Design of a Reliable Portable Power Supply Chain for an Embedded System

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***Abstract*— Microcontrollers and electrical circuits are fail in case of low supply voltage. They can switch off, oscillate or do unpredictable things because they complexity. To prevent such scenario additional protection circuits and firmware elements should be added. In this article shows a reliable energy supply chain and proposes solutions to prevent this problem. The research aimed to show various PCB designs for diverse environments and supply voltages. The article deals with battery cells, charging and protection circuits, in-circuit current measurement and USPs.**

Keywords— voltage supervisor, digital current measurement, in-circuit current measurement, lithium iron phosphate, LiFePo4 protection, reliable microcontroller supply, reliable Raspberry PI supply

I. INTRODUCTION

Low power supply voltage can cause instabilities and vulnerabilities. While powering-up a device, the voltage starts at 0V and ends around the supply voltage. During this surge it passes the hazardous voltage range. In battery powered operation, if the battery discharges, the output cell voltage is decreasing, without proper under voltage protection, the power supply also can fall to the hazardous voltage range, especially with high temporary type load current spikes.

High value capacitors in the supply lines can slow down the startup voltage rise time, and corrupt microcontroller operation. The fail of the system can handle by a restart button, but it is inconvenient for the user, especially in a remote location. Till the stable supply voltage is reached, it is advisable to keep the reset pin in active state or the enable pin in inactive logic level. In practice the task can be done with an RC element connected to the reset pin, it will delay the supply voltage on the pin, but there are further solutions.

Numerous solutions exist to power MCUs and computers, like Raspberry Pi [1-3], within this portable [4] and data acquisition hardware and software realizations have got a wide range of solutions [5, 6]. MCUs can be hardened for external disturbances and also well controllable [7, 8]. Many of supply chains can be realized in the field of the embedded systems [9-11].

The experimental system is based on modular sub-circuits, due to easier modifiability [12, 13]. The optimization of the layout is considered according to the following papers [14-16]. Real time data monitoring and logging is also a significant part of the development [17-20].

One of the effective ways of controlling the system is closed-loops and compensation of disturbances [21-23]. Various optimized solutions and compensating for uncontrolled disturbances are discussed in a series of papers [24-26]. Numerous schemes of control systems architecture are considered [27, 28].

II. SYSTEM ELEMENTS

A. Battery cells

To power mobile applications several energy sources can be considered. Alkaline cells are starts at 1.5V and ends around 1V. The capacity of an AAA battery is about 1200mAh, and an AA battery is about 3400mAh. Alkaline batteries are not rechargeable in default. For a 3.3V power supply with three cells, a low dropout voltage regulator is needed. For a 5V power supply with one, two or three cells, a boost converter is needed. Regulators and converters are shortening the life capacity due to the voltage conversion losses. Alkaline cells do not need external protection circuit, and they do not explode under non-operating conditions.

Nickel cadmium (NiCd) cells are starts under 1.4V and ends above 1V. The capacity of an AAA battery is around 300mAh, and an AA battery is about 800mAh. Nickel cadmium batteries are rechargeable. In the discharge cycle the cell voltage mostly between 1.2V and 1.3V. Three fully charged cells voltage (4.2V) is too high for 3.3V components, and LDO also needed for secure operation.

Nickel metal hydride (NiMH) battery discharge voltage curve is similar to the nickel cadmium batteries. The capacity of an AAA battery is about 900mAh, and an AA battery is around 2200mAh, and they are also rechargeable.

Lithium polymer (LiPo) cells are starts at 4.2V and ends around 2.8V. For a 3.3V power supply an LDO, and for a 5V power supply, a boost converter is needed. Lithium polymer batteries are made with different packages, with different capacities, and they are rechargeable. Lithium polymer cells are good for indoor usage, but performs poorly at low temperature field applications.

Lithium iron phosphate (LiFePo4) cells voltage starts at 3.6V and ends just under 3V (2V in the edge of deep discharge). Most of the discharge curve the cell voltage stays above 3V, so no voltage regulator is necessary. Lithium polymer batteries are made in cylindrical and rectangular packages. The capacity of an AAA (14500) battery is about 700mAh, and an 18650 cell is around 1500mAh. The main advantages of LiFePo4 are its excellent low temperature performance (LiPo cells are losing capacity under 0°C).

