Review and guidelines for voltage monitor based Energy harvesting power management

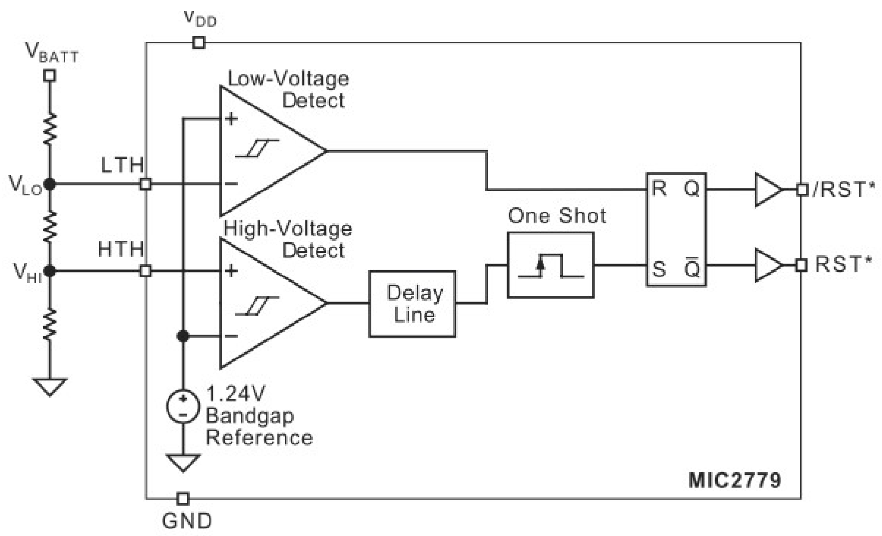
Introduction

In a typical energy harvesting system, it is necessary to charge a storage element to certain level before the application load can be activated. In a case of supercapacitor storage, the charge level is a function of voltage. In a battery storage system, the relationship between the voltage level and charge level isn't as straightforward, but voltage can still be used to get a rough idea of the available energy level. In either case, it is necessary to monitor the voltage level and react when a certain threshold has been reached.

Circuits typically used for detecting voltage levels are based on some sort of voltage comparator. These circuits use operational amplifiers and a voltage reference to determine when the storage element has reached the required threshold. We will look at three different ways of performing power management using a voltage comparator and a combination of two comparators that will form a window monitor. The third option is based on configurations without comparators that for example use specially designed MOSFETs with precise threshold voltages for this application. These solutions will be investigated in the end.

Window comparator power management

Window comparator voltage monitors are typically used in battery powered systems to power the load on and off based on the voltage on the battery. Image below shows a typical IC with a window comparator that can be also used for energy harvesting applications.



Internal schematic of the MIC2770 Voltage monitor with adjustable hysteresis.

These circuits have a high threshold voltage and low threshold voltage setting. The existence of two threshold voltages that can be set individually allows for implementation of a hysteresis. The hysteresis allows stable operation of the load. Namely when the storage is being charged up the voltage on the storage must reach the high threshold before the load is activated. Once the load is activated it will be deactivated once the voltage on the storage drops below the "low threshold". This feature makes sure that the load will be disconnected regardless of the state it is in and prevents over-discharge of the storage element.

First shortcoming of this type of voltage monitoring is the requirement of two comparators, hence it has higher current consumption.

Second shortcoming lies in the fact that there is no communication with the load. In the case where the load doesn't require to deplete the storage down to the low threshold level this energy will be lost while the load is idling and waiting to deplete the storage to the low threshold value. This could be mitigated by adding a switch that would pull the LTH input low once the load is done with its task, thus resetting the output of the window comparator.

Due to the higher current consumption of around 1.5uA with the resistor chain included, this type of circuit is recommended only for applications that have sufficiently high-power budget.

