ORIGINAL PAPER

PORTABLE LITHIUM-ION BATTERY UPS WITH BMS FUNCTION FOR RASPBERRY PI AND OTHER IOT EMBEDDED SYSTEMS

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Abstract. *The increasing number of IoT (Internet of Things) based embedded systems, used nowadays in every aspects of our lives, inherently generates new challenges that require specific technical attention regarding: the increasing power demand directly proportional with the rising of their computational power and wireless communication functions, a more complex and flexible UPS (Uninterruptible Power Supply) design with load sharing function, a correctly balanced BMS (Battery Management System) consistent with the battery technology used and the manufacturer technical specifications, a more stable DC to DC converter output, a smarter system fail-safe algorithm, all concentrated in a more compact form factor. Taking all that into consideration, this article addresses all the previously mentioned issues in order to design, evaluate and present a fully functional UPS prototype for most IoT embedded systems. Although the proposed UPS prototype design can also be successfully used on non-OS (Operating System) IoT embedded platforms, with minor adaptations, the focus experimentation in this article will be on the every student's favorite, but power demanding, Raspberry Pi 4 Model B. Basically, being a complete and miniaturized OS computer, the popular Raspberry Pi 4 is a very adamant candidate for tight input DC power parameters, that work in direct correlation with the system's stability and performance. The final goal of the proposed UPS prototype is to provide Raspberry Pi 4 with enough independent runtime, until it safely shuts down the OS, in case of an external power blackout, and start back on at an external power restore event, all in order to protect the file system stability, or the data acquisition and storage processes from corruption.*

Keywords: *power blackout; Raspberry Pi IoT embedded system; UPS; BMS; lithium-ion battery; load sharing.*

1. INTRODUCTION

The UPS systems are not a new concept as they have been around for decades, mostly in the IT&C domain, with the precise purpose to protect the network storage and distribution systems like servers, firewalls, routers, media converters, desktop computers and so on [1]. They also play an important role in the hybrid renewable energy smart grids that require stored electrical energy operation from batteries, in case of the off-grid operation, because of a blackout from the utility grid [2].

Nowadays, these power backup systems have been scaled-down and embedded into smart homes, or smart portable devices such as smartphones, MP3 players, GPS navigators and geodetic surveying kits, portable speakers, flashlights, and basically any small and

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portable or fixed, electronic device [3]. On the other hand, with the advent of device miniaturisation through SMDs and advanced semiconductor electronic components, the compact embedded IoT systems begun to gain a lot of traction in the civilian, industrial, millitary, medical and all the commercial markets, sold in a variety of applications, with more and more powerful multi-core microprocessors (MPUs) that can do more tasks faster and more energy efficient, than its bulky power demanding predecessors [4].

As a consequence of device miniaturisation, the design physics trade-offs never hesitate to show up. Thus, having such a big computing power at high frequencies (GHz range), condensed in such a small volume silicon die, translates into additional power consumption generated by the conduction losses due to resistance or material impurities, which converts to heat. Added to the equation, are also the cooling systems (heatsink fans) that also require a certain percent of the overall input power, and the AC-DC or DC-DC converters operating efficiencies, that can never be ideal, thus more losses and current draw will be required from the main power supply, either from batteries or from a direct source [5].

From the diversity and availability point of view, there is no secret that the global electronics markets, are overflooded with all kinds of UPS, BMS and power bank devices or modules, either cheap or expensive, and more or less safe to use, where many of the manufacturers state ”the best experience for the user” regarding their products, which later prove to be only „misleading advertising claims”, in the user experience feedback comment section [6]. In short, diverse as they come, remarkably, only few of them manage to serve the real purpose that were designed for.

In this regard, this article investigates a possible UPS (with BMS) system approach, for IoT embedded systems, with affordable costs, components availability and moderated energy consumption.

2. THEORETICAL ASPECTS AND PROTOTYPE DESIGN OPERATION

Unlike most of the portable Li-Ion or Li-Po powerbanks, that don’t support load sharing function, being either used in charging mode (i.e. connected to a 230 V_{AC} wall charger), or in battery mode (i.e. connected to a smartphone as a DC backup charger), the proposed UPS system needs to continuously operate, provide enough power and protect the power consuming device, either in external supply source with battery charging mode, or in the battery power source mode [7].

In order to develop such a demanding load sharing UPS system that is up to the task for Raspberry Pi 4 or other similar platforms, a variety of factors were needed to be taken into account, such as:

- USB-PD (Power Delivery) compatibility for power demanding IoT systems with 5 V (± 0.25 V) output voltage standard at 3A output current sourcing;
- system components electrical parameters dimensioning for compatibilization;
- system load sharing function with UPS function;
- circuit electrical safety and system components protection with BMS function;
- components availability at moderate costs;
- power efficient;
- support Li-Po battery alternative;
- small form factor and portability.

Based on multiple research areas, acquired information and technical data availability from the manufacturers, a theoretical UPS system design was proposed in (Fig. 1.), described as a block diagram [8]. As a reference for simulation and experimentation, the popular

Raspberry Pi 4 IoT embedded system was used and also an aftermarket 3.2A adjustable electronic load (EL). The UPS system consists in several dedicated modules as well as passive and active components, all interconnected and each with its specific function as follows in the diagram description list:

- U1 is the external SMPS (Switch Mode Power Supply) power source;
- U2 is the internal Li-Ion battery pack power source;
- IC1 is the Li-Ion battery charger;
- IC2 is the Li-Ion battery protection module;
- IC3 and IC4 are DC-DC boost converters;
- D1 is the Schottky diode;
- Q1 and Q2 are logic P-Channel MOSFET transistors;
- C1 is the boost regulator input electrolytic capacitor;
- R1, R2, R3, R4, R5 and R6 are typical resistors;
- F1 is the Li-Ion battery pack fuse;
- LED1 and LED2 are the Fuse Fault (FF) and the Battery Fault (BF) warning LEDs;
- MCU is the Attiny microcontroller (where A0 and A1 are the ADC analog input pins, while D0, D1, D3 and D4 are the digital output logic pins);
- MPU is the Raspberry Pi 4 IoT embedded system under evaluation (consumer).

