Texas Instruments

Application Report
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Efficient Super-Capacitor Charging with TPS62740

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ABSTRACT

Long-life batteries with $LiSOCl_2$ chemistry in a bobbin type cell construction have a very high specific energy (Wh/kg) but are unable to provide currents higher than 20 mA, for example. Long-life batteries also suffer with reduced operation runtimes when higher currents are drawn.

The TI Design PMP9753 shows a concept to buffer energy in a super capacitor and therefore decouples load peaks from the battery.

This application note helps designers to calculate and define the parameters like minimum and maximum voltage levels, storage capacitor size or maximum battery current.

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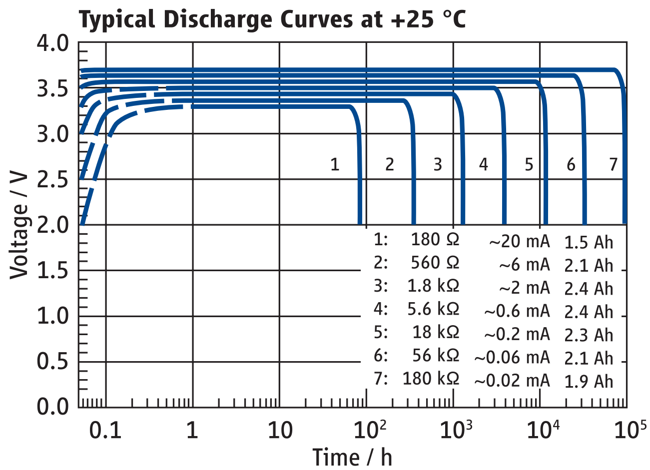
1 Introduction

Battery chemistries like the $LiSOCl_2$, offer great benefits in terms of application runtime. These battery chemistries bring operation runtimes of 15 years and more to reality. The technology, however, has a limited characteristic in terms of supporting higher loads.

Higher load pulses cannot be supported by the battery itself due to the internal impedance. As well, the higher the drawn current, the shorter the battery operation. Figure 1 shows how different battery currents translate to different battery runtimes.



NOTE: http://www.tadiranbatteries.de/pdf/lithium-thionyl-chloride-batteries/SL-360.pdf

Figure 1. Typical Discharge Curve of a TADIRAN SL-360 Over Several Loads

To overcome these limitations, peak power assistance concepts must be considered.

For example, a wireless sensor node transmits its gathered data once a day to a base station. The data transmission requires 500 mA for 200 ms. This short power peak cannot be supported by the primary cell itself. The pulse needs to be buffered somewhere else.

2 Circuit Concept Description

This reference design shows an energy buffering concept based on the TPS62740, a 360-nA quiescent current buck converter, in combination with an electric double-layer capacitor (EDLC) or a so called super capacitor.

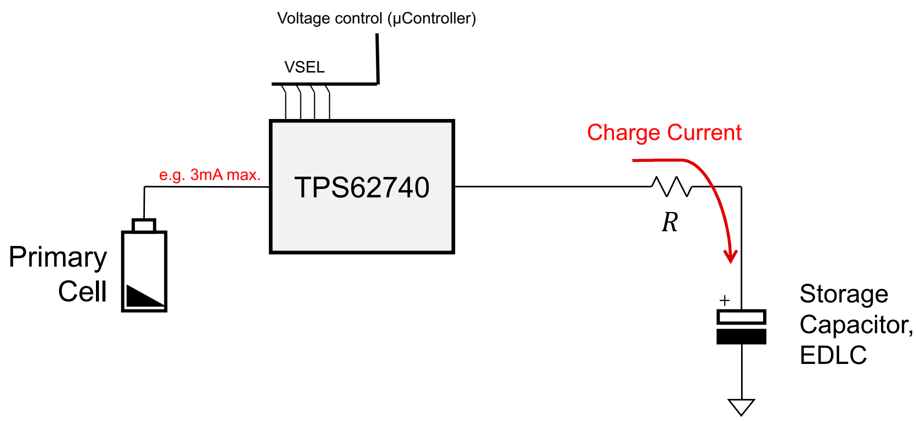


Figure 2. Simplified Charging Block Diagram

The circuit uses a resistor at the output of the TPS62740 to limit the current into the storage capacitor as well as the battery current drawn from the primary cell. The resistor will be selected in a way to keep the load, and thereby the battery current, below a level the primary battery can support. The TPS62740 features a digital input to adjust the output voltage by four VSEL Pins. During the charging of the EDLC, the output voltage can be stepped up in 100-mV steps. This helps to minimize the power losses caused by the resistor.