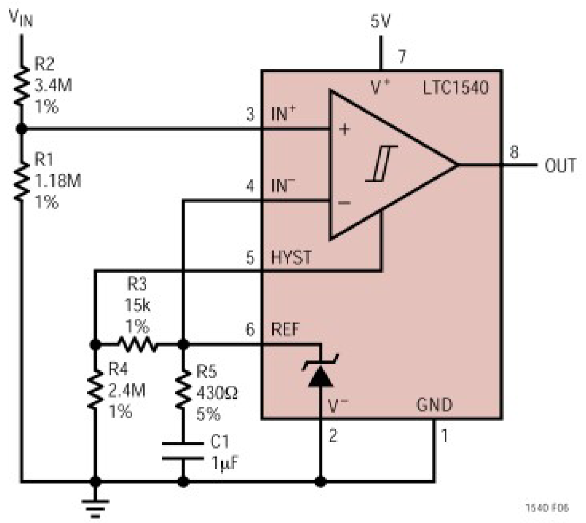
Single comparator power management

In the case of ultra-low power systems, a single comparator power management circuits that are preferred. There are several ways of implementing them:

- Using comparators with and internal or external reference
- Using voltage supervisor circuits

Comparator circuits

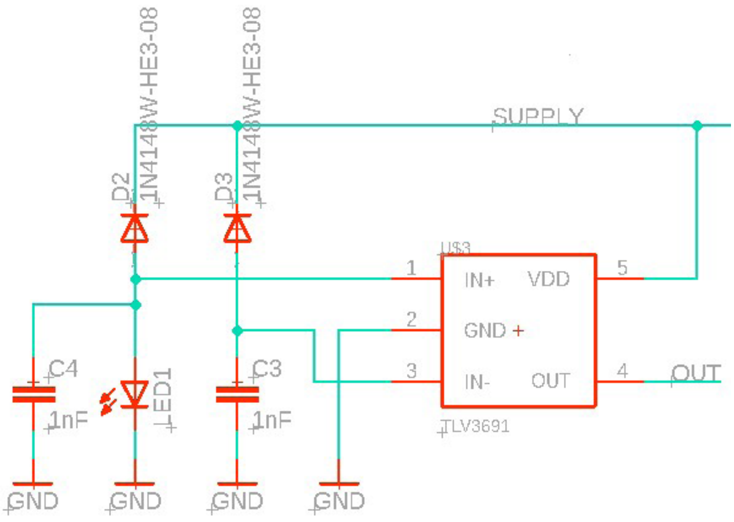
The simple voltage threshold circuit is a comparator with a voltage reference attached to it.



LTC1540 has a dedicated pin for implementing hysteresis.

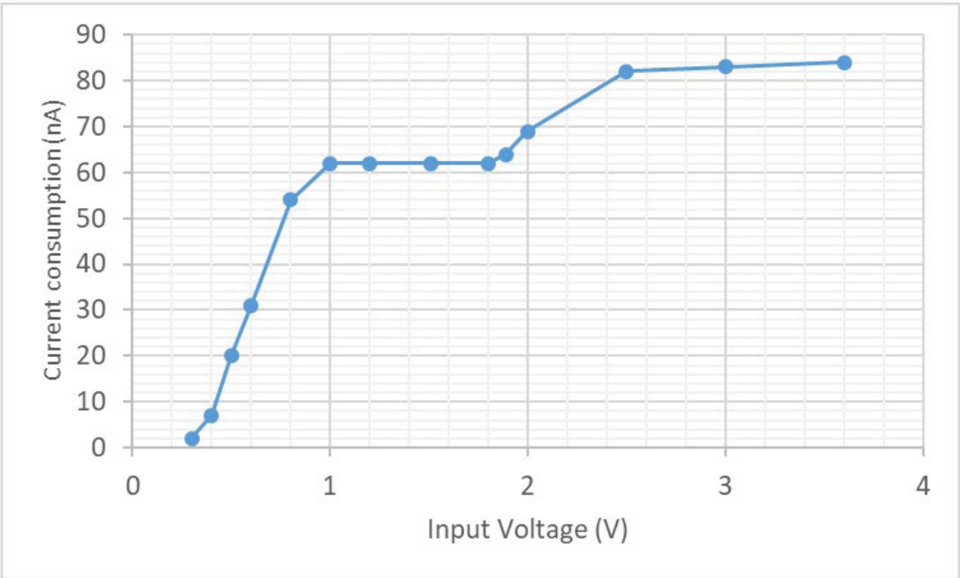
In the case where very low power consumption is critical an alternative method of providing a voltage reference can be done using diodes and an LED in combination with ultra-low power comparators. Namely the LED will not conduct any current until the forward voltage drop is reached where the LED turns on sharply. Therefore, the forward voltage drop of the LED can be used as a voltage reference.