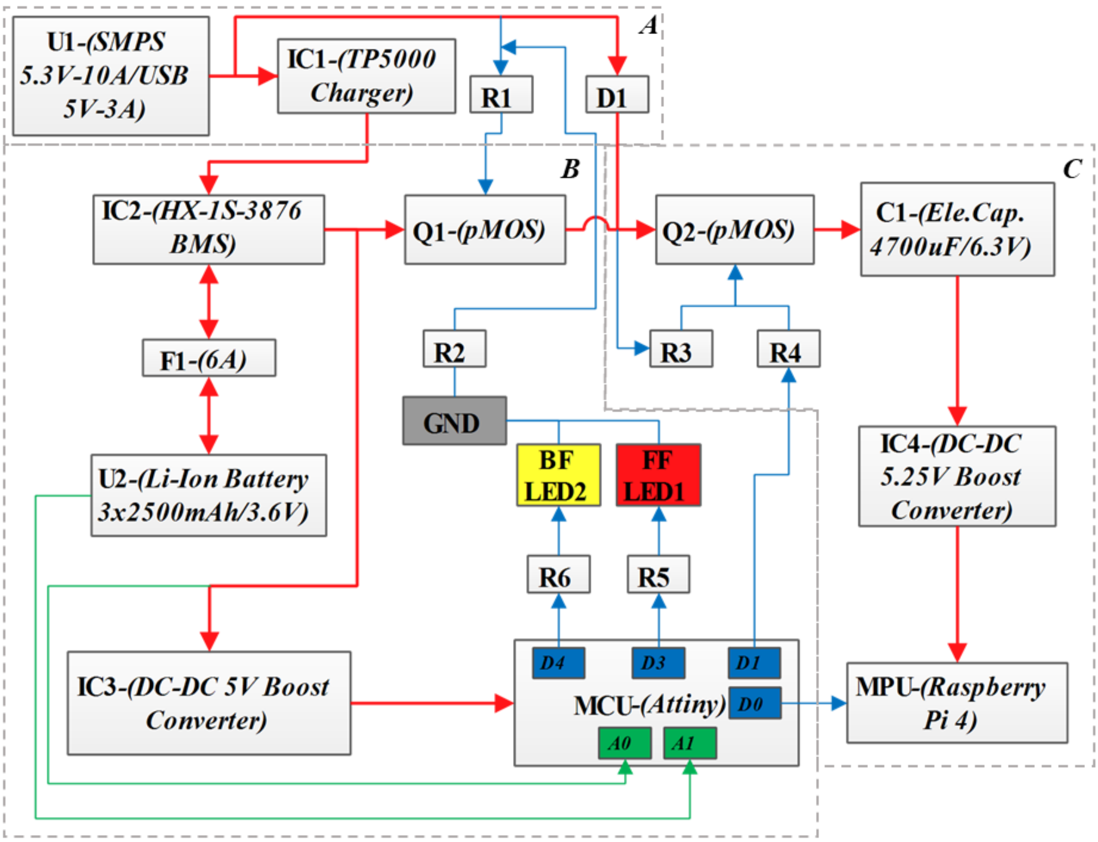


Figure 1. Theoretical block diagram of the proposed UPS system with logic signals (blue) and power path (red).

As it is observed, the diagram consists of three main blocks, where block ***A*** (external SMPS power supply block) is represented by the U1, IC1, and D1, block ***B*** (internal Li-Ion battery power supply block with the logic block) is represented by the IC2, F1, U2, IC3, Q1, R1, R2, LED1, LED2, R5, R6 and MCU, while block ***C*** is interleaved with power blocks ***A*** and ***B***, and is represented by Q2, R3, R4, C1, IC4 and MPU.

In order to compatibilize the UPS system modules and components, a particular set of electrical parameters of interest were extracted from the manufacturer datasheets, best described in Table 1.

Table 1. Particular electrical parameters of the UPS system modules and components.

Component/module	Model name/serial	Electrical minimum and typical parameter ratings	Electrical maximum parameter ratings
***U1*-Industrial SMPS**	Mean Well LRS-50-5 [9]	- Input voltage: 230 V_{AC} - Output current: 10 A - Adjusted output voltage: 5.3 V_{DC} - Efficiency: 83 %	-
***U2*-Li-Ion battery pack**	Samsung INR18650-25R (3 identical balanced pcs. connected in parallel with 7500mAh capacity in total) [10]	- Nominal capacity: 2500 mAh - Nominal voltage: 3.6 V_{DC} - Discharge cut-off voltage: 2.5 V_{DC} - Standard charge: 4.2 V (± 0.05 V) at 1.25 A	- Continuous discharge: 20 A
***IC1*-Battery charger module**	Sanya buck regulator module (TP5000 chip) [11]	- Charge current: 1 A - Input voltage: 5 V_{DC} (typ.) - Output voltage: 4.2 V_{DC} - Charging cut-off voltage: 4.15 V_{DC} (min.), 4.2 V_{DC} (typ.) - Trickle charge voltage threshold: 2.8 V_{DC} (min.), 2.9 V_{DC} (typ.)	- Input voltage: 9 V_{DC} - Charging cut-off voltage: 4.24 V_{DC} - Trickle charge voltage threshold: 3 V_{DC}
***IC2*-Battery protection module**	HX-1S-3876 6 x MOSFET Li-Ion protection module (DW01B-G chip) [12]	- Overcharge protection voltage (VOCP): 4.25 V_{DC} (min.), 4.30 V_{DC} (typ.) - Overcharge release voltage (VOCR): 4.05 V_{DC} (min.), 4.10 V_{DC} (typ.) - Overdischarge protection voltage (VODP): 2.30 V_{DC} (min.), 2.40 V_{DC} (typ.) - Overdischarge release voltage (VODR): 2.90 V_{DC} (min.), 3.00 V_{DC} (typ.) - Operating charging/discharging current: 9 A (typ.)	- Overcharge protection voltage (VOCP): 4.35 V_{DC} - Overcharge release voltage (VOCR): 4.15 V_{DC} - Overdischarge protection voltage (VODP): 2.50 V_{DC} - Overdischarge release voltage (VODR): 3.10 V_{DC} - Operating charging/discharging current: 12 A

Component/module	Model name/serial	Electrical minimum and typical parameter ratings	Electrical maximum parameter ratings
***IC3*-Boost converter module**	USB module (CE8301 chip) [13]	- Input voltage: 0.9 V_{DC} - V_{OUT} - Efficiency: 85 % - Output voltage: 5.05 V_{DC} - Output current: ~500 mA (typ.)	-
***IC4*-Boost converter module**	Pololu U3V50ALV boost regulator module (TPS55340 chip) [14]	- Input voltage: 2.9 V_{DC} - V_{OUT} - Efficiency: 80 % to 95 % - Output current: 5 A (typ.) - Adjusted output voltage: 5.25 V_{DC}	- Output current: 5.5 A
***D1*-Schottky diode**	Yangjie Technology SR520 [15]	- $I_{F(AV)}$: 5 A (typ.) - V_{RRM}: 20 V - V_{FM} at 5 A: 0.55 V (typ.) - I_{RRM} at 25°C: 200 µA	-
***Q1*, *Q2*-P-MOS**	Infineon IPP80P03P4L-04 P-ch. logic level MOSFET [16]	- V_{GS}: + 5 V to – 16 V - $V_{GS(th)}$: ($V_{DS} = V_{GS}$, I_D = 253 µA) = 1.0 V (min.), 1.5 V (typ.) - V_{DS}: 30 V - $R_{DS(on)}$: (V_{GS} = 4.5 V, I_D = 80 A) = 5.0 mΩ (typ.) (V_{GS} = 10 V, I_D = 80 A) = 3.7 mΩ (typ.) - C_{iss}: 8670 pF (typ.)	- $V_{GS(th)}$: ($V_{DS} = V_{GS}$, I_D = 253 µA) = 2.0 V - $R_{DS(on)}$: (V_{GS} = 4.5 V, I_D = 80 A) = 7.0 mΩ (V_{GS} = 10 V, I_D = 80 A) = 4.4 mΩ - C_{iss}: 11300 pF
***C1*-Electrolytic capacitor**	Samwha WL1C478M1631MB B - low ESR electrolytic capacitor [17]	- Capacitance: 4700 µF - Operating voltage: 16 V_{DC} - Ripple rms current: 2600 mA - Impedance at 20C°, 100 kHz: 0.025 Ω	-
***R1*, *R2*, *R3*, *R4*, *R5*, *R6*-Resistors**	Standard carbon film and metal film resistors [18]	- Rated power: 0.25 W - Resistance: 270 Ω and 100 kΩ	-
***F1*-Fuse**	Fast burning fuse [19]	- Rated current: 6.3 A - Rated voltage: 250 V	-
***LED1*, *LED2*-Light emitting diodes**	Bicolor LED [20]	- Operating voltage: 2.4 V - Rated current: 20 mA	-
***MCU*-Microcontroller**	Attiny13 microcontroller [21]	- Operating voltage: 2.7 V_{DC} to 5.5 V_{DC}	-

Component/module	Model name/serial	Electrical minimum and typical parameter ratings	Electrical maximum parameter ratings
***MPU*- Microprocessing Unit**	Raspberry Pi 4 [22]	- Input voltage: 4.7 V_{DC} (min.), 5.25 V_{DC} (typ.) - Input current: 1.2 A (min.) - Internal operating voltage: 3.3 V_{DC}	- Input voltage: 5.5 V_{DC} - Input current: 3 A

These essential electrical values offer a more comprehensive understanding on how each module will work when connected in the UPS system, what are its electrical thresholds or limits and if it is the best suited module for the purpose in the overall system.

