Power Supplies & Signals Conditioning in Low Voltage MCU Motor Control Application

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1. Abstract

Power management is of extreme importance to small, portable battery powered appliances, such as electric razors, electric toothbrushes and hand held fans. This paper discusses the design considerations which should be taken into account when moving a motor control application, based on a microcontroller, from 5 V to 3.3 V technology and how that shift affects these appliances.

The challenge is to provide an adequate power supply and suitable control signals to the 3.3 V microcontroller and also provides power, and signal measurements from the low voltage microcontroller, to the legacy 5 V peripherals. Advantages and disadvantages of different types of power supplies and interfacing of motor control parts will be discussed.

2. Interfacing to Motor Control Parts

A motor drive system, controlled by an MCU, includes the power supply stage, the power transistors and their gate drivers and the motor.
The AC input line is rectified in the input power supply stage and it provides the DC voltage for switching the power transistors that deliver the power to the motor.

The transition from 5V to 3.3V for motor control applications needs to be considered both for the analogue and digital signals.

2.1 Analogue Signals

In motor control applications the feedback signals are typically analogue in nature. Most motor control applications utilize voltage and current feedback for control algorithms and safe operation. The auxiliary feedback signals, like temperature sensing, depend on the requirements of the actual application.

A voltage measurement (e.g. back emf) is commonly used as an indication of motor speed. This signal is digitized by the microcontroller's on-board A/D converter. Resistor dividers are used to ensure that the voltage at the input of A/D converter (MCU pins) does not exceed the maximum rated voltage (Figure 2.1a). The two (and sometimes three) resistors R1 and R2 are normally used for high motor voltage. It is necessitated because of the maximum voltage rating of the resistors. For lower voltage motor control applications, even a single resistor is usually sufficient. Moving to a lower MCU operating voltage will not have any impact on 3.3 V MCU applications.

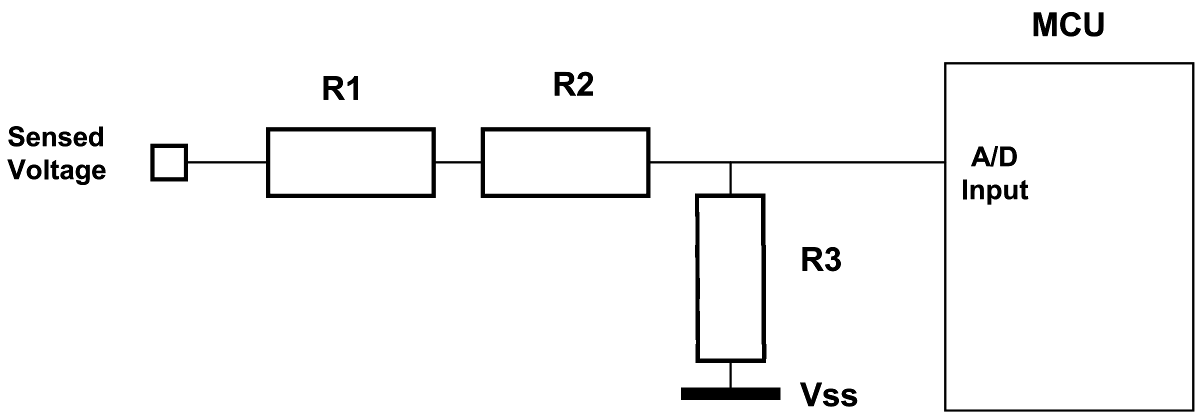

Fig 2.1a Voltage Sensor

Current sensing is used for motor over-current protection as well as determination of accurate back emf voltage. A current sensing resistor is often used in low-cost applications (Figure 2.1b). This resistor is placed in the ground return path of the DC-Bus lines for DC-Bus current measurement, or in the individual legs of the inverter bridge for phase current measurements. The voltage drop created on the current sense resistor is amplified using an operational amplifier. The gain of the operational amplifier is set to get the output signal in the MCU voltage range reference, i.e. 0V – 5V, 0V – 3.3V.

The output voltage for zero input current is set to the middle of the ADC range by the Voltage GND level, which is usually derived from a reference voltage generator.