The following schematics depicts an ultra-low power solution for voltage detection using LED and reverse polarized diodes. Diodes are used instead of pullup resistors as the reverse current of the diode doesn't change as much with the change of applied voltage of several volts, which is not the case when using pull-up resistors.



Voltage monitor circuit with LED as a voltage reference.

The total current consumption of this circuit can be seen in the image below.



Current consumption as a function of input voltage of the comparator with LED voltage reference with a threshold voltage of 1.9V.

One drawback of this circuit is the lack of precise selection of the threshold voltage as the voltages are limited to the selection of the forward voltage drop of different colored LEDs. Furthermore, the LEDs threshold voltage will be impacted by temperature variations and the light levels as the LED will behave as a solar cell and generate current when exposed to light. This current, though small, can impact the threshold voltage greatly.

Voltage supervisor circuits

Voltage supervisor circuits are typical used in battery operated systems to prevent the system from entering brown out state. This is the state where the electronics can stop behaving correctly due to low supply voltage. As these circuits are active all the time, the goal is that they have minimal power consumption. This can come in handy for energy harvesting applications, because during the charging of the storage the only current consumption would be coming from the voltage monitor circuits.

Voltage monitors typically consist of a comparator with hysteresis and a voltage reference. As everything is integrated in a single package these solutions have the smallest PCB footprint. Voltage monitors are available from multiple vendors some with current consumptions under

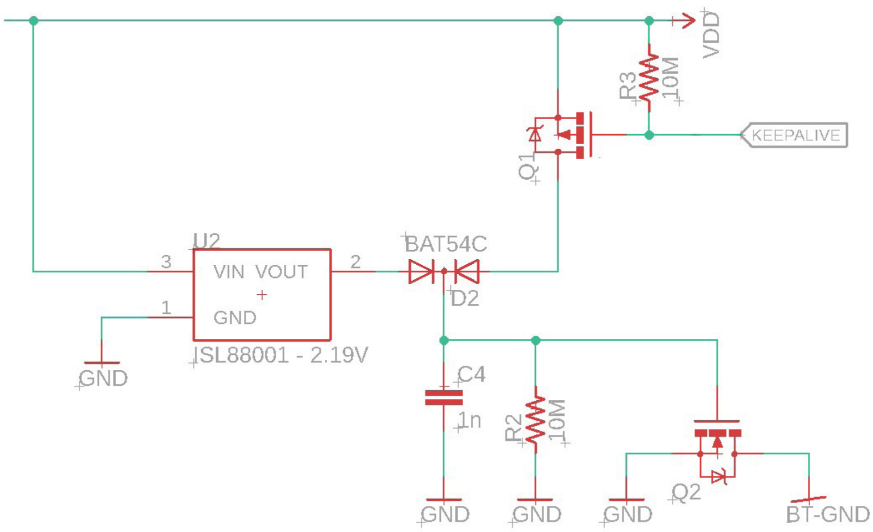
500nA. for example: Torex semiconductors XC6136 Series with operating current of 88nA and XC6135 with 44nA operating current; Intersil ISL880xx series with 160nA; Ablic S-1009 with 270nA and S-5471 with the lowest operating current of 3nA.

One of the big challenges when working with the voltage monitoring circuits is the fact that they are primarily designed for detecting when a threshold had been reached and changing their output stage with rather small hysteresis around the threshold voltage. This means that once the load is connected, when the threshold was reached, there could be only mV of hysteresis before the output would change state effectively disconnecting the load. Placing a large storage capacitor can mitigate this but for majority of applications this isn't a practical solution as it would require a prohibitively large capacitance.

Therefore, it is necessary to increase the hysteresis of the voltage monitor in order to provide the load with sufficient energy. As the negative pin of the comparator isn't available and the positive input is tied to the supply it is not easily possible to apply a negative feedback to implement a hysteresis in a way it is typically done with comparators. Therefore, a different solution is required.

One possible solution is applying a delay circuit between the voltage monitor and the gate of the MOSFET that is driving the load. In this way it is possible to prolong the duration of time the MOSFET driving the load is active and furthermore it is possible to provide a "keep-alive" feedback from the load that can recharge the capacitance on the gate of the controlling transistor, thus allowing the load to keep itself active for extended period of time. This approach has a drawback that the lower threshold voltage isn't monitored thus there is no hardware protection against over-discharging the storage element.