The next step is represented by the conception of an electrical circuit schematic of the prototype UPS system, that will further materialise in an experimental prototype (Fig. 2.).

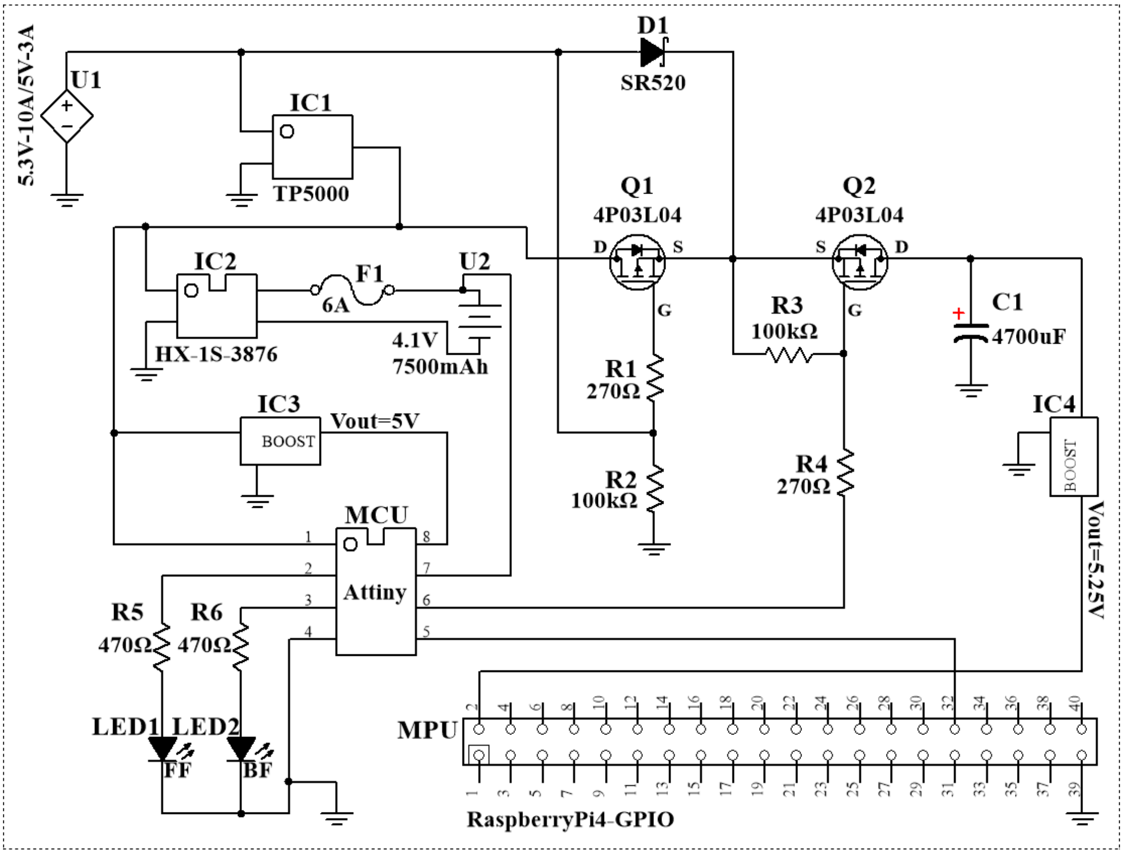


Figure 2. Circuit diagram of the practical prototype UPS system.

Taking into consideration all the electrical parameters of the UPS system modules and components, described in Table 1, a theoretical operation explanation is elaborated below, with two working scenarios.

➢ ***External Power Supply Operation Mode***

As the UPS system, with the MPU load connected, is being powered up by U1, which has a fixed 5.3 V_{DC} adjusted output voltage and can deliver a maximum 10 A of current, the input of the IC1 draws a maximum of 1.2 A current at the same voltage, which being a buck converter will output a fixed 4.2V_{DC} voltage at a maximum preset 1 A of current. This current goes through the IC2 and F1 protection block to the U2, charging it according to its initial Depth of Discharge (DOD) [23]. Consequently using three Li-Ion cells in parallel, a total capacity of 7500 mAh of the battery pack is reached, and if the cells are evenly balanced and discharged to a minimum of 2.9 V_{DC} threshold voltage recommended by the IC1 manufacturer, the maximum theoretical charging current for each cell will be (1):

$$U2_{CELL[I\_IN\_MAX]} = \frac{IC1_{[I\_OUT\_MAX]}}{3} = \frac{1000mA}{3} = 333.33mA \quad (1)$$

where $U2_{CELL[I\_IN\_MAX]}$ is the theoretic maximum input current in each individual battery pack cell, while $IC1_{[I\_OUT\_MAX]}$ is the maximum charging output current of the Li-Ion battery charger.

As an important mention, the IC1 will trickle charge the U2 if a voltage equal or smaller than 2.8 V_{DC} is detected, and will end the normal charge if a 4.2 V_{DC} voltage is reached [24]. Also, the BMS function of the UPS system is sustained by the IC1 and IC2 modules.

While operating, the UPS system will always power IC3 either from U1 or from U2 that raises the input voltage from a maximum of 4.2 V_{DC}, to almost 5.05 V_{DC} on the output, for the MCU to properly function. The MCU input voltage is important as it serves for the full 10 bit ADC of the microcontroller, in reading the maximum 4.2 V_{DC} U2 voltage, on the analog pin. The MCU has multiple functions and uses all the I/O digital and analog pins, for system monitoring, control and protection, as follows:

- PB5 (or pin 1) – is configured as an Analog-In ADC pin that monitors the U2 voltage before the IC2 and F1, and compares it to the voltage sensed by the PB2 connected to U2. When the voltages of the two analog input pins match exactly, LED1 of FF is turned off, else is turned ON.
- PB3 (or pin 2) – is configured as a Digital-Out pin that turns LED1 ON, when F1 is burned (FF), due to a short circuit of U2 or an overcurrent of more than 6 A.
- PB4 (or pin 3) – is configured as a Digital-Out pin that turns LED2 ON, when U2 reaches a critical voltage lower than 3.3 V_{DC} (BF). Also, when U2 voltage is higher than 3.3 V_{DC}, the LED2 representing BF, is turned off.
- GND (or pin 4) – is the ground pin of the MCU.
- PB0 (or pin 5) – is configured as a Digital-Out pin that initiates the shutdown procedure of the MPU with a LOW signal pin, when U2 voltage level is critical of under 3.3 V_{DC}, and there is no external supply power from U1 to charge U2 above the mentioned threshold voltage.
- PB1 (or pin 6) – is configured as a Digital-Out pin that keeps Q2 Gate turned on through R4 resistor with a LOW signal pin, as long as U2 is over 3.3 V_{DC} as the MPU is operating. Else, the Q2 is turned off through R3 pull-up resistor if the U2 voltage level drops under 3.3 V_{DC}, but only after PB0 initiate the shutdown procedure which is immediately followed by the standby mode of the MPU.
- PB2 (or pin 7) – is configured as an Analog-In ADC pin that monitors the voltage of U2 to be compared to PB5 voltage read and to signal the PB4 LED2 if there is a BF event.
- VCC (or pin 8) – is the 5V_{DC} supply pin of the MCU.