In an application like a wireless sensor, the µController will be supplied from the output of the TPS62740 step-down converter. Therefore, the voltage must stay above the µController minimum supply voltage (for example, 1.9 V). The maximum voltage of a single layer super capacitor is typically 2.7 V, which leads to a usable capacitor voltage range of 1.9 V to 2.7 V. Figure 3 shows the basic flow of a recharge cycle.

Most of the time the voltage is kept at 1.9 V to minimize the losses of the micro-controller and other leakage currents in the application (Phase 1). Prior to a wireless data transmission, the capacitor is charged up to 2.7 V (Phase 2). During transmission, the stored energy in the capacitor can be extracted down to 1.9 V (Phase 3).

For appropriate measurement results, see the PMP9753 Test Report (TIDU628).

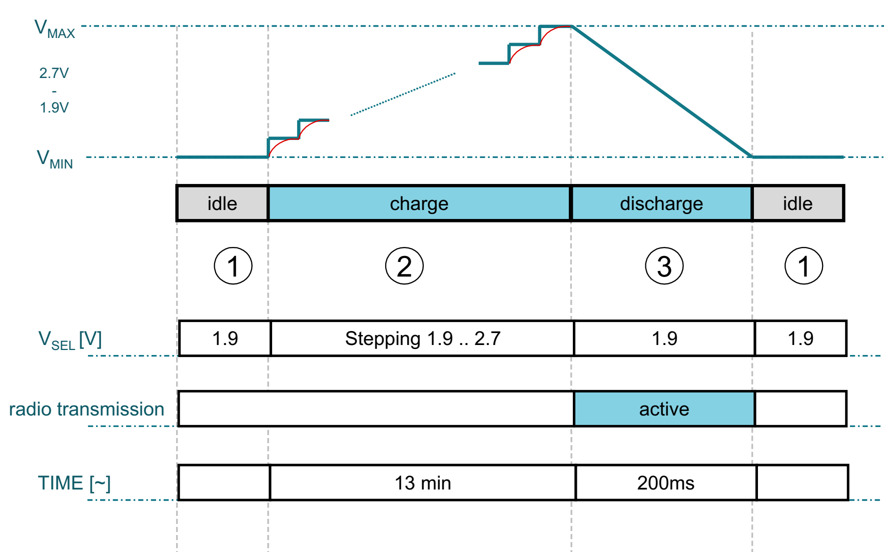


Figure 3. Recharge Cycle Sequencing

2.1 Detailed Block Diagram

Figure 4 shows the block diagram of the energy buffering reference design consisting of following main blocks:

- Primary cell
- TPS62740 buck converter
- Current limiting resistor network
- Storage capacitor
- Connection to the µController

The $LiSoCl_2$ primary cell is directly connected to the TPS62740. The buck converter is controlled by the available µController in the application. The MCU enables/disables the buck converter, adjusts the output voltage, and enables the efficient charging as shown in Figure 3.

The output of the DC/DC converter is connected to the current limiting resistor. Figure 4 shows two resistors, one resistor can be connected by a switch. This is designed to handle the start-up procedure which is necessary to pre-charge the EDLC to the minimum voltage of 1.9 V. To not exceed the maximum battery current, only the 300-Ω resistor is used.

Once the storage capacitor is pre-charged, the switch is turned on and the current is limited by the combined resistance.

A load like a radio power amplifier can now be directly connected to the storage capacitor which does support larger peak currents to be drawn from it.

