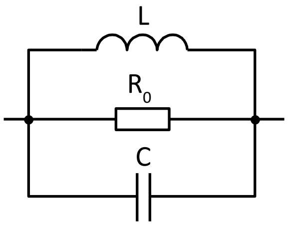


Figure 2 shows a simplified equivalent circuit diagram of an LC tank. L and C are ideal components and R_{res} simulates all losses of real components. At its resonant frequency the currents through L and C fully compensate and the LC tank behaves like a resistor R_0.

The LC tank's resonant frequency is:

$$fres = \frac{1}{2\pi\sqrt{LC}}$$

and its quality factor Q, i.e. the ratio of resonant frequency over -3dB bandwidth, is given by:

$$Q = R_0\sqrt{\frac{C}{L}}$$

Figure 3 shows an equivalent circuit diagram of a real inductor with the winding resistance R_L and the parasitic winding capacitance C_{par}. Actually, RL also contains the losses of the magnetic core which is typically mandatory for proximity switches.

Figure 3: Equivalent Circuit Diagram of Real Inductor

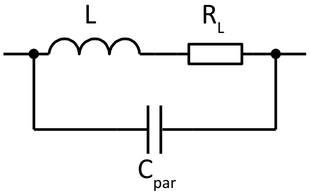


Figure 4: Equivalent Circuit Diagram of Real capacitor

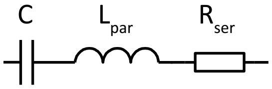


Figure 4 shows an equivalent circuit diagram of a real capacitor with the series resistance R_{ser} and the parasitic inductance L_{par}.

When using a high-quality foil capacitor for the LC tank its parasitic components R_{ser} and L_{par} may be neglected. In most cases C_{par} of the inductor is also negligible, since it is paralleled to the much bigger capacitor of the LC tank. Thus, R_L is the only relevant component that defines the Q factor. In the region around the resonant frequency R_L can be transformed into an equivalent parallel resistor R_0:

$$R_0 = \frac{1}{R_L} \times \frac{L}{C}$$

Inserting equation 3 into equation 2 yields the quality factor:

$$Q = \frac{1}{R_L}\sqrt{\frac{L}{C}}$$

Consequently, low R_L and/or a high ratio L/C is necessary to achieve a high Q factor. A high Q factor in turn allows the detection of a relatively low impact on the resonant resistance caused by the target, and thus a wide proximity detection range.

The alternating magnetic field causes eddy currents in the conductive object (called target) and thus power dissipation which is taken from the magnetic field. Inductor and target can be considered as a transformer with small coupling factor where the inductor is the primary winding, and the target is a shorted single turn secondary winding. The coupling factor k depends on the shape of the inductor's stray field and the target's geometry and increases with the target getting closer.

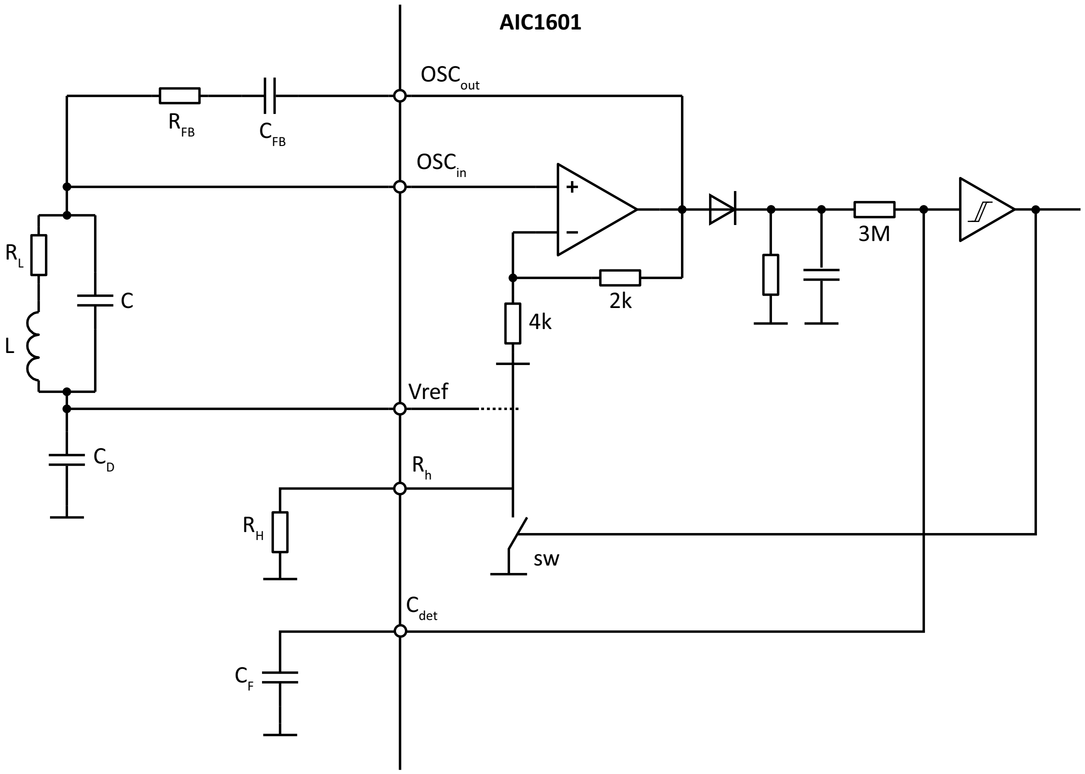
The eddy currents transform into a "resistive" (i.e. in phase with the voltage across the inductor) primary current according to the winding ratio n_{sec}/n_{prim} times k, where n_{sec}= 1. In other words: the target transforms into a resistor in parallel with the inductor.