Fig. 3 describes a simplified algorithm of the MCU that reflects the previous interpretations and operation of the UPS system logic.

Two important aspects are explained, by observing the flowchart.

The first aspect, is that digital pin D1 is kept HIGH when A1 input pin value is lower or equal to 3.3VDC threshold voltage of U2 which does not conflict with the voltage difference at [Q1,Q2]S common node because of the R3 pull-up high resistance, but on the contrary, it helps Q2 Gate to be more biased into the off state through R4 low resistance, receiving a 5 V_{DC} signal from MCU.

The second aspect, is that D0 pin is declared in the program loop as an input pull-up pin, when A1 input pin value is higher than 3.3VDC threshold voltage of U2, in order to reset the MCU pin state going into MPU GPIO pin.

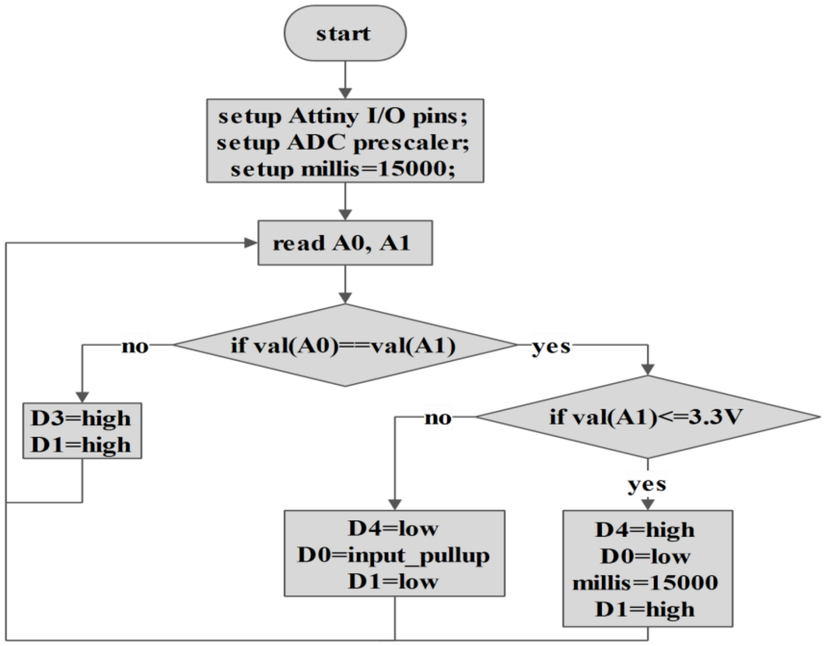


Figure 3. Simplified flowchart of the program in the MCU.

As a side note, the MPU has a script installed that will call a shutdown procedure of itself (Fig. 4.), when the MCU sends a LOW signal on the GPIO12 MPU pin, when U2 is under the safe operation voltage threshold.

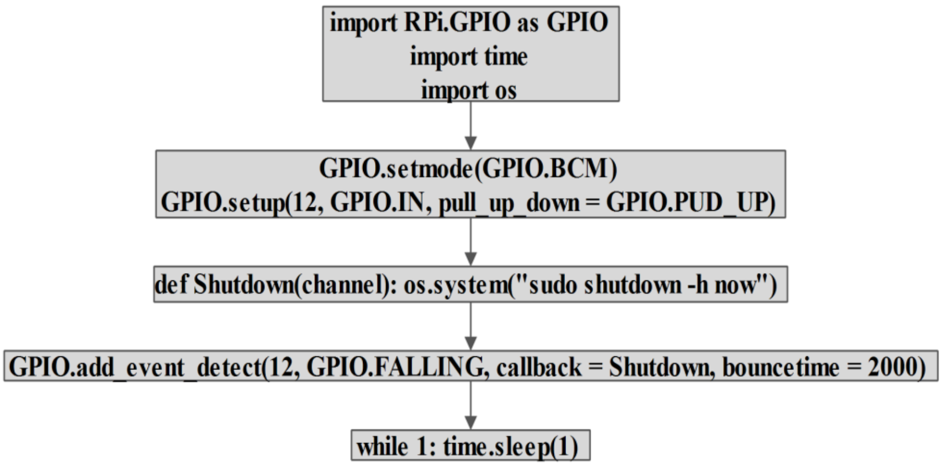


Figure. 4. MPU shutdown procedure script when the GPIO12 is pulled LOW by the MCU.

As long as U1 power delivery to the circuit is present, Q1 Gate will always be turned off through R1 pull-up resistor, while the internal body diode $Q1_{BD}$ will be blocked from conducting current from the U2 to the Q1,Q2 Source, due to the reverse voltage bias formed. Therefore the voltage potential at Q1,Q2 Source will always be higher than at Q1 Drain, when in external power mode, from U1.

Also, when in external power mode from U1, D1 is forward biased and has a typical voltage drop of approximately $0.55V_{DC}$ at a 5A operation current.

Thus the common Source node voltage of Q1 and Q2 will theoretically be (2):

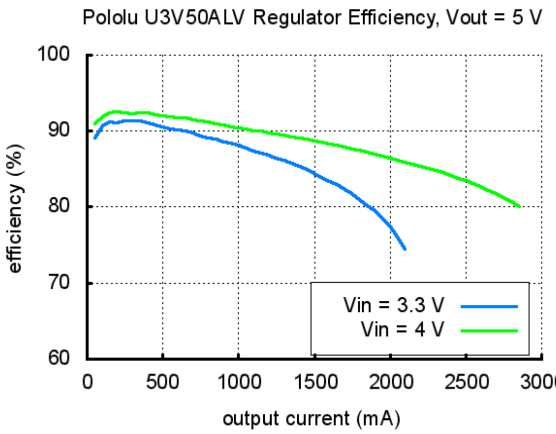
$$[Q1,Q2]_{VS} = U1_{V\_OUT} - D1_{VF} = 5.3V - 0.55V = 4.75V \tag{2}$$

where $[Q1,Q2]_{VS}$ is the common Source node voltage of the two P-MOS transistors ($Q1$,$Q2$), $U1_{V\_OUT}$ is the nominal output voltage of 5.3 V_{DC} of the external power supply, and $D1_{VF}$ is the typical forward voltage drop of 0.55 V_{DC} of the diode, at 5 A operation current, stated in the datasheet [15].

Just as in the Q1 case, the Q2 Gate is by default turned off through R3 pull-up resistor, whenever a voltage is present at the Q1 and Q2 common Source node, but turned on through R4 by the MCU with a LOW signal pin, when firstly F1 is verified as operational and U2 is verified as having a safe upper voltage level described earlier in the upper section, therefore the MPU will be operational only if these two conditions are met. This is just another safety feature implemented in the UPS system in order to protect the MPU system files and storage process from corruption, but also to protect U2 from damage and misuse.

C1 is in parallel with the input electrolytic capacitor of the IC4, and form a voltage ripple filtering block that also serves as a voltage buffer to protect the IC4 from sudden voltage changes, when the power supply to the MPU load is shared between U1 and U2. It is not an essential component, but just adds an extra layer of protection to the system.