An example of voltage supervisor circuit with a delay and a control pin from the load is shown in the figure below:

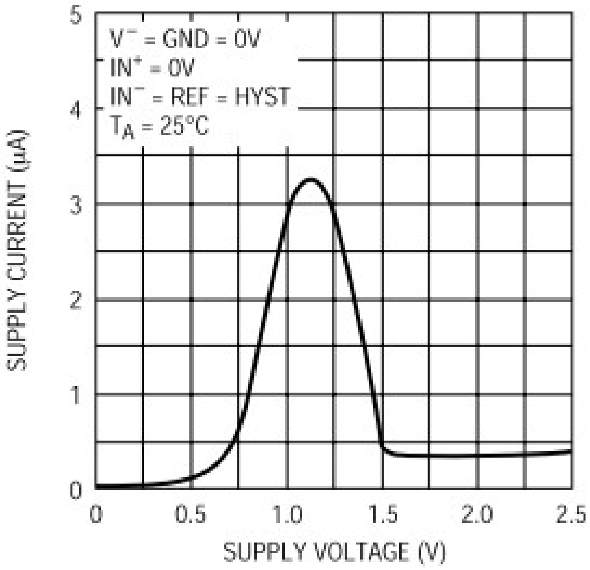


In this circuit once the threshold voltage is reached the output of the voltage supervisor circuit rapidly charges the gate of the Q2 that is then activating the load. Once the load is active the MCU inside the load, or some other electronics pulls the gate of Q1 low thus keeping the Q2 active. Once the load is done with its operation it can close the Q1 by pulling the line high again and the load will be disconnected once the voltage on the gate of Q2 drops below the threshold as the C4 is discharged through R2.

Cold start

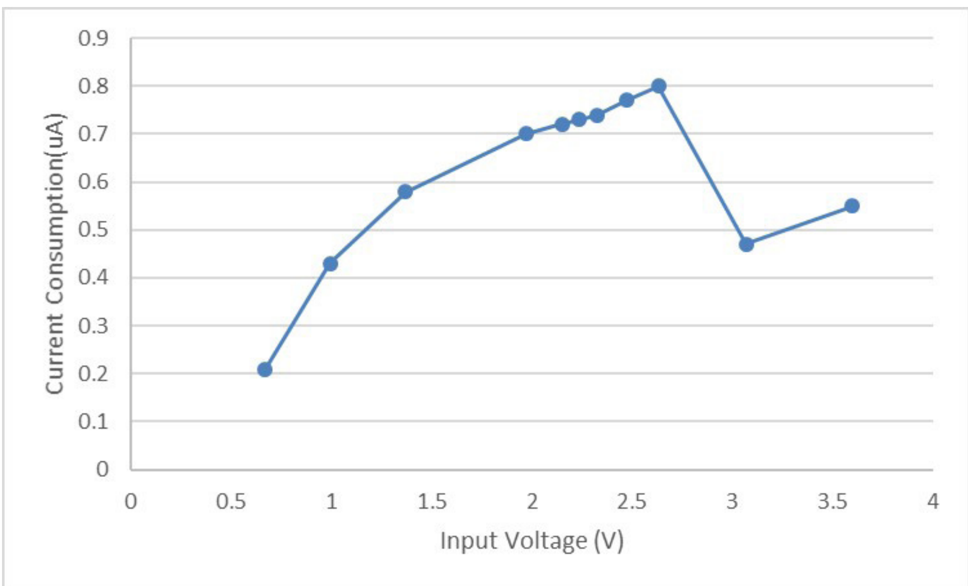
In the case of using storage supercapacitors as storage elements there might be times when the storage element gets completely depleted and the system must cold start. Under these conditions the power management should be capable of stable operation even though the supply is below the minimum specified operating voltage for the voltage supervisor.

It is necessary to choose components that have tested defined behavior until the minimum operating voltage is achieved. It is especially critical to note the current consumption during cold-start as some circuits can have high current consumption during this period. For example, LTC1540 can have current consumption of up to 3uA during this phase. Such high current can be more than the energy harvesting source can deliver, thus preventing the system from ever starting up.