Compared to 5V systems there is no change except that the chosen operational amplifiers must operate on 3.3V single supply with rail-to-rail output. Among suitable amplifiers are the On Semiconductor MC3320x and the MC3350x rail-to-rail types.

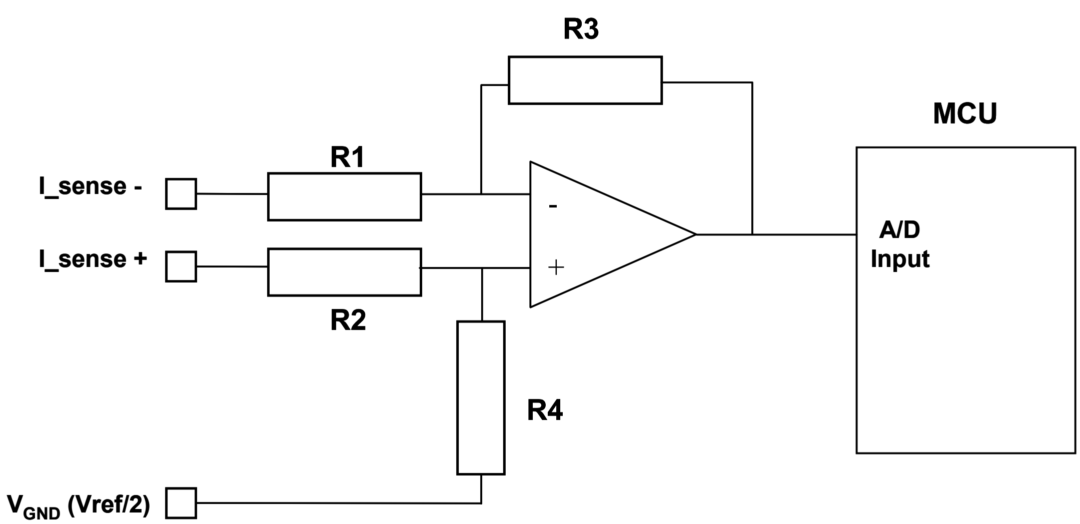

Fig 2.1b Current Sensor

2.2 Digital Signals

In motor control applications the MCU input signals serve as a user interface (i.e. switches, push buttons), communication and detection of state of control/feedback signals (i.e. zero crossing detection, enable signal, etc.).

Compared to 5V systems, the input signals need to be adjusted to the 3.3V level and the implementation of this adjustment depends on the actual signal circuitry.

The main objective for interfacing circuits is to avoid over voltages on 3V inputs (and outputs for bi-directional pins), which are connected to 5V outputs and limit the current flowing from 5V parts.

Input pin structures usually contain ESD protection diodes, which clamp input voltages when they go below V_{SS} (GND) or beyond V_{DD} levels.

For a 5V output being applied to a 3V input, when the maximum input voltage is exceeded on the 3V input, the ESD protection diode on the input of the device can be forward biased and current will flow into the 3V V_{DD}. This could take the voltage level of the 3V power supply up to the input voltage minus the voltage drop across the protection diode. Therefore, this difference in voltage will cause a high current to be drawn (near enough short-circuit), which will provide heat and possible long-term reliability problems.

To avoid such problems, the voltage on inputs should not exceed V_{DD3} + 0.5V in order not to conduct the clamping diode. This means that for 3V minimum (V_{DD3min}) voltage the maximum input voltage V_{Imax} will be 3.5V. In many cases, the easiest work around when interfacing a 5V TTL output to a 3V MCU input is to use simple series resistors, which limit currents flowing into 3V inputs, but usually these can add delays and board space. So care should be taken in choosing the correct resistor value as if too high a value is chosen it can cause significant signal propagation delay because of the RC constant created by the resistor and the input capacitance, which is typically about 5-10 pF plus the PCB capacitance.

Also, excessive current increases the power consumption because the current flows into the MCU input when the driving component is outputting a logic high.