Additionally, to the equivalent primary resistor, the "shorted secondary" reduces the primary inductance according to the coupling factor k. E.g. k = 0.1 means that 10% of the primary inductance is "mutual inductance" with the secondary (i.e. an ideal transformer), and since the secondary is shorted the primary inductance reduces by 10%. This leads to an increasing resonant frequency (by 4.9%). Since in this application the LC tank is excited on its resonant frequency the frequency change can be ignored.

OSCILLATOR

The AIC1601 contains an internal operational amplifier which is used to excite the LC tank on its resonant frequency. The op-amp's bandwidth allows operation of the LC resonant circuit up to a frequency of 1MHz.

Figure 5: Oscillator and Detection Circuit



If the switch “sw” is closed the op-amp’s gain is internally set to:

$$g = 1 + \frac{2k\Omega}{4k\Omega} = 1.5$$

Its non-inverting input is connected to the “hot” side of the LC tank. The “cold” side of the tank is connected to the IC’s internal reference voltage Vref of typ. 1.2 V, feeding a DC bias level to the op-amp’s input. A capacitor from Vref to ground provides a virtual ground potential for the “cold” side of the LC tank.

The output of the op-amp is fed back to the positive input via a decoupling capacitor C_{FB} and a resistor R_{FB}. C_{FB} avoids DC bias current through R_{FB} since the op-amp’s quiescent output voltage is 1.5 x Vref = 1.8 V. With a gain of 1.5 the AC voltage across R_{FB} equals half the voltage across the LC tank. When R_{FB} becomes smaller than 0.5 x R_0 of the LC tank the total feedback becomes positive and the oscillation amplitude increases exponentially until the op-amp reaches its internal supply limitation.

DETECTION CIRCUIT

As shown in figure 5 the output voltage of the op-amp is rectified and fed to a comparator via a low pass filter consisting of an internal 3 MΩ resistor and an external filter capacitor C_F. A low value of C_F enables fast sensor reaction while a high value increases robustness of the application. As a rule of thumb the cut-off frequency of the low pass filter should be in a range of 50 to 150 times lower than the sensor frequency. C_F can be calculated by:

$$C_F = \frac{1}{2\pi f_{cutoff} \times 3M\Omega}$$

If e.g. the sensor frequency is 500kHz, the recommended cut-off frequency range would be 3.3kHz to 10kHz giving a range for C_F from 15.9pF to 5.3pF (15pF to 4.7pF, considering standard values). In case C_F is calculated only a few pF the pin Cdet might as well be left open.

The comparator output drives the output state. The pin NO/NC (normally open/normally closed) defines whether it turns on (NO/NC left open) or off (NO/NC to gnd) when a target is detected.