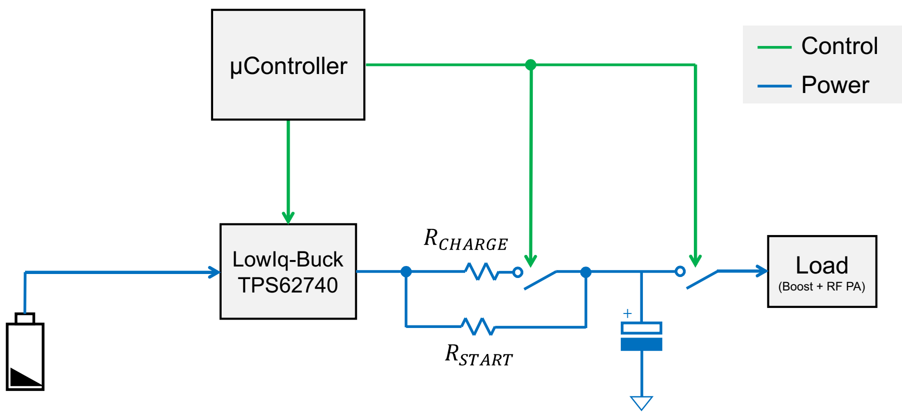


Figure 4. Application Circuit Block Diagram

3 Parameter Calculation

This section describes how to calculate the necessary parameters of the circuit for the final end-application.

The parameters like the minimum and maximum voltage at the super capacitor and its capacitance are calculated as well as the resistance of the limiting resistor.

All subchapters present the dedicated formula and how to use it. For further details, the included sub-subchapters provide derivations and examples.

3.1 Voltage Levels

Before selecting the capacitance value of the storage capacitor, the minimum and maximum voltage are chosen.

The minimum voltage is mainly defined by the lowest supply voltage of the micro controller. The voltage at the capacitor must not fall below this voltage to guarantee the operation of the MCU. This value can be extracted from the controllers' datasheet.

An example value is $V_{MIN} = 1.9\ V$.

The maximum voltage is defined by the highest voltage that the EDLC is allowed to be exposed to without any lifetime issues. The voltage is depending on the capacitor and can be found in its datashett.

A ypical maximum value of an EDLC is $V_{MAX} = 2.7\ V$.

The voltage difference between V_{MAX} and V_{MIN} is the voltage range in which the capacitor can be charged and discharged

From the example above, the voltage difference is $\Delta V = 2.7 – 1.9\ V = 800\ mV$.

3.2 Storage Capacitor

The size of the capacitor is determined by following parameters:

E_{LOAD}	The required energy from the load (for example, the radio power amplifier)
V_{MIN}	The minimum system voltage (minimum supply, for example, MSP430)
V_{MAX}	The maximum capacitor voltage

The capacitor size can be calculated according to the parameters previously given, as in: Equation 1.

$$C = \frac{E_{LOAD} \times 2}{\left(V_{MAX}^2 - V_{MIN}^2\right)} \quad (1)$$

For calculating the capacitance to buffer the energy for a radio transmission pulse, the following Equation 2 can be used. Here the boost converter losses are already considered.

$$C = \frac{E_{RADIO} \times 2}{\left(V_{MAX}^2 - V_{MIN}^2\right) \times \eta_{BOOST}} \quad (2)$$

With:

E_{RADIO} = Energy of the radio power amplifier during transmission
η_{BOOST} = Efficiency factor of the boost converter
E_{LOAD} = The required energy from the load (for example, the radio power amplifier stage)
V_{MIN} = The minimum system voltage (minimum supply; for example, MSP430)
V_{MAX} = The maximum EDLC voltage

3.2.1 Equation Derivation

First, the required energy for a radio telegram transmission is calculated:

$$E_{RADIO} = P_{RADIO} \times t_{RADIO} = V_{PA} \times I_{RADIO} \times t_{RADIO}$$

The energy, which is required by the radio power amplifier, is the multiple of the voltage level needed by the PA, the drawn current and the duration.

As the PA needs a higher voltage, a step-up converter needs to be placed between the storage capacitor and the amplifier. Therefore, the conversion efficiency is taken into account as well:

$$E_{LOAD} = \frac{E_{RADIO}}{\eta_{BOOST}} \quad (3)$$

With this equation, the desired energy from the capacitor E_{LOAD} is calculated.