The most important component of the UPS system is the IC4 that raises the input voltages between ~3.28 V_{DC} (min.) and ~4.89 V_{DC} (max.), in order to supply the MPU with a steady voltage of 5.25 V_{DC} and a 3 A maximum required current operation, at the specified 80% to 95% boosting efficiency. The IC4 power efficiency is comparatively depicted in Fig. 5 for a 4 V_{DC} and a 5 V_{DC} input voltage corresponding to a 5 V_{DC} and a 6 V_{DC} output voltage.



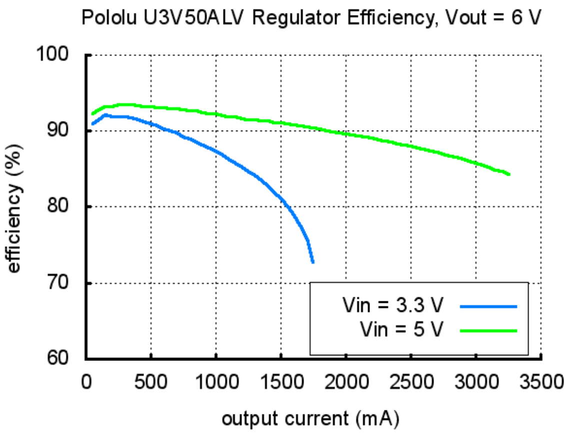


Figure. 5. IC4 (U3V50ALV boost converter) power efficiency comparison at two different input and output voltages.

In in general, in order to calculate the power efficiency for a single output, DC-DC regulated switch converter, as the one discussed, relation (3) is calculated:

$$\eta = \frac{1}{1 + \frac{P_{IN(I0)}}{P_{OUT}} + \frac{P_{OUT}}{P_{IN(I\max)}}} \tag{3}$$

where η is the power efficiency of the converter, $P_{IN(I0)}$ is the measured input power with no output load (just internal losses), P_{OUT} is the output power, $P_{IN(Imax)}$ is the measured input power at the maximum current load. As an important mention, basically in any electronic circuit, there will be power losses regardless if there is an output current load or not, due to internal losses, through semiconductor material, resistance and heat.

Another way of looking at the $P_{IN(I0)}$ and $P_{IN(Imax)}$ is in relation (4) and (5):

$$P_{IN(I0)} \equiv I_{OUT} = 0 \tag{4}$$

and

$$P_{IN(I\max)} \equiv \frac{P_{OUT(\max)}^2}{P_{IN(\max)} - P_{OUT(\max)} - P_{IN(I0)}} \tag{5}$$

where $P_{IN(max)}$ is the maximum input power and $P_{OUT(max)}$ is the maximum output power [25].

- ***Internal Power Supply Operation Mode***

The primordial rule for the system to function is that F1 must be operational, else, if F1 is blown, the whole system remains shut down until the fuse is replaced because there is no power going into IC3 for the MCU logic to function. Also, if U2 is under 3.3 V_{DC}, the system waits for the U1 to become available to charge U2 over 3.3 V_{DC}, in order to power up the MPU. If U1 becomes available in an external power restore event, IC3 is powered through IC1 with 4.2 V_{DC} and consequently the MCU is also powered, which assess the BF and FF condition and acts in accordance over Q2. If the FF condition is met (F1 is broken), LED1 is lit and Q2 is kept turned off until the issue is addressed, and if the BF condition is met, LED2 is lit and Q2 is also kept turned off until U2 charges over 3.3 V_{DC}, therefore in these two scenarios, the MPU is kept in a shutdown mode. This safety feature was designed in order to give U2 enough time to charge up to a safe operation voltage level, in order to properly conduct the complete power up and shutdown procedure of the MPU, in case U1 is repeatedly in an ON and OFF state a few times, in a short period of time.

As the UPS system, with the MPU load connected, is being powered up by U2, because U1 is not available due to a power outage, the current of U2 travels through F1 and IC2 protection block (which is bidirectional), and then powers up the MCU through IC3, which assesses the BF and FF condition explained earlier and acts over the Gate of Q2. Assuming the BF and FF conditions are not met (both U2 and F1 are in an operational state), the current flows through $Q1_{DS}$ (Drain-Source), as the Gate is pulled low by R2, forming an internal current flowing channel and bypassing the internal body diode $Q1_{BD}$, with a minimum voltage drop induced by the $R_{DS(on)}$ of Q1. The D1 is in reverse bias mode and therefore its main role is to block the current from reaching back to U1 thus also biasing through R1 of Q1, pulling the Q1 Gate high (turning it OFF), and forcing the transistor to conduct only through $Q1_{BD}$, which in consequence would mean a higher voltage drop on $Q1_{DS}$ and a greater power loss due to heating. In this configuration, Q1 is not allowed to conduct through the $Q1_{BD}$, but if D1 has a large reverse leakage current of over several mA, or is not the right type of diode, then theoretically, relation (6) would hint towards a faulty operation of Q1:

$$Q1_{VS} = U2_{V\_out} - Q1_{BD(VF)} = 4.2V - 1.2V = 3V \tag{6}$$

where $Q1_{VS}$ is the Q1 Source voltage, $U2_{V\_out}$ is the maximum output voltage of 4.2 V_{DC} of the internal power supply, and $Q1_{BD(VF)}$ is the maximum forward voltage drop of 1.2 V_{DC} of the transistor body diode, stated in the datasheet [26]. Thus a 3 V_{DC} would not suffice for the IC4 input, to properly boost the voltage to 5.25 V_{DC} required by the MPU at a 3 A current draw.

As an important mention, the only time $Q1_{BD}$ is forward biased, is when Q2 is off because the Gate is pulled HIGH by the MCU, and it is also biased by $[Q1,Q2]_S$ node positive voltage potential through R3, when U1 is not available. The $Q1_{DS}$ and $Q2_{SD}$ (Source-Drain) would not impose any significant voltage drop even at a maximum of 5.5 A current draw of the IC4, from U2, as the $R_{DS(on)}$ (Drain-Source ON-resistance) of these types of MOSFETs produce an insignificant voltage drop of few tenths of millivolts at the specified current, in the proposed UPS system [27]. To calculate the $R_{DS(on)}$ of a MOSFET, relation (7) is computed:

$$R_{DS(on)} = \frac{V_{DS}}{I_D} \tag{7}$$

where $R_{DS(on)}$ is the Drain-Source resistance of the MOSFET in the ON state, while V_{DS} is the voltage drop across the Drain-Source of the MOSFET at a fixed current source I_D.

3. EXPERIMENTAL RESULTS AND CALCULUS

The entire experimentation was conducted on the proposed UPS system prototype, with all the modules and components assembled according to the proposed electric circuit schematic. The practical system is best described in Fig. 6. The resistors R1, R2, R3, R4, R5 and R6 were omitted from numbering from obvious reasons.