HYSTERESIS

A hysteresis can be added to avoid toggling of the output e.g. caused by mechanical vibration if the target stops right at the detection distance. An external resistor R_H (see figure 5) reduces the op-amp's gain once the oscillation amplitude has dropped below the detection threshold and sw opens, thus additionally reducing the oscillator's drive current. The drive current is proportional to the current through the internal 2k resistor (same AC voltage drop) which is identical to the current through the 4k resistor. Thus, increasing the 4k resistor by e.g. 10% = 400Ω reduces the drive current by roughly 9.1% (1/1.1 = 0.909…).

It must be noted that a wide hysteresis reduces the possible detection distance. When the target is removed, the reduced drive current has to be high enough to get the oscillation started again. Therefore, with no target present the resistor R_{FB} should, starting from a high value, be reduced until the oscillation starts and the device detects the absence of the target in order to determine the maximum value of R_{FB}.

Recommended values for R_H range from 100Ω to 500Ω, resulting in a reduction of the oscillator's drive current between 2.4% and 11.1%, respectively.

DETECTION RANGE AND PRODUCTION TOLERANCES

The sensor's achievable detection range is determined by the geometry of the inductor on the one hand and by the LC resonant circuit's Q factor on the other. Ferrite pot cores have become the standard for proximity sensors since their magnetic stray field is well directed perpendicularly on the “open” side of the core, while the core itself shields the sensor coil from undesired impact along its back and sidewalls.

The size of the core, mainly its diameter, determines the range of the magnetic stray field in which a target produces a noticeable change of the sensor coil's impedance suitable for stable detection. Basically, bigger cores are needed for greater detection distance. Achievable distances are in the order of 50%, with optimized components up to 75% of the coil diameter for a robust design.

On the electrical side a high Q factor of the resonant tank is advantageous since it allows detection of a relatively high “transformed resistance” caused by a target at some distance. Q is mainly determined by L, C, and RL, the latter being not only the resistance of the inductor's copper winding but also representing the losses of the ferrite core. According to equation 4, Q increases with $1/R_L$ and with the square root of L/C. Unfortunately, component dimensioning is always a trade-off. Increasing L by increasing the number of turns simultaneously increases R_L (both as a square function of the number of turns n, assuming the winding area is fully utilized). Increasing the frequency “automatically” increases L/C for a given inductance, so this is a first step in the right direction. Nevertheless, care must be taken because higher frequencies may lead to higher effective winding resistance caused by skin and proximity effects. Furthermore core losses increase non-linearly with frequency, which also increases R_L. Using ferrite material with low losses at high frequency typically comes along with lower magnetic conductivity ($\Rightarrow$ small AL value) which leads to a higher number of turns for a given inductance.

Many state of the art proximity switches operate in a frequency range between 100kHz and 1 MHz. This is also the range covered by the APEX AIC1601.

Resistors with a tolerance of 1% have widely become standard as well as capacitors with 10% tolerance or better. The accuracy of inductors is typically worse especially when the mechanical dimensions are small. For maximum or precise switching distance it may be necessary to trim R_{FB} for each sensor individually. In case the requirements are more relaxed it may be sufficient to identify R_{FB} for each individual production lot of sensor coils and apply some margin, i.e. reduce the value of R_{FB} appropriately.