When interfacing a 5V CMOS output to a 3V MCU input the maximum differential voltage for logic high in the worst case, which is for V_{DD5max} = 5.5V and for V_{Imax} = 3.5V, it is 2V. Also in this case it is possible to use a series resistor with a larger value, but this may probably lead to higher propagation delay. A better solution is to use a resistor divider network between the CMOS output and the MCU input such that a signal voltage level of logic high appears at the input at approximately 3.0V.

Another level conversion from a 5V output (TTL or CMOS) to a 3.3V MCU input circuit can employ a device from the LCX logic family powered at 3.3V, which has 5V tolerant inputs (V_{Imax}=5.5V), or one from the LVX family, which has V_{Imax}=7V.

In motor control applications the MCU output signals serve as user interface (LED, display), communication and control signals (IGBT / MOSFET control, Triac control, etc). The IGBTs / MOSFETs and Triacs are key control parts in motor control applications, so the implication of moving to lower operating voltages will be analysed in detail in the following paragraphs.

2.2.1 Controlling IGBTs & MOSFETs with Drivers

IGBTs and MOSFETs are mostly used in the power stage design. Both types of power switches are controlled in the same way using high side and low side drivers.

The input characteristics of the drivers are very important for the power stage topology and its interface to 3.3V control signals.

The logic level requirement that is the key factor for the selection of the driver type is “1”, because the logic level “0” requirement is near to the ground voltage and it is satisfied by all types of drivers.

For direct interfacing to a 3.3V MCU, the driver logic “1” threshold level, V_{IH}, should be well below 3.3V. This condition is met by drivers which have TTL compatible input levels with $V_{IH} < V_{DD3min}$ (3.0V), like for example the IR2181, from International Rectifier, that has V_{IH} = 2.7V.

For other types of drivers with logic “1” input voltage = V_{DD3min} a level shifter needs to be used in order to prevent the current leakage.
For CMOS technology the input switching levels are defined as:
$V_{IL} <= (0.3 * V_{DD})$, and $V_{IH} >= (0.7 * V_{DD})$.
Therefore for 5V V_{DD} the maximum input level for logical "0" must be <= 1.5V and the minimum input level for logical "1" must be >= 3.5V.
A simple resistor and diode is sufficient to provide a 0.6V upward level shift of the MCU output's voltage.

2.2.2 Controlling MOSFETs without Drivers

Small power MOSFETs can sometimes be driven directly without drivers, such as the IR2181 and similar. In these circumstances, because of the large MOSFET gate capacitance, the transient response is considerably slower than when a driver IC is used. This is due to the fact that a MCU has a lower output current and voltage rating compared to the output of a driver, therefore this solution is appropriate only for slow changing outputs, i.e. controlling lamps, solenoids, etc. Also if the transition from the on to the off state and vice versa is slow, switching losses increase and they have to be taken into account during design.

For direct driving, the MOSFET used should have a gate threshold voltage V_{GTH} well below V_{DD3min} (3.0V). Among suitable MOSFET types are the On Semiconductor MMDF6N03HD dual 6A N channel MOSFET in SO8 package and similar types and the International rectifier IRF7501 dual N channel MOSFET in Micro8 package with $R_{DS(ON)}$=0.135ohm at V_{GS}=2.7V and others marked as "3V drive" types.

2.2.3 Driving TRIACs

Driving of TRIACs does not bring any issues for 5V to 3.3V transition, except that the value of R1 in Fig 2.2.3 should be lowered compared to that in a 5V system in order to have enough TRIAC gate current.

The number of MCU pins to use should be chosen according to the driving capability of the MCU outputs to comply with the TRIAC minimum gate current requirement, which is 15mA for MAC4DC type for example. The circuitry on Fig. 2.2.3 has a galvanic connection to the power outlets.