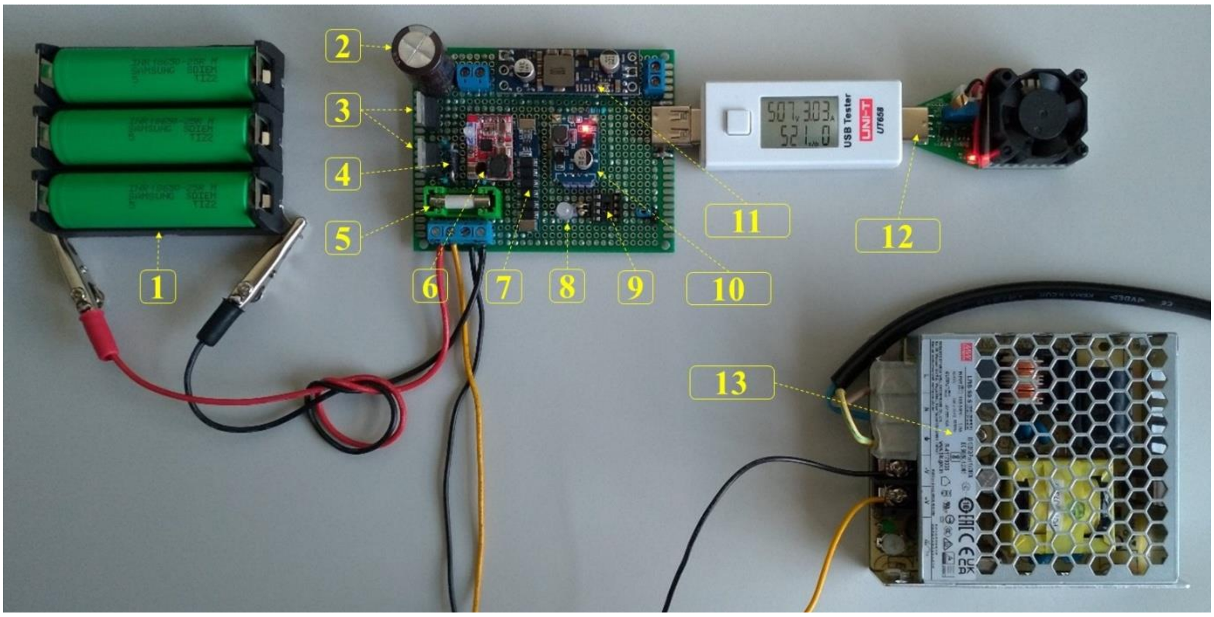


Figure 6. Assembled UPS system prototype on a testing board with modules and components as follows: 1-Li-Ion battery pack (U2), 2-electrolytic capacitor (C1), 3-MOSFET transistors (Q1 and Q2), 4-Schottky diode (D1), 5-fast blowing fuse (F1), 6-battery charger module (IC1), 7-battery protection module (IC2), 8-bicolor LED1,2 (BF and FF), 9-microcontroller socket (MCU), 10-MCU boost converter (IC3), 11-MPU boost converter (IC4), 12-electronic load with USB voltage and current tester (EL or MPU), 13-switched mode power supply (U1).

As a practical aspect, the Raspberry Pi 4 (MPU) can be either used in headless mode as a data server, with minimum peripherals or without any, to achieve a lower power consumption (~4.62 W), or fully equipped with peripherals for maximum performance and storage advantages, which also come with a higher power demand (~9.9 W). These power consumptions were calculated taking into consideration the internal $3.3V_{DC}$ voltage bus of the MPU and the additional heatsink case cooling fans, that draw up to 200mA while operating.

The MPU without peripherals or heatsink fans, can draw almost 1.2 A of current, by using all the four processor cores at once, in a 100% usage session. Using external hard drives or other power consuming peripherals attached to the MPU will increase the total current draw to a maximum of 3 A supported by the MPU's internal voltage regulator. In the experimentation session, the MPU was equipped with a dual fan, aluminum heatsink case, for optimal cooling, while benchmarking (Fig. 7), while after powering and booting the Raspberry Pi OS, a stress test software was installed in order to evaluate the total power consumption and system stability of the MPU, in headless mode without peripherals.

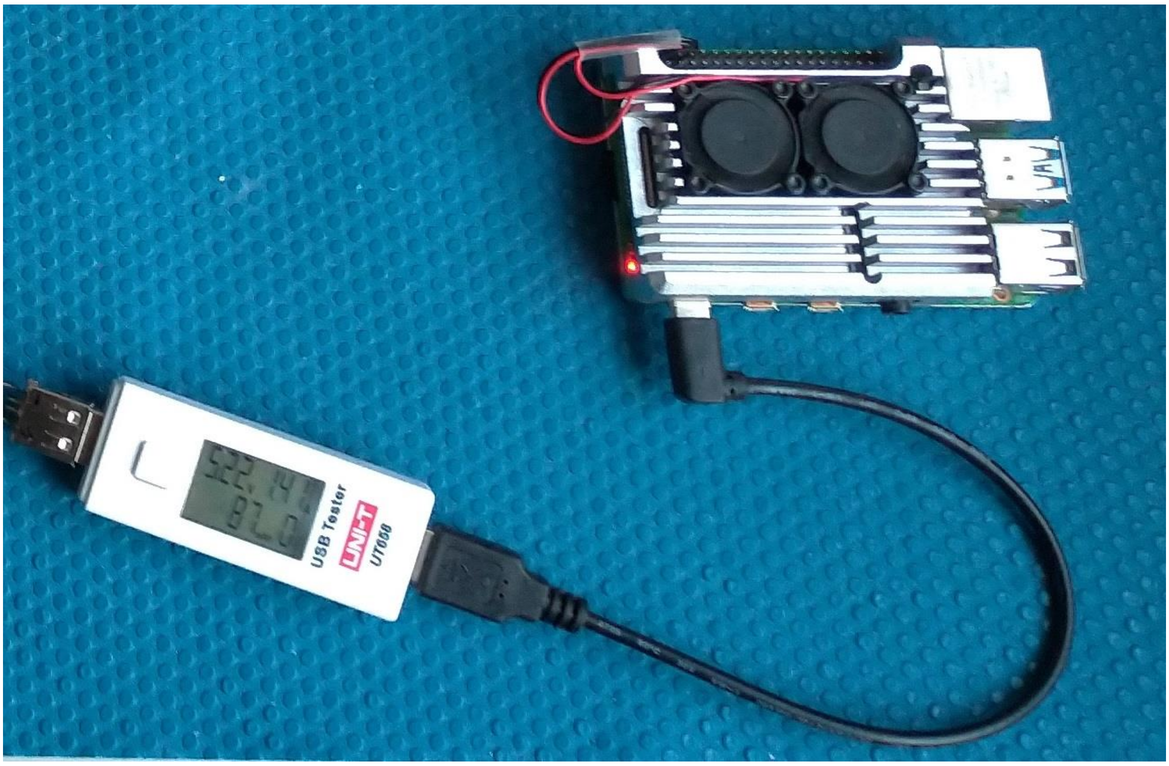


Figure 7. Headless mode MPU equipped only with a dual fan aluminum heatsink case, under stress test with 1.4A total current draw (4 cores).

A USB tester was also used in order to confirm the calculated output current draw and voltage drop of the Raspberry Pi4, when powered from U2 through IC4, under the stress test [28]. Reports showed the MPU performed very stable under the stress tests, and did not record a higher temperature than 42.3°C, due to the performant cooling system (Fig. 8.).