TEMPERATURE EFFECTS

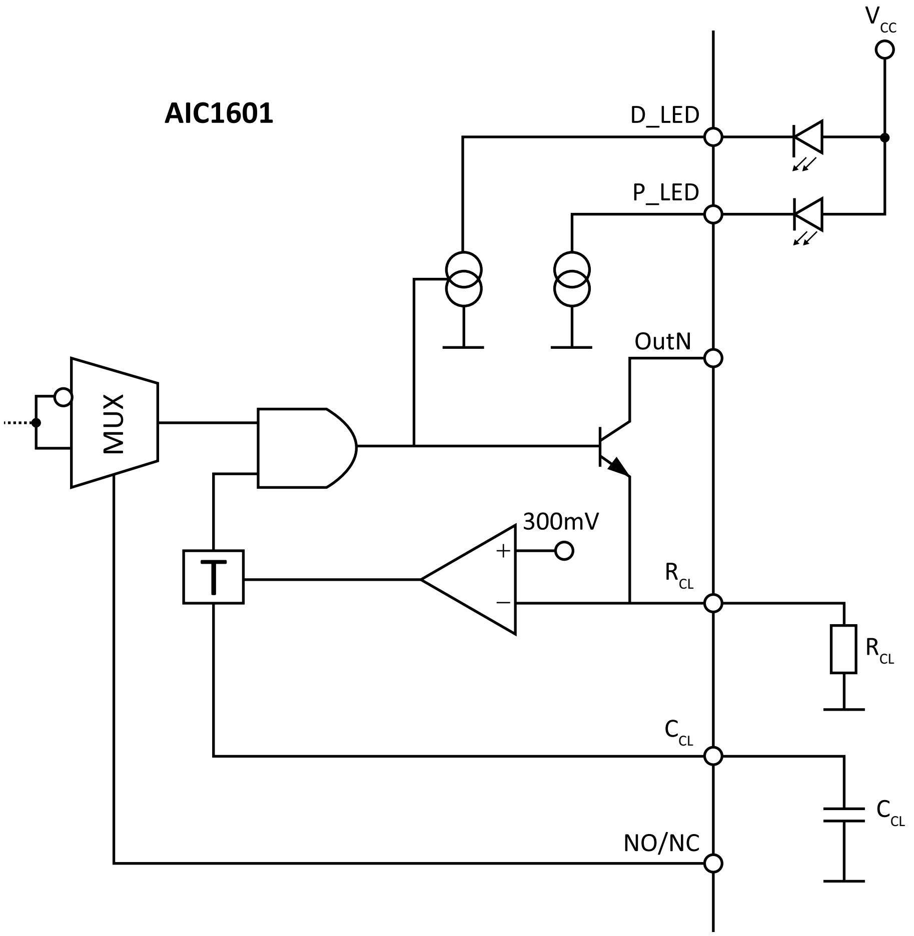
APEX AIC1601 features internal temperature compensation of voltages and currents. However, the external components will cause some temperature dependency of the switching point. Switching distance is reached when the resonant resistance of sensor equals twice the feedback resistor R_{FB} (see chapter 3, Oscillator). The resonant resistance is the parallel connection of the “intrinsic” resistance of the resonant circuit and the transformed resistance of the target (see chapter 2, Principle of Operation).

When temperature increases, both the winding resistance of the coil and the losses of the magnetic core increase. Consequently, the Q factor and thus the intrinsic resistance are reduced. Higher temperature of the sensor typically goes together with higher temperature of the target. The reduced conductivity of the target material reduces eddy currents and thus leads to a higher transformed resistance in parallel with the LC tank's intrinsic resistance.

Advantageously, these two effects point in opposite directions, so they partially compensate. Temperature compensation works quite well as long as the total resonant resistance does not come too close to the intrinsic resistance. In other words: there should be some margin between the actual and the maximum achievable switching distance. As mentioned in chapter 6, the reasonable switching distance for a robust design lies between 50% and 75% of the coil diameter, depending on the sensor's Q factor.

OVERCURRENT PROTECTION

Figure 6: Apex AIC1601 Over Current Protection Circuit



The over current protection prevents damage of the output transistor in case of a short or a low resistive connection to a positive voltage, e.g. to VCC. An external resistor R_{CL} is connected from the emitter of the output transistor to gnd. The voltage drop across R_{CL} is compared to an internal threshold voltage of 300mV. The over current trip point is thus given by:

$$I_{CL} = 0.3\frac{V}{R_{CL}}$$

When the threshold is exceeded the output transistor is switched off after a delay of typically 8µs. During this period the transistor can drive a current in the order of 500mA. Simultaneously, an external capacitor C_{CL} gets discharged. C_{CL} will thereafter be charged by an internal current of typically 1.2µA, and when the voltage reaches 1.7V the output transistor is turned on again. C_{CL} defines the off-time given by:

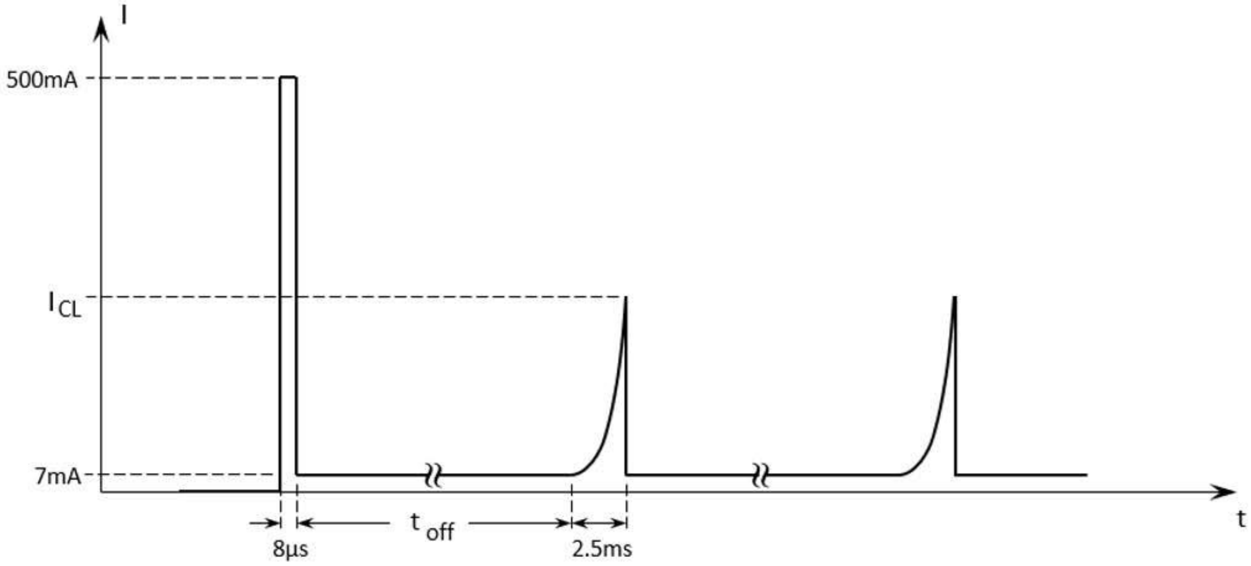
$$t_{off} = 1.7\frac{V \times C_{CL}}{1.2\mu A}$$

E.g., C_{CL} = 22nF leads to t_{off}= 31ms.

During t_{off} a small DC sink current of typically 7mA is drawn from OUTN to gnd. This current supports charging of a capacitive load on OUTN which might have caused the shut-off of the output.

After t_{off} has elapsed the output transistor is turned on again. Output current gradually increases to its maximum in case the overload condition is still present. Assuming the current limit is set to 200mA the current increases within 2.5ms to this value featuring a hyperbolic current shape.

Figure 7: OUTN Current When Turning on in Continuous Overload Condition (Not to Scale)



The gradual increase of the output current allows driving a combination of resistive and capacitive load even if the capacitor has several µF, as shown in figure 9. In case the resistive load current is < 7mA there is actually no limitation for the capacitor value since it can be charged by the off-current plus the on-current during repetitive cycles.

Figure 8: Turning on a Load with Significant Capacitance of Several µF (Not to Scale)