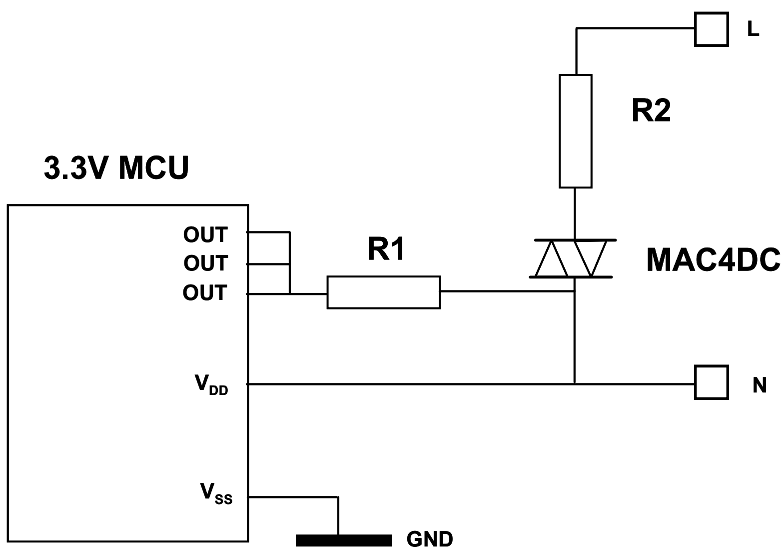

Fig 2.2.3 Driving of TRIAC

When galvanic isolation is necessary the standard opto-triac or opto-coupler can be used for connection to the TRIAC. With 3.3V MCU the situation is the same as in the 5V system, only the resistor limiting the opto-coupler current should be lowered to get the same driving current as in the 5V system.

The situation is similar for driving LEDs, although considering that the LED forward voltage drop is in the range of 1.6-2V there is a smaller headroom for the MCU output pin voltage drop compared to 5V system. Therefore the output characteristic of the MCU must be taken into consideration in these circumstances.

3. Power Supplies for Low Voltage Systems

The challenge is to provide a power supply that will satisfy the new technology, operating at 3.3 V and also provide power for legacy 5 V devices. The 3.3 V power supply may be either a switching or a linear design. For most applications, a linear regulated power supply minimizes the number of additional components.

3.1 Linear Voltage Regulators

Linear voltage regulators are the simplest to design, as they do not require any magnetic components, and are much more forgiving from a standpoint of printed circuit layout and grounding requirements. Linear voltage regulators are not as efficient as switching voltage regulators. The linear voltage regulator operates by reducing a higher input voltage to a lower output voltage by linearly controlling the conduction of a series pass power device in response to changes in the output load. This results in a voltage being dropped across the series pass device with the load current passing through it. Because of the voltage drop across the series pass device, the linear voltage regulator may be only 30 to 50 percent efficient. Linear voltage regulators become somewhat uneconomical above 10 W due to a significant increase in the heat sink requirements.

For a hybrid 5 V-3 V system it is reasonable to use a 5 V regulator, which supplies 5 V logic, and derive the 3.3 V for the rest of the system from it. As there are only 1.7V of drop between the 5 V power supply and the 3.3 V power supply, a low dropout regulator is a necessity. Typically low current linear voltage regulators supplying less than 500 mA use PNP pass transistors. A PNP pass transistor linear voltage regulator usually requires about 500 mV of dropout. Modern designed low dropout voltage regulators utilize FET transistors as the pass transistor, yielding dropout voltages of less than 100 mV. Higher current output linear voltage regulators typically use a NPN pass transistor and their dropout voltage is typically greater than 1 V. An advantage of deriving the 3.3 V necessary for the system from the 5 V regulated power supply is the increased ripple rejection from the 5 V pre-regulation device.

There are a number of semiconductor suppliers manufacturing both adjustable and fixed linear voltage regulators. The following table is a partial list of 3.3 V linear regulators:

Manufacturer	Part Number	Output Current	Dropout Voltage	Tolerance
ON Semiconductor	MC78PC33NTR	150mA	300mV	+-2%
ON Semiconductor	CS5201-3L	1.0A	1.2 V	+-1.5%
ON Semiconductor	CS52015-3L	1.5A	1.4V	+-1.5%
ON Semiconductor	CS5203-3L	3A	1.15V	+-1.5%
ON Semiconductor	CS5206-1GT3	6A	1.3V	+-2%
ON Semiconductor	CS5207-3GDP3	7A	1.4V	+-2%
National Semiconductor	LM2936DT-3.3	50mA	200mV	+-3%
National Semiconductor	LM3940IT-3.3	1A	500mV	+-3%
Linear Technology	LT1121N8-3.3	150mA	400mV	+-3%
Linear Technology	LT1086CT-3.3	1.5A	1.5V	+-2%
Linear Technology	LT1085CT-3.3	3A	1.5V	+-2%
Linear Technology	LT1083CK-3.3	7.5A	1.5V	+-2%