Supply Current vs Supply Voltage of LTC1540.

Some voltage supervisor circuits only provide the value for the power consumption when operating above the threshold voltage in their datasheet. However, this information can be misleading as the power consumption can be significantly higher when the device is operated below the threshold voltage. Unfortunately, that is the area of interest in the case of energy harvesting devices. An example is a ISL88001 device from Intersil. The graph below shows the current consumption as a function of voltage.



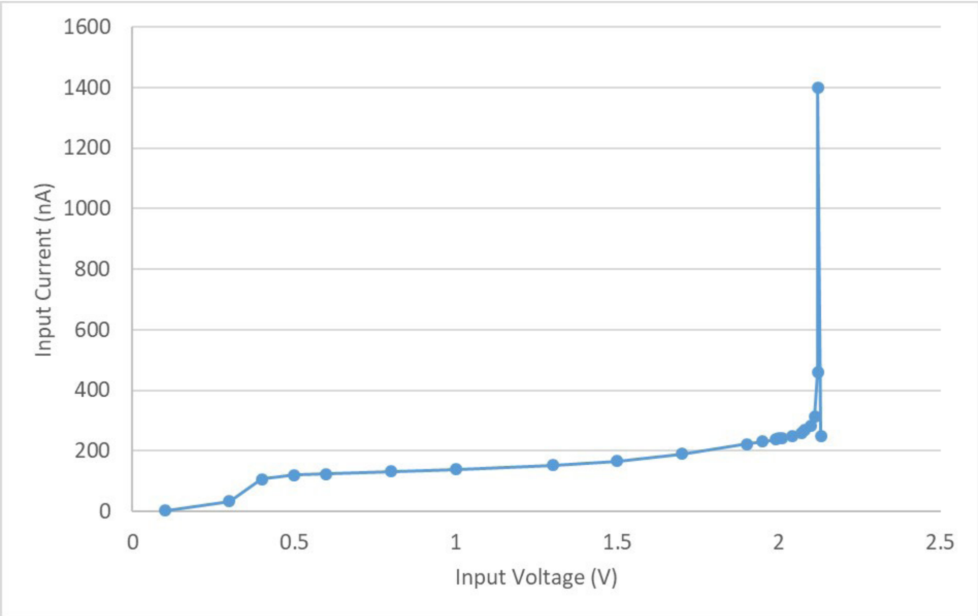
Current consumption as a function of input voltage for ISL8801 with a threshold voltage of 2.63V.

Shoot-through current

Once the internal electronics of the voltage comparator detect that the threshold has been reached an internal signal is generated that changes the output state of the device. During this transition for a very brief period of time both NMOS and PMOS transistors on the output are partially open which can lead to high current consumption. This behavior is typical for inverters, however in the case of energy harvesting power management, especially if the capacitance of the buffer is very small, this ”shoot through” current can depilated the capacitor sufficiently for the voltage to fall below the threshold voltage. This in turn leads to the comparator reverting to previous state and as a result not changing state at all. Following this the voltage level will rise again to the threshold and the process repeats.

From the outside it might seem like the circuit got “stuck” at the threshold due to this oscillation. Therefore, it is important when choosing the voltage supervisor that the supply can provide sufficient current and that there is sufficient decoupling to allow the device to change state.

The following graph shows the current consumption of a ABLIC S-1009 supervisor circuit as a function of input voltage. This is recorded with the input voltage rising and note the sharp increase of the current consumption close to the threshold voltage.



The current consumption of the S-1009 CMOS output with 1.9V threshold when the supply is swept from 0 to threshold voltage.

The Ablic S-5471 circuit has a current consumption of 3nA away from the threshold voltage but right before the triggering the current consumption can rise up to 100nA. We have tested this, but the few units we have tested on, we haven’t measured this increase in current consumption when used with a 100nF decouing capacitor on the input.