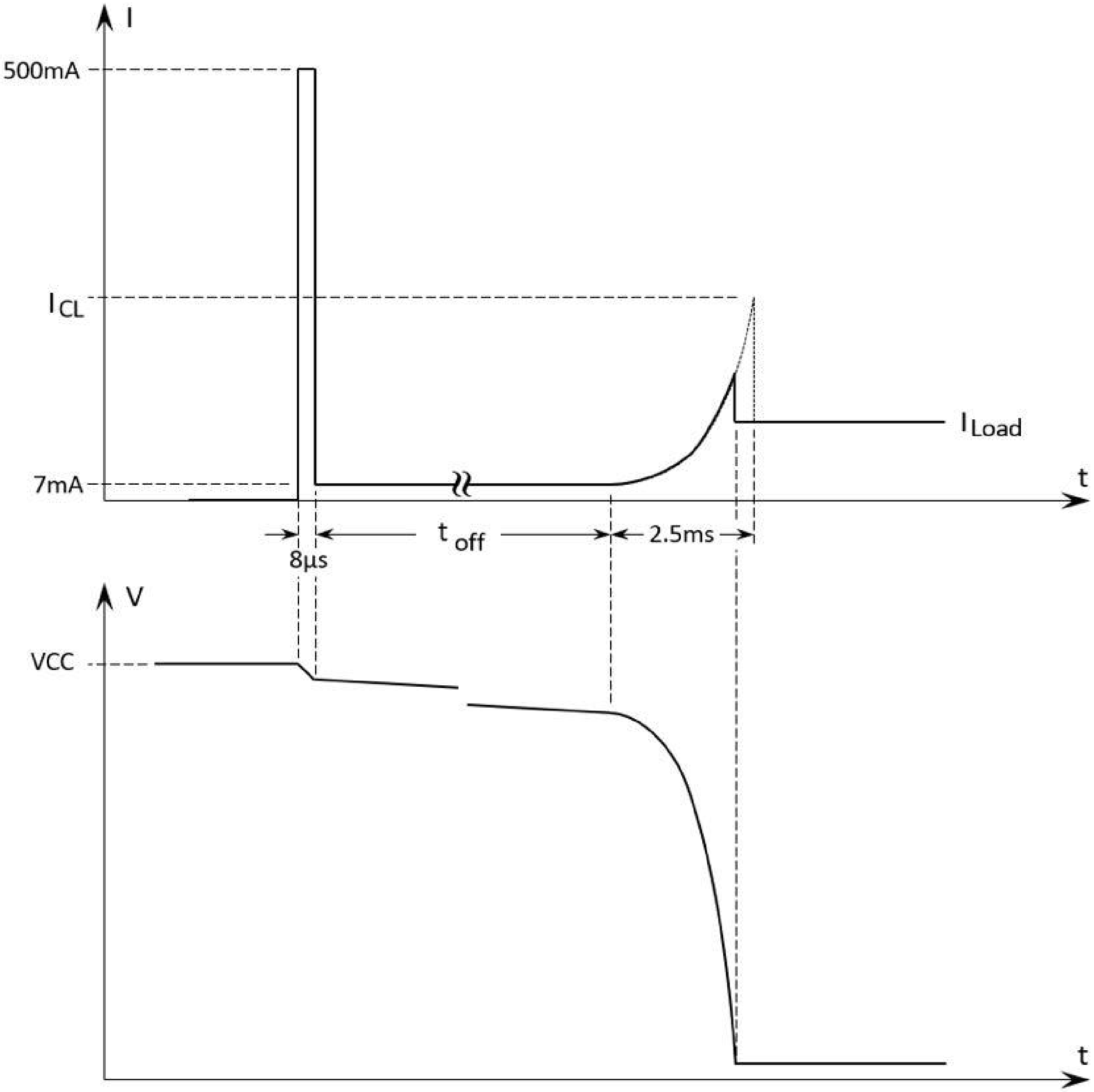


Figure 9 shows the situation when turning on a load with a significant capacitive component. During the first current pulse the voltage on OUTN drops by approximately:

$$\Delta V_{OUTN} = 8\mu s \times 0.5\frac{A}{C_L} = 4\frac{\mu As}{C_L}$$

For a capacitor of e.g. 4µF eq. 9 yield ΔV = 1 V.

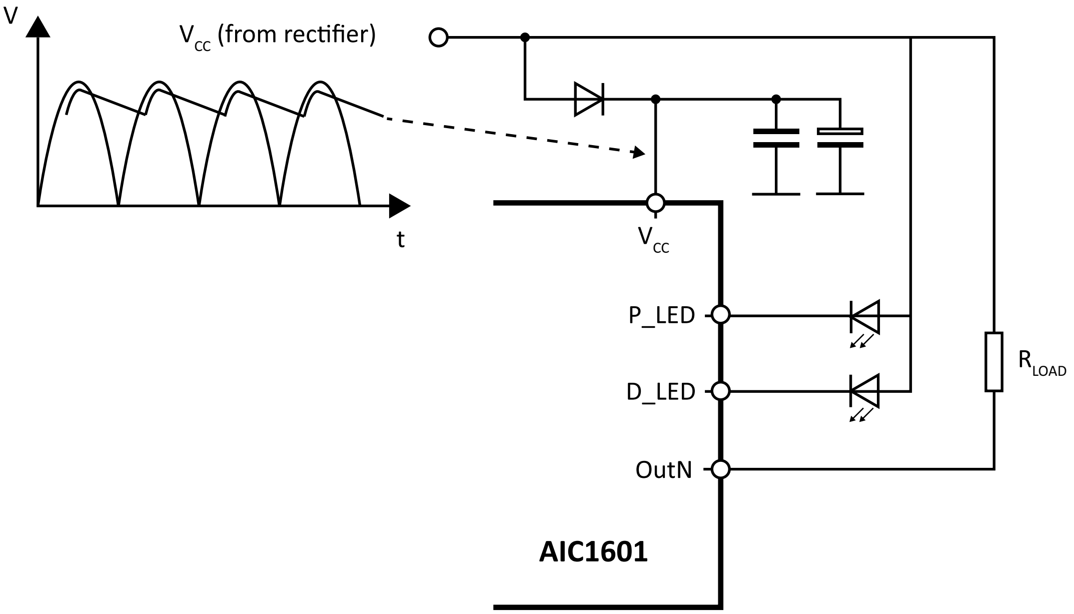
During t_{off} the combination of R_L and C_L causes exponential charging or discharging to a source voltage which is 7mA x RL lower than VCC.