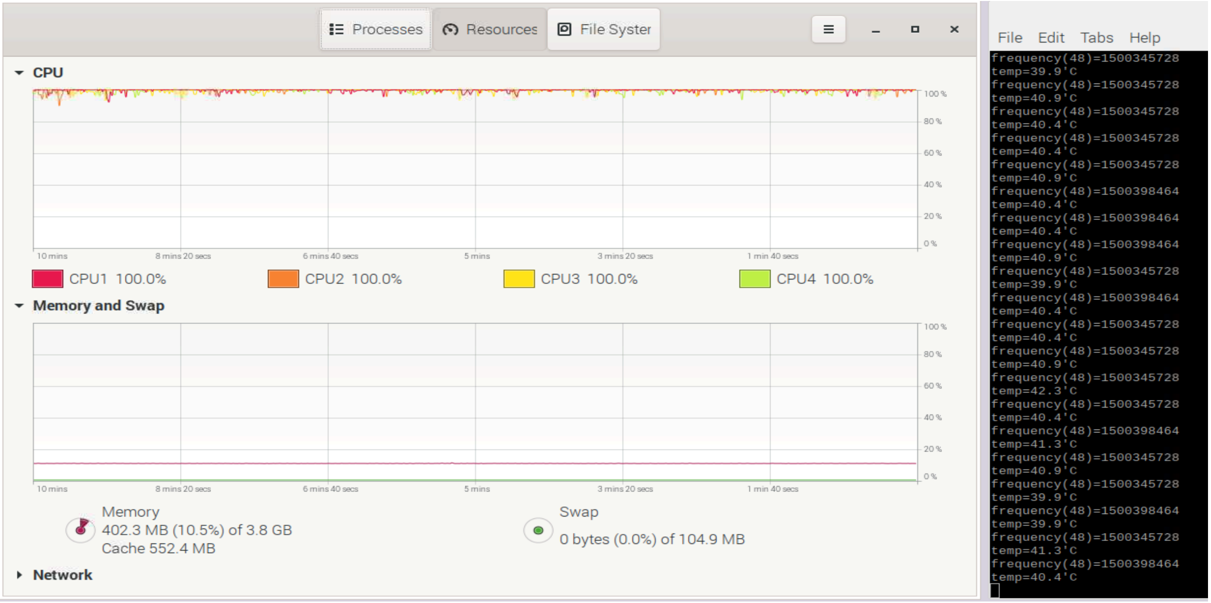


Figure 8. Benchmark and CPU monitor programs ran in parallel on the MPU, with all four cores at 100% exploitation.

The described benchmark was conducted during a 10 minute timespan with a maximum of 1.4 A current draw recorded in the presented configuration. The prototype UPS system was also subjected to two separate consumption sessions with an electronic load (EL), in order to simulate a 1.4 A current load of the MPU in headless mode without any external peripherals, and a 3 A current load of the MPU in full external peripherals mode. Measurements were conducted on U1 external power supply (SMPS) and on U2 internal power supply (Li-Ion battery pack) comprised by the UPS system. The measured results are presented in Table 2.

Table 2. Q1 and Q2 Drain-Source voltage drop measurements conducted with an electronic load adjusted at 1.4 A and 3 A with U1 and U2 current draw for each case.

<table>
<tr><td colspan="2">Electrical parameters</td><td colspan="5">4.19 V_{DC} (7500 mAh)</td><td colspan="5">5.3 V_{DC} (10 A)</td></tr>
<tr><td colspan="2">Current draw</td><td>$U2_{I\_out}$ at $U2_{V\_out}$</td><td colspan="4">Li-Ion battery pack voltage drop $U2_{V\_drop}$</td><td>$U1_{I\_out}$ at $U1_{V\_out}$</td><td colspan="4">SMPS voltage drop $U1_{V\_drop}$</td></tr>
<tr><td rowspan="12">EL current (I_{EL})</td><td rowspan="6">3 A</td><td rowspan="6">5.40 A at 3.85 V</td><td rowspan="2">$Q1_{VD}$</td><td rowspan="2">3.47 V</td><td rowspan="12">Measured D-S voltage drop</td><td rowspan="3">0.04 V</td><td rowspan="6">4.39A at 5.26 V</td><td rowspan="3">$Q2_{VS}$</td><td rowspan="3">4.73 V</td><td rowspan="12">Measured S-D voltage drop</td><td rowspan="6">0.02 V</td></tr>
<tr></tr>
<tr><td rowspan="2">$Q1Q2_{VS}$</td><td rowspan="2">3.43 V</td></tr>
<tr><td rowspan="3">0.05 V</td><td rowspan="3">$Q2_{VD}$</td><td rowspan="3">4.71 V</td></tr>
<tr><td rowspan="2">$Q2_{VD}$</td><td rowspan="2">3.38 V</td></tr>
<tr></tr>
<tr><td rowspan="6">1.4 A</td><td rowspan="6">2.15 A at 3.97 V</td><td rowspan="2">$Q1_{VD}$</td><td rowspan="2">3.91 V</td><td rowspan="3">0.01 V</td><td rowspan="6">1.90A at 5.28 V</td><td rowspan="3">$Q2_{VS}$</td><td rowspan="3">4.89 V</td><td rowspan="6">0.01 V</td></tr>
<tr></tr>
<tr><td rowspan="2">$Q1Q2_{VS}$</td><td rowspan="2">3.90 V</td></tr>
<tr><td rowspan="3">0.02 V</td><td rowspan="3">$Q2_{VD}$</td><td rowspan="3">4.88 V</td></tr>
<tr><td rowspan="2">$Q2_{VD}$</td><td rowspan="2">3.88 V</td></tr>
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</table>

As expected, because of the low input voltage and also the total system voltage drop, the IC4 boosting efficiency dropped dramatically to the almost maximum limit of 5.5 A current draw from the U2, while sourcing 3 A to the EL. This physical phenomenon occurred because of the voltage conversion difference between input and output of the IC4, that required more input current in order to keep the output voltage stable. Thus the overheating and overcurrent protection of the IC4 boost converter module occurred only for the 3A EL current draw scenario, after ~5 minutes of operation [29].

Measurements over C1 and D1 were also made, to test the input voltage ripple ΔV into the IC4 with or without C1 connected on the input, and the D1 voltage drop at $U1_{I\_out}$ of 4.39 A and 1.90 A respectively, corresponding with the 1.4 A and 3 A I_{EL} (Electronic Load current), with U1 power supply and U2 power supply respectively (Table 3.).

Table 3. C1 measured voltage ripple with and without it and D1 measured voltage drop for U1.

Component	$\mathbf{I_{EL}}$	Measured parameters		***Li-Ion battery pack (U2)***	***SMPS (U1)***
C1	3 A	With C1	ΔV voltage ripple	18.80 mV	26.40 mV
		Without C1		14 mV	30 mV
	1.4 A	With C1		14.60 mV	36.80 mV
		Without C1		16 mV	104 mV
D1	3 A	V_F		N/A	0.53 V
	1.4 A				0.39 V

As expected, the C1 mitigated most of the voltage ripple when the UPS prototype was in U1 external power supply mode at 1.4 A I_{EL} which corresponds to 1.90 A $U1_{I\_out}$ at 5.28 V_{DC} $U1_{V\_out}$, which being an AC-DC SMPS it inherited an AC ripple as well as a switching ripple from the internal variable duty cycle [30].

In U2 internal power supply mode, the voltage and current was mostly linear due to the nature of the battery construction and internal resistance. Some ripple was indeed recorded from the IC4 and IC3, but with minimum impact on the total output power or MPU stability.

Not surprisingly, D1 performed according to the expectations, as the V_F forward voltage drop at an almost 4.39 A $U1_{I\_out}$, was close to the datasheet stated values.

Another essential observation from the experimentation was that IC4 began to drop the output current when the input voltage dropped under 3.2 V_{DC}, in the 3 A I_{EL} current draw scenario, therefore confirming that the UPS system optimum threshold voltage for operation should remain at 3.3 V_{DC} programmed into the MCU logic.