Next, the extractable energy from the storage capacitor is calculated as follows:

$$E_{CAP} = E_{MAX} - E_{MIN} \quad (4)$$

$$E_{CAP} = \frac{1}{2} \times C \times V_{MAX}^2 - \frac{1}{2} \times C \times V_{MIN}^2$$

$$E_{CAP} = \frac{1}{2} \times C \times \left(V_{MAX}^2 - V_{MIN}^2\right)$$

Equalizing Equation 5 and the Equation 4 leads to:

$$\frac{E_{RADIO}}{\eta_{BOOST}} = E_{CAP} \quad (5)$$

$$\frac{E_{RADIO}}{\eta_{BOOST}} = \frac{1}{2} \times C \times \Delta\left(V_{MAX}^2 - V_{MIN}^2\right)$$

Dissolving the equation to isolate C, gives the equation to calculate the minimum capacity of the EDLC:

$$C = \frac{E_{RADIO} \times 2}{\eta_{BOOST} \times \left(V_{MAX}{}^2 - V_{MIN}{}^2\right)} \quad (6)$$

3.2.2 Calculation Example

A radio power amplifier in a wM-bus application has the following parameters:

$V_{PA} = 3.5$ V
$I_{RADIO} = 300$ mA
$t_{RADIO} = 200$ ms
$\eta_{BOOST} = 0.93$ for 2.2 V to 3.5 V conversion (worst-case condition)
$V_{MIN} = 1.9$ V
$V_{MAX} = 2.7$ V

With Equation 7 and Equation 8:

$$C = \frac{V_{PA} \times I_{RADIO} \times t_{TX} \times 2}{(V_{MAX}{}^2 - V_{MIN}{}^2) \times \eta_{BOOST}} \quad (7)$$

$$C = \frac{3.5\text{ V} \times 300\text{ mA} \times 200\text{ ms} \times 2}{\left(2.7^2 - 1.9^2\right)\text{V} \times 0.92}$$

$$C = 0.12\text{ F} \quad (8)$$

This means the theoretical required storage capacitance has to be 120 mF to store the required energy.

3.3 Current Limit Resistor

In this circuit, the maximum battery current is limited by a resistor placed at the output of the DC/DC converter. The TPS62740 is able to set the output voltage according to the levels at the VSEL pins in a resolution of 100 mV.

For calculating the resistance, the maximum voltage over the resistor of 0.1 V is considered. The resistance value can be calculated with Equation 9:

$$R_{LIM} = \frac{\Delta V \times V_{MAX}}{I_{BAT} \times V_{BAT} \times \eta_{BUCK}} \quad (9)$$

With:

ΔV = Maximum voltage across the resistor, 100 mV
V_{MAX} = Maximum voltage of the storage capacitor
I_{BAT} = Maximum battery current
V_{BAT} = Primary battery voltage
η_{BUCK} = Efficiency factor of TPS62740 for the current previously listed

3.3.1 Equation Derivation

The resistor limits the current at the converter output; the input current limit needs to be transformed to the input current of TPS62740, which is the battery current:

$$I_{CHARGE} = \frac{I_{BAT} \times \eta_{BUCK}}{D} \quad (10)$$

For the duty-cycle D, the value which gives the highest battery current is chosen:

$$D = \frac{V_{MAX}}{V_{BAT}} \quad (11)$$

$$I_{CHARGE} = \frac{I_{BAT} \times V_{BAT} \times \eta_{BUCK}}{V_{MAX}} \quad (12)$$

The resistor is calculated by the voltage across itself and the charge current as shown in Equation 13. Equation 12 is inserted for the charge current to calculate it according to the desired battery current.

$$R_{LIM} = \frac{\Delta V}{I_{CHARGE}}$$

$$R_{LIM} = \frac{\Delta V \times V_{MAX}}{I_{BAT} \times V_{BAT} \times \eta_{BUCK}} \quad (13)$$

3.3.2 Calculation Example

For a $LiSOCl_2$ primary battery, a battery current of approximately 3 mA is the optimum discharge current for the battery to extract the most energy and achieve the longest lifetime.

Considering this value gives Equation 14:

$$R_{LIM} = \frac{0.1\ V \times 2.7\ V}{3\ mA \times 3.6\ V \times 0.92}$$

$$R_{LIM} = 27.2\ \Omega \quad (14)$$

According to use-typical E-Series resistors, the following resistor is chosen:

$$R_{LIM} = 30\ \Omega \quad (15)$$

Due to the fact that, the about ten times higher, start-up resistor is in parallel, the effective resistance is slightly smaller.

3.4 Start-up Procedure

Considering a maximum battery current as well in the pre-charge (or start-up) phase, a different resistor must be chosen.

Figure 5 shows the block diagram using a bigger resistor to charge the EDLC to the minimum system voltage.