Typically, in a linear voltage regulator design, the input bypass (bulk) capacitor is placed close to the input terminal of the regulator. The input bypass capacitor provides a low impedance source into the voltage regulator. Typical input bypass capacitors are in the 5 uF to 100 uF range. Connected to the output side of the voltage regulator will be another bulk capacitor (output bypass), in the range from 1 uF to 100 uF. This capacitor helps stabilize the regulator during current transients until its internal control loop can take over. It is also standard practice to bypass the logic elements, connected to the 3.3 V voltage regulator, with small bypass capacitors located close to their power leads. These small bypass capacitors help provide a low impedance power source during very fast transient current demands. Depending on the frequency of the transients, the value of these capacitors will range from 100 pF to 1000 pF. Figure 3.1 shows a schematic for a typical linear voltage regulator.

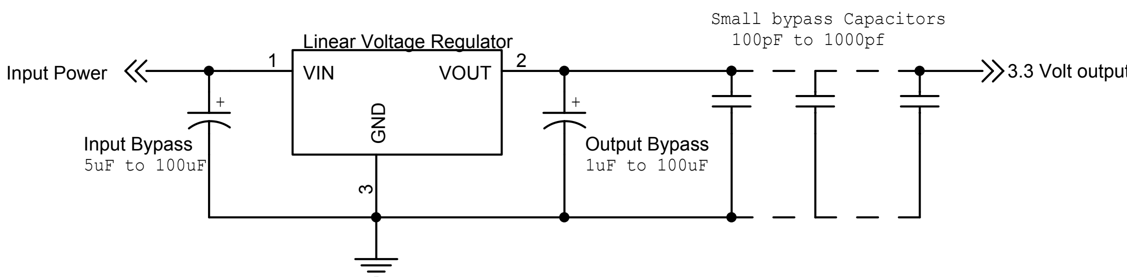

Figure 3.1 Typical Linear Regulator Schematic

3.2 Switching Voltage Regulators

Switching regulation is accomplished by the control of the on-time and off-time ratio of the pass transistor in a fast switching technique. Therefore the switching voltage regulator operates the power device in a full-on or full-off mode. This control technique is known as pulse width modulation (PWM) and is commonly working at switching frequency above 20 kHz.

Switching voltage regulators have a distinct advantage over linear ones in that their efficiencies can exceed 90%. This operation mode results in much lower power being dissipated across the power device. Switching power supply regulators become very cost effective when used for output powers greater then 10 W. The disadvantage of a switching voltage regulator is that it requires more components, including magnetics, than a linear design and is less forgiving from a printed circuit board layout and grounding prospective (most switching regulators do not provide isolation between the input and output circuits). Similar to linear regulators, a switching regulator in a typical system is powered by an input voltage that is much higher than the output voltage. In a typical 3.3 V only system, its power supply will use some voltage source greater than 3.3 V and then regulate it down to 3.3 V. A step-down, or buck converter, will be used in the application. Input bulk capacitors and output bypass capacitors used in switching design follow the same configuration as those in linear voltage regulators.

The following table is a partial list of switching voltage regulators appropriate for use with 3.3 V circuits from a few manufacturers:

Manufacturer	Part Number	Output Current	Ext. MOSFET Required
ON Semiconductor	LM2575D2T-3.3	1A	No
ON Semiconductor	LM2576D2T-3.3	3A	No
ON Semiconductor	MC33163P	3.6A	No
National Semiconductor	LM2574-3.3	500mA	No
National Semiconductor	LM1575-3.3	1A	No
National Semiconductor	LM2655-3.3	2.5A	Yes
National Semiconductor	LM2576-3.3	3A	No
Linear Technology	LTC1701	500mA	No
Linear Technology	LTC1878	600mA	No
Linear Technology	LTC1772	2.5A	Yes

Figure 3.2 shows a basic schematic for a switching voltage regulator containing an internal MOSFET power device.