After t_{off} has elapsed the transistor is turned on smoothly again. During the maximum on-time of approximately 2.5ms (I_{CL} = 200mA) the available charge to drive the load is in the order of 180µAs . Assuming the resistive part of the load requires no more than half of the charge there is 90µAs left to charge the capacitor. A 4µF capacitor could be charged by up to 22.5V.

SUPPLY VOLTAGE

In case there is high ripple on the power supply it is recommended to decouple the IC's supply voltage by means of a diode and a capacitor to gnd. An electrolytic capacitor of 10µF or more would be a good choice if the ripple is caused by 100Hz or 120Hz rectified AC voltage. A ceramic capacitor of 100nF connected in parallel should be added for improved HF rejection.

Figure 9: Supply Voltage Ripple Rejection



PNP OUTPUT

Figure 10: Simple High Side Output Without Overload Protection

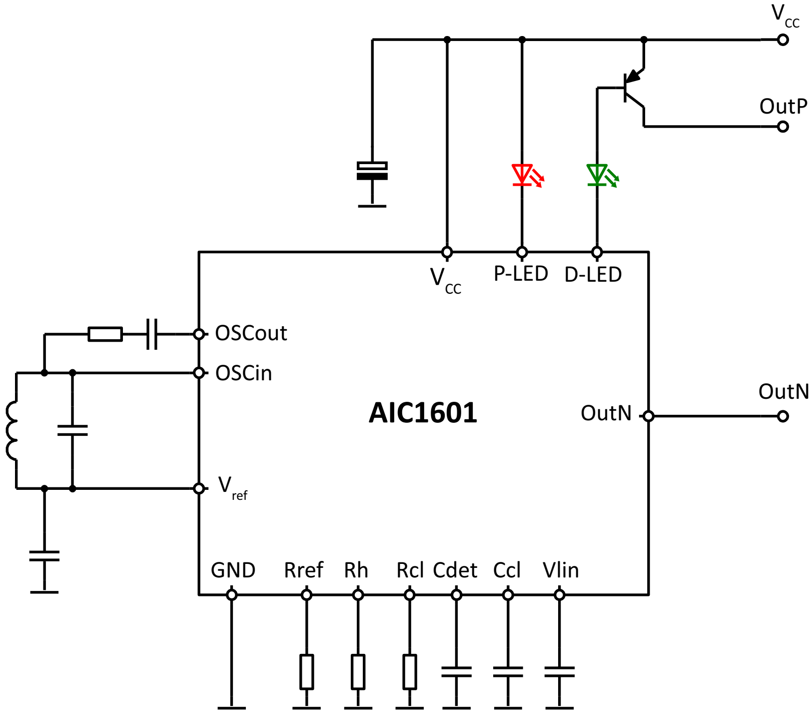
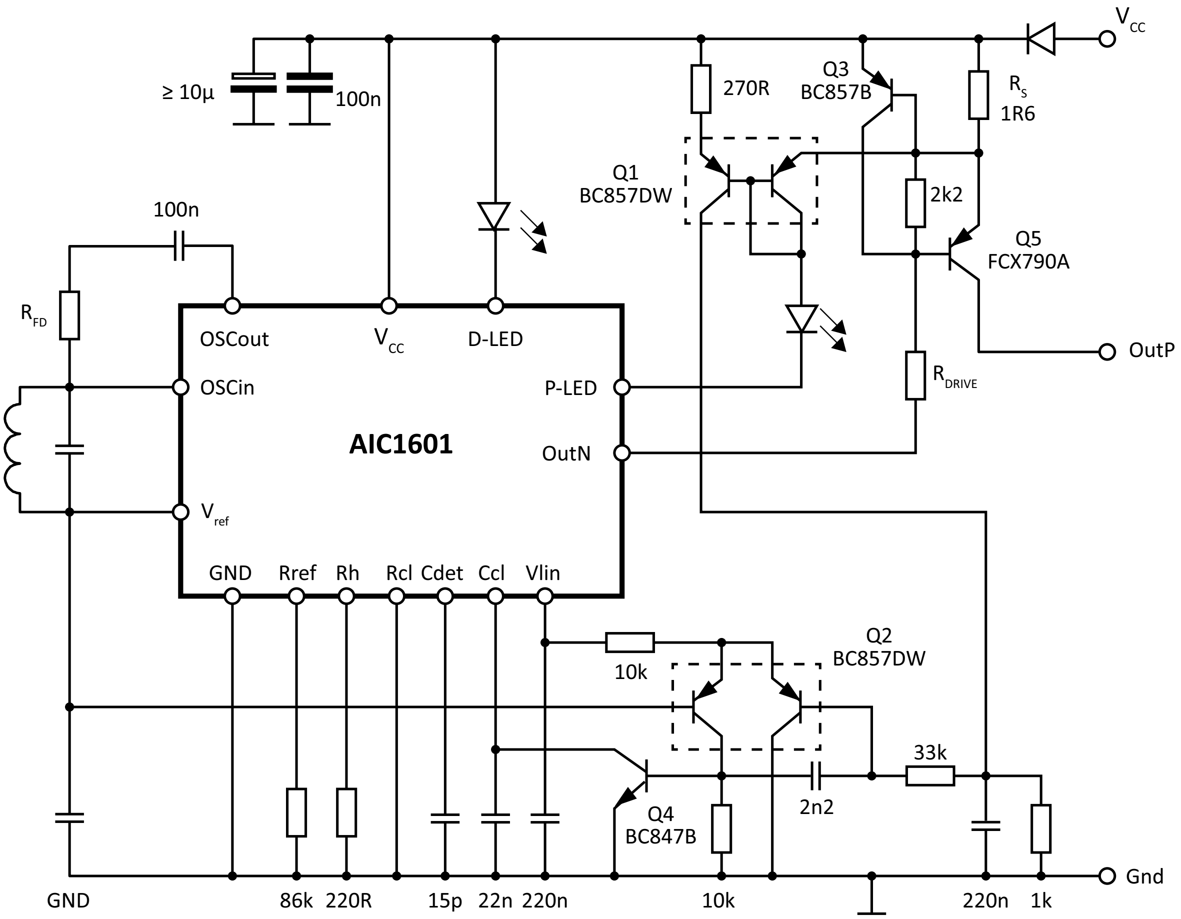


Figure 11 shows a simple realization of a high side output. The base of a pnp transistor is driven by the current through the detection LED which is typically 1.2mA. A resistor in parallel with the base-emitter diode avoids amplification of the LED output's leakage current in off-state. The resistor should be 10kΩ or higher in order to take only a small fraction of the LED drive current away from the transistor's base.

This circuit should only be used if any overload condition of the high side output can be excluded since it does not feature overload protection.

Figure 11: High Side Output with Accurate Over Current Threshold and Overload Protection



The circuit in figure 11 features a high side pnp output with overload protection. The pnp pair Q1 amplifies the voltage drop across the high side shunt resistor Rs and shifts it to gnd reference level. The pnp pair Q2 compares this voltage with the AIC1601's internal reference voltage Vref of typically 1.2 V. Q4 pulls the voltage on the timing capacitor CCL low and the output OutN is turned off without activating the 7mA sink current (this happens only after the voltage on Rcl has exceeded 300mV).

OutN provides the base current for the pnp output transistor Q5. Rdrive should provide 2mA base current at minimum supply voltage. In case a different type of transistor is used the drive current has to be adapted according to the transistor's minimum current gain at an output current somewhat higher than the over current trip point, which is typically 300mV/Rs.

Q3 senses the voltage across Rs. When its base-emitter threshold voltage is exceeded it pulls the base voltage of Q5 high. This limits the output current to approximately twice the over current threshold at room temperature until the over current shut-off pulls in. This current limit has got a negative temperature coefficient in the order of 0.35%/K.

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