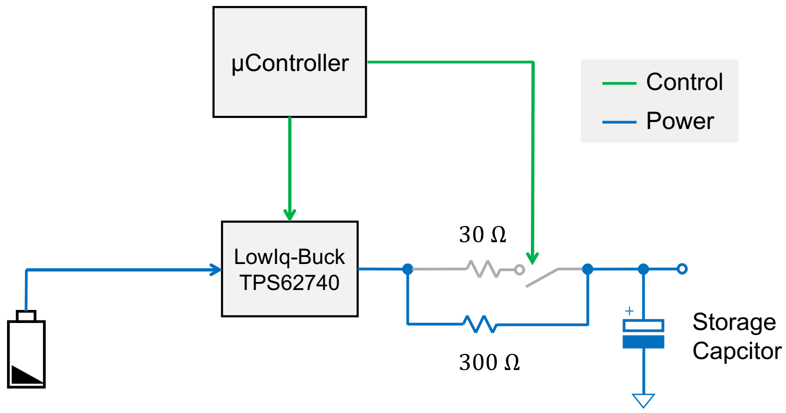


Figure 5. Application Circuit During Start-up Sequence

To calculate the resistor value, the higher ΔV from zero to V_{MIN} needs to be considered as in Equation 15:

$$R_{START} = \frac{V_{MIN} \times V_{MIN}}{I_{BAT} \times V_{BAT} \times \eta_{BUCK}} \quad (16)$$

3.4.1 Equation Derivation

Please refer to Section 3.3.1.

The stepsize of the voltage is now changing due to the step from zero to e.g. 1.9V.

3.4.2 Calculation Example

With the example values used in the previous sections, the following example is calculated:

$$R_{START} = \frac{1.9\ V \times 2.7\ V}{4\ mA \times 3.6\ V \times 0.92}$$

$$R_{START} = 272.5\ \Omega \quad (17)$$

According to typical-use E-Series resistors, the following resistor is chosen:

$$R_{START} = 300\ \Omega \quad (18)$$

4 Summary

Due to the characteristics of certain batteries, applications with ultra-long runtimes need new concepts for buffering energy.

Using an EDLC in combination the TPS62740 brings the following main advantages:

- Single cell super capacitor with a maximum voltage of below 3 V can be used.
- Storage capacitors like Murata DMF series enable an application runtime of > 15 years.
- Pulsed currents are decoupled from batteries leading to more extractable energy.
- Application runtimes are extended because of the high efficiency of the solution.

The charging sequence can be implemented efficiently due to the digital output voltage selection feature of the TPS62740 device.

This buck converter is designed to operate with a quiescent current of typical 360 nA and is ideal for a direct connection to the battery and ultra-long runtimes.

Applications like a wireless sensor node can use the existing µController to handle the charging sequence of the EDLC.

List of Parameters and Acronyms

A.1 List of Parameters

V_{MIN}	Minimum voltage in the system, minimum discharge voltage
V_{MAX}	Maximum voltage in the system, maximum voltage for the EDLC
V_{BAT}	Voltage of the battery
I_{BAT}	Current drawn from the battery
$V_{DC/DC}$	DC/DC-converter output voltage
V_{CAP}	Storage capacitor (EDLC) voltage
P_{RADIO}	Power required by the load, for example, a radio power amplifier
C_{CAP}	Storage capacitor (EDLC) capacitance
R_{CHARGE}	Resistor to limit the current during charging cycle
R_{START}	Resistor to limit the current during start-up sequence
E_{RADIO}	Energy required by the load, for example, a transmission of a radio telegram
ΔV	Voltage delta between the minimum and maximum voltage at the EDLC
t_{RADIO}	Telegram transmission duration
V_{PA}	Supply-voltage for the radio power amplifier
η_{BOOST}	Conversion efficiency of the boost converter stage
η_{BUCK}	Conversion efficiency of the buck converter stage
E_{PA}	Energy required by the radio power amplifier for one telegram transmission
E_{CAP}	Extractable energy from the storage capacitor

A.2 List of Acronyms

ALPS	Advanced Low Power Solutions
TI	Texas Instruments
VSEL	Voltage selection, input pins of TPS62740
EDLC	Electric Double Layer Capacitor
MCU	Micro Controlling Unit
MSP430	Texas Instruments' Micro Controller family
PA	Power Amplifier