For a 3.3V power source, in case of powering a mobile device, three alkaline cell is equal to one lithium iron phosphate cell. Lithium iron phosphate batteries are suitable for higher current applications, maximum discharge current is less than 1.5C, and they are rechargeable. LiFePo4 cells are also safer than LiPo cells, and have got lower self-discharge rate. A 100% depth of discharge (DoD) is also less detrimental to battery life. The capacity of LiFePo4 batteries are smaller and the price is approximately the same than LiPo batteries.

Lithium iron phosphate cells need to charge with 3.6V, the charging current is 0.4C, the fast charging current is close to 0.9C.

B. *Battery charging and protecting*

For a 5V power source, in case of powering a mobile device two lithium cell and a voltage regulator or one lithium cell and a boost converter is needed. Most of mobile applications (expect the high power applications) energy density and charging time is not primary, but safety is quite important.

Lithium polymer cells are protected against overcharge and deep discharge with (for example) TP4056 integrated circuit. Lithium iron phosphate cells can be protected with TP5000 and CN3058 ICs.

A rechargeable battery with a boost converter can supply embedded microcontrollers. For protection against over-discharge, an additional - for example - a TP4056 board is advisable between the battery cell and the boost converter. It also prevents the battery from short circuits and also can charge it from 5V.

The TP5410 IC based modules can charge a LiPo cell, it also has got a boost converter, with a low quiescent input current (under 15uA), but it has no over-discharge and short circuit protection.

To cover the needs, the TPS6109x synchronous boost converter is suitable till 2A output current, it has a built-in low battery comparator and it disconnects the load during startup and shutdown, to prevent fail controller operation.

For higher current applications the TPS6123x is a possible choice till 5A output current, with all the previously mentioned features, it also has programmable soft start operation, and output over voltage protection.

C. *Portable PV extension*

For portable operation, it is a good practice to add a small solar panel to the system. Solar panels output power is depending from the incoming solar radiation and from the output load. Both parameter can alter during operation. An MPPT charge controller can optimize the PV cell output for maximum power. CN3791 is a photovoltaic cell maximum power point tracker and a complete charge controller for single cell lithium batteries, it works up to 28V input voltage ant to 4A charge current. The charging current is programmed with a current sense resistor, the IC has battery overvoltage protection, the precharge phase (16% of the charge current at CN3791) threshold voltage is 2.8V. It is low enough not to compromise the operation, the battery cell protection circuit is disconnecting the load before the cell would discharge till 2.8V.

D. *Current measurement*

In-circuit current measurement requires a serially placed shunt resistor. With current sensors the solar power, the load current and the battery charge level can be measured. The INA219 is a bi-directional DC current, voltage sensor and power monitor, with I2C interface. The INA3221 is also capable for the task, it is a three channel high-side voltage and current sensor device, with I2C interface. Fig. 1 is showing the measuring concept. With the help of an 0.1Ohm shunt resistor, the measurable current range is ±1.6A and the resolution is 0.4mA. The shunt resistor should be high precisions and with a power of at least 2W.

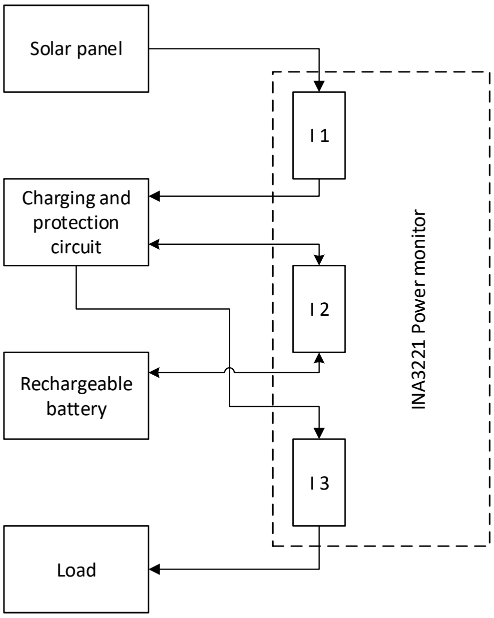

Figure 1. In-circuit current measurement

In the shunt resistor there is always some small, but potentially significant voltage drops, which is called burden voltage. Hall sensor based current sensors can measure charge movement with electrically isolated from the power leads, they can be used both in the low and the high side of the power supply loop, and they will not create a burden voltage. Most of the hall sensor based current measuring modules are designed for high currents, so they are not accurate at low currents (for example the ACS712 is designed ±5A, ±20A and ±30A). Hall sensors can be disturbed with electromagnetic fields.