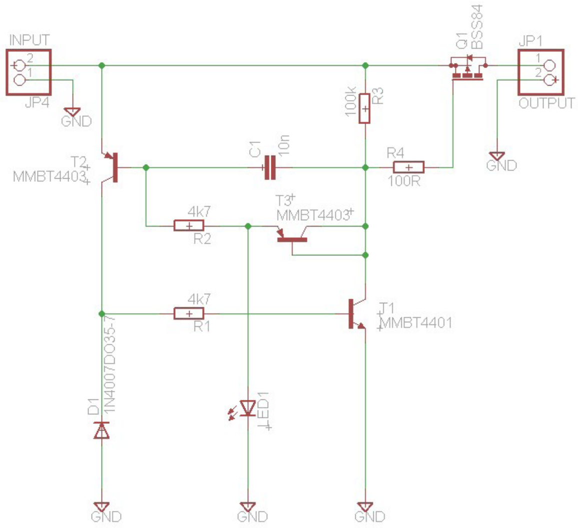
Voltage detectors not based on comparators

For some applications it is also possible to use implementations of voltage detectors that are not based on comparators. These solutions typically have a larger footprint due to use of multiple components and can be more susceptible to noise as there are longer exposed high impedance lines. We will look at two examples of such circuits:

- Novotil circuit
- ALD transistor solution

Novotil circuit

The schematic of the Novotil circuit is given in the figure below:



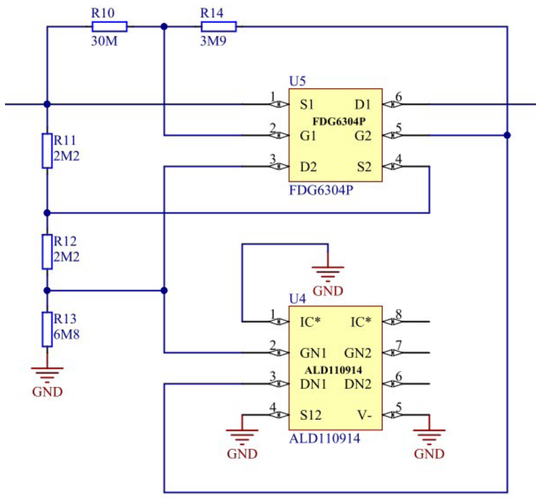
The implementation of the Novotil circuit using discrete components.

The Novotil circuit is using an LED voltage reference in combination with a bipolar transistor thyristor implementation. Once the trigger voltage is reached the current that starts flowing latches up the thyristor and keeps the input connected to the output until the bipolar transistors turn off at 0.7V input voltage.

Even though the input current of this circuit is below 10nA before triggering, once the circuit does trigger it consumes milliamperes of current which can be unacceptable in some applications. Beside the limitation of the threshold voltages due to using LEDs as are voltage reference, as it was discussed earlier, another shortcoming of this circuit is the low threshold voltage of 0.7V. This means that the load can discharge the storage element beyond what is necessary, as the majority of modern digital electronics would stop operating at 1.8V.

EPAD MOSFET transistor implementation

The EPAD transistor implementation is based on proprietary Advanced Linear Devices transistor technology where the transistors can have very precisely trimmed threshold voltages. This allows these transistors to act as almost an ideal voltage-controlled switch. In combination with a hysteresis loop, it is therefore possible to implement a power management stage similar to a comparator solution. An example can be seen in the schematic from the board PCA20014 from Nordic Semiconductor shown below:



Implementation of the voltage monitoring circuit using a EPAD transistor.

This solution's power consumption is defined by the size of the resistors used. The drawback of this solution is the use of the unique transistors that might lead to a vendor lock in, and their relatively high price compared to other solutions outlined in this document.

Device selection guideline

The voltage detection method choice will primarily be driven by the storage technology, available power budget and the size of the solution.

Based on the selected storage technology in the case of batteries the cold start performance of the circuit and the shoot through current don't play a major role while in the case of capacitor storage these elements must be considered.

According to the available power budget the solution choice can be chosen. For applications that can support 1-2uA current consumption for power management the most reliable way forward would be a window comparator. However, if the minimal current consumption is required, it would be necessary to look into some of the solutions using voltage monitors or a single comparator solution. Based on the available board space and the environmental conditions the device will be operating in, it is possible to choose among different manufacturers and implementations demonstrated in this document.

Conclusions

This document outlines some of the most commonly used configurations for voltage monitor based power management for energy harvesting. Different approaches were discussed and some of the common issues when evaluating voltage monitor solutions. By looking into these options, in combination with the knowledge on what to look out for it is possible to determine the type of voltage monitoring circuit that would fulfill a given application.

Want to know more?

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