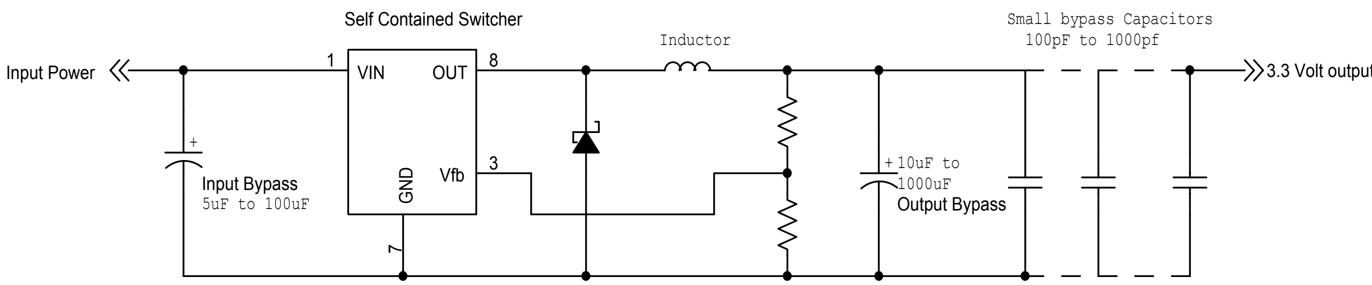

Figure 3.2 Typical Step-down Switching Voltage Regulator Schematic With Internal MOSFET

Figure 3.3 shows a basic schematic for a switching voltage regulator using an external MOSFET power device.

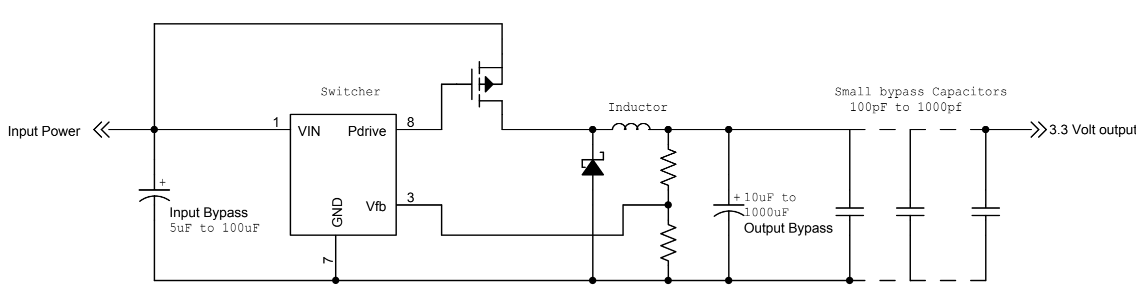

Figure 3.3 Typical Step-down Switching Voltage Regulator Schematic With External MOSFET

In summary, designing a power supply for 3.3 V microcontroller systems requires looking at the system as a whole. Power requirements of the system will dictate if a linear or switching voltage regulator will satisfy the system's power requirements. Most systems will have 3.3 and 5 V logic mixed in them. Deriving small amounts of current for the 3.3 V portion of the system from the 5 V regulated power supply with a linear voltage regulator is a simple choice. In the case where higher amounts of power are necessary for the 3.3 V portion of the system, a close look at a switching voltage regulator will be prudent. If the system only has the requirement for a 3.3 V power supply, the components in this document will suffice for those needs as well.

4. Outlook

This article discusses the design considerations, which should be taken into account when moving a microcontroller application from 5V technology to 3V technology.

Designers now moving from 5V to 3V technology will be required to create systems in an interim period using a mixture of both 5V and 3V components. During this transition time, components allowing the translation from 3V to 5V and vice versa will be needed.

The new generation of low voltage MCUs will bring various advantages, in fact it will be possible to reduce the power consumption, to have smaller on board power sources, to increase the operational lives of battery powered applications and to decrease the battery weight of portable applications; therefore an overall lower cost for the system.