LTC4150 also a useful tool, a coulomb counter, with two voltage sensor and one current sensor. It can measure the input and output charge before a rechargeable battery, and can monitor the amount of stored charge. These solutions can be useful for low power microcontroller based portable devices, a small solar panel also can be integrated into the system.

III. REALIZATION

A. *Energy supply chain*

For a portable power supply, mains or sun could be the power source. Microcontrollers and sensors are run on 3.3V or 5V, or sometimes both. To get 5V from mains, a USB charger or a power supply can be used. For 3.3V supply, the use of a low dropout voltage regulator (LDO) is recommended. Some of the microcontroller boards have got a built-in 3.3V voltage regulator, if they accept 5V supply.

For portable devices, where the device should be independent from mains voltage from time to time an energy storage element is required. From the solar cell, a battery charger charges the battery, it is proposed to implement a LiFePo4, a LiIon or a LiPo battery. The batteries must also be able to be charged from mains voltage, a charging circuit is required for this task. The protector circuit should cut off the battery before over charge or over discharge. An LDO or a boost converter provides the power supply for the microcontroller and the additional elements. Fig. 2 shows the described architecture.

B. *UPS for Raspberry Pi*

The energy chain is able to charge the battery and supply the load at the same time, most of the external uninterruptible power supplies (UPS) do not have this feature. The used UPS module can intelligently switch between main power and standby power, even in case of small load current. The operation enables to use multiple power supplies and energy storages in a portable device. In the prototype it switches between a wall adapter DC output and the PiFePo4 battery’s boost converter output. The first way is the main power source, and the second one is the battery cell.

The UPS module also can be used in redundant portable applications, where are duplicated batteries. When the first battery become empty, the module automatically switches to the second battery. The user also could parameterize the switching algorithm, and decide a priority list – the function assumes continuous power supply to the microcontroller

Because of the battery charging IC charging curve, the load should be disconnected for a few minutes if the battery cell voltage is under 3V. The charging process is starting with a trickle current, which is 1/10 of the charging current. Most of the microcontrollers are not consume more power in normal operation than the trickle current, in case of an 18650 cell. For a Raspberry Pi, an additional voltage supervisor system can be added, to shut down the Raspberry Pi if the cell voltage goes under 3V, and starts up if the cell voltage is higher than 3V.

In a Raspberry Pi the software is stored in SD cards most of the time. SD cards can become corrupted if the Raspberry Pi loses power without a proper shutdown. Reliability with SD cards can be achieved by decreasing writing cycles. SSDs are a good solution to swap SD cards, but they are relative expensive, they take up a lot of space, for connection they need an external cable and they block one of the USB3 connectors.

Voltage supervisors are also a good opportunity to solve the problem, they increase the reliability of the device. They have got a voltage reference, a comparator and an output driver transistor. The component keeps the reset pin low, till the power supply voltage level is under the reference voltage. With a MOSFET it is feasible to handle the whole project.

Voltage supervisors are working on lower voltages than the supply voltage and with hysteresis to prevent oscillation. KA75xxx series is made by TO-92 packages, KA75330 is for 3.3V, KA75290 is for 2.9V, from the TPS383x series TPS3839 is switches at around 3.14V. The voltage supervisor pin is also connected to a Raspberry Pi GPIO pin to start a shutdown sequence. An auto-launch application during the booting process, a Python script is checking the GPIO pins, and automatically shut down the Raspberry Pi in case of low supply voltage.

With a 5.5V supercapacitor bank, the MCU can safely shut down. Capacitors sore energy in electrostatic fields, can handle heavy charging, discharging currents and they can be used in harsh environments. Supercapacitors energy density is much higher than ordinary capacitors, but they store less energy than batteries.

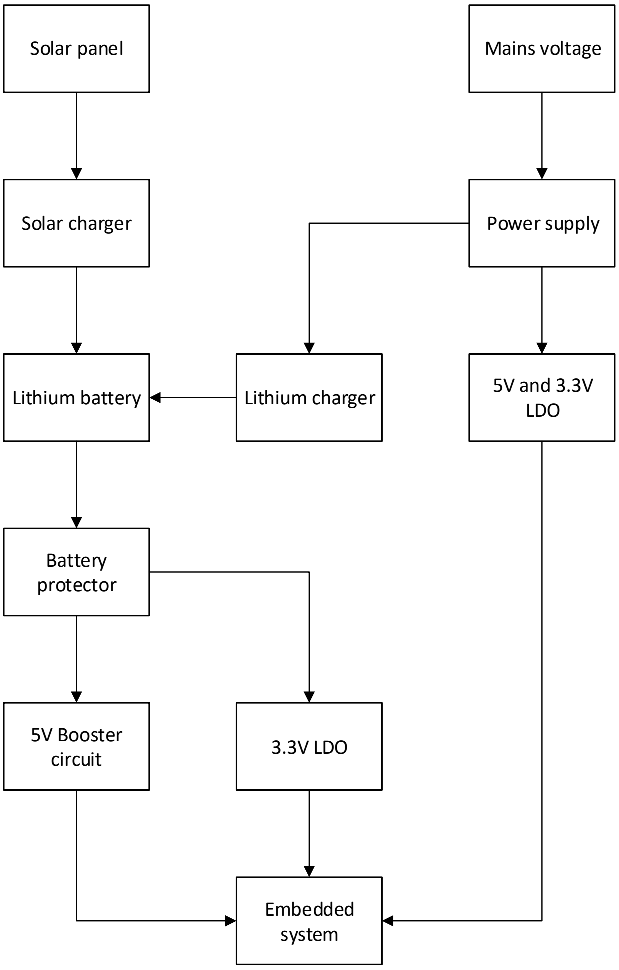

Figure 2. Portable supply chain architecture

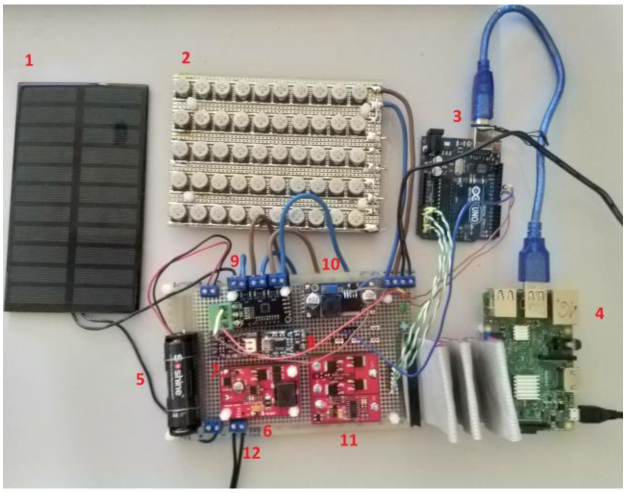

Figure 3. Experimental environment (1 – Solar panel. 2 – Supercapacitor bank, 3 – microcontroller with ADC, 4 – Raspberry Pi, 5 - PiFePo4 cell, 6 – Solar charger, 7 – Coulomb counter, 8 – Battery charger and protector, 9 – Power monitor, 10 – Boost converter, 11 – UPS, 12 – PSU input)

IV. CONCLUSION

The paper proposed reliable solutions to prevent MCUs and computers to fail due to power supply imperfections. The realizations shown voltage indication possibilities detailed the types of electrochemical energy storage and in-circuit current measurement techniques, for portable embedded systems in a practical manner. The results of the development showed that the use of voltage supervisors are capable to increase reliability. The shown modular design can also be used for other supply chain applications. The proposed architecture is easily scalable and user-friendly. The article describes the relationship between the system components. Eventually conclusions were drawn about the feasibility and requirements of such a system to make it possible to implement.

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