One interesting fact noticed in the conducted measurements was that the highest $R_{DS(on)}$ was recorded obviously when the highest current load passed through Q1 and Q2 Drain-Source. As a result, in the 3 A I_{EL} current draw for the $U2_{I\_out}$ scenario, an operating current of 5.40 A and a $U2_{V\_drop}$ of 0.04 V_{DC} voltage drop were measured, thus according to relation (7), the $R_{DS(on)}$ was 0.007 Ω, which it is the maximum internal resistance value, stated in the transistors datasheet, at a particular V_{GS} voltage (Fig. 9.).

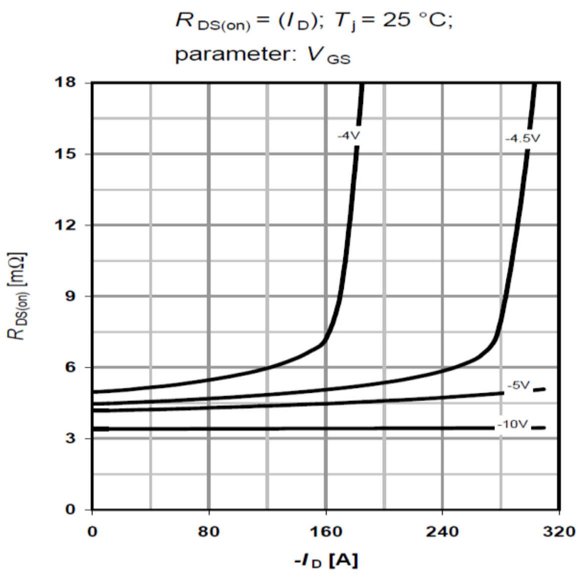

Figure 9. $R_{DS(on)}$ vs V_{GS} characteristic of Q1 and Q2 found in the datasheet [31].

The dissipated power either in Q1 or Q2 while operating under the largest measured current, is calculated as (8):

$$P_{diss} = I_D^2 \times R_{DS(on)} = 0.204W \tag{8}$$

where P_{diss} is the dissipated power in the transistor of 0.2W, I_D^2 is the drain current and $R_{DS(on)}$ is the Drain-Source internal resistance [32].

In this case, the TO-220 package of Q1 and Q2 can easily withstand up to 1W of dissipated power, without generating heating problems that can increase the $R_{DS(on)}$ value above the mentioned threshold.

The total U1 and U2 current source (I), at the maximum I_{EL} current draw of 3A, is calculated in (9) and (10):

$$I_{U1} = \sum_{k=1}^{N} i_{nk} = i_{IC1} + i_{IC2} + i_{IC3} + i_{MCU} + i_{D1} + i_{Q2} + i_{IC4} + i_{MPU} = 4390mA \tag{9}$$

and

$$I_{U2} = \sum_{k=1}^{N} i_{nk} = i_{IC2} + i_{IC3} + i_{MCU} + i_{Q1} + i_{Q2} + i_{IC4} + i_{MPU} = 5400mA \tag{10}$$

where I_{U1} and I_{U2} is the total current source for the UPS system components from U1 or U2 respectively in milliamperes, N is the total number of consumers, i_{nk} is the current draw of each module or component.

In Table 4, the ON and OFF condition of Q1 and Q2 are verified, by the V_{GS} calculated values.

Table 4. Q1 and Q2 On/Off state calculations.

	ON state	**OFF state**
E-MOS logic rule	$V_G < V_S$ $V_{GS} < V_{GS(th)}$	$V_G > V_S$ $V_{GS} > V_{GS(th)}$
Q1 electrical	$V_S = U2_{V\_out} - V_{DS} = 3.43$ V	$V_S = U1_{V\_out} - VD1_{VF} = 4.73$ V

	ON state	OFF state
parameters logic	$V_G = 0$ V	$V_G = 5.26$ V
	$V_{GS} = V_G - V_S = 0 - 3.43 = - 3.43$ V	$V_{GS} = V_G - V_S = 5.26 - 4.73 = 0.53$ V
	$V_{GS(th)} = - 2$ V (max)	$V_{GS(th)} = - 1$ V (min)
	- 3.43 V < - 2 V	0.53 V > - 1 V
Q2 electrical parameters logic	$V_S = U1_{V\_out} - VD1_{VF} = 4.73$ V	$V_S = U1_{V\_out} - VD1_{VF} = 4.73$ V
	$V_G = 0$ V	$V_G = 4.73$ V
	$V_{GS} = V_G - V_S = 0 - 4.73 = - 4.73$ V	$V_{GS} = V_G - V_S = 4.73 - 4.73 = 0$ V
	$V_{GS(th)} = - 2$ V (max)	$V_{GS(th)} = - 1$ V (min)
	- 4.73 V < - 2 V	0 V > - 1 V

Based to the measured values found in Table 2, the operation voltage of the logic level transistors that were used as a switch in the UPS system, were then calculated in Table 4 for each case. Also the maximum and minimum threshold values of $V_{GS(th)}$ were taken into account for better precision and certainty that they are fully operating in the ON or OFF state, and consequently provide the maximum demanded current at the minimum possible $R_{DS(on)}$. Therefore as long as the P-Channel MOSFETs Q1 and Q2 receive a positive voltage biasing on the Gate, they will be OFF.

In order to estimate the total runtime of the UPS system with U2, in the 3 A I_{EL} maximum power consumption scenario, with the 3.6 V nominal voltage, relation (11) is computed:

$$\begin{aligned} &Q_{nom} = 2500mAh \\ &V_{nom} = 3.6V \\ &E_{nom} = V_{nom} \times Q_{nom} = \frac{3.6V \times 2500mAh}{1000} = 9Wh \\ &P_{tot} = A \times V = 5.40A \times 3.85V = 20.79W \\ &t_{UPS} = \frac{3 \times E_{nom}}{P_{tot}} = \frac{3 \times 9Wh}{20.79W} = 1.29h \end{aligned} \tag{11}$$

where t_{UPS} is the total time that the UPS system can provide backup power to the MPU at maximum load (3
A), Q_{nom} is the nominal capacity of each Li-Ion battery cell, V_{nom} is the nominal cell voltage, E_{nom} is the nominal energy in a single Li-Ion battery cell, while P_{tot} is the total instantaneous power drawn from U2 Li-Ion battery pack at that moment [33].

4. CONCLUSIONS

The main conclusion drawn from the presented experimentation and calculations, is that the proposed UPS system prototype, at a maximum of 3 A load scenario from the MPU (simulated with the electronic load *EL*), and with a maximum power consumption and power losses mainly from the IC4 boost converter, the U2 internal power supply composed of 3 Li-Ion cells, would theoretically provide enough runtime of the MPU for 1.29 hours. Realistically speaking, the runtime would be three times or even four times lesser, of about 30 minutes, as the current draw is indeed large enough to drain the three Li-Ion cells in a short timespan, within the current discharge rate of the batteries. For the 1.4 A current draw scenario, with Raspberry Pi in headless mode, with no additional power consuming accessories, the t_{UPS} theoretical runtime is calculated to be 3.16 hours according to relation (11).

Another important conclusion is that at the previously measured current draw of 5.48 A at the IC4 input, in order to source 3 A output load with the required voltage boost, the measured input current value was very close to the 5.5 A maximum stated input current of the boost converter in the datasheet. Thus as the voltage of U2 dropped because of the power consumption, the IC4 begun to overheat due to the larger and larger voltage differences between the input and the output, resulting in a loss of conversion efficiency because of internal power losses due to heating. This resulted in a *hiccup mode* overcurrent and over-temperature protection of the IC4 after approximately 5 minutes of uptime. A practical solution to this is to either use forced cooling on the IC4 module (especially to the diode and the inductor), which is not very energy efficient, or to raise the minimum U2 low voltage threshold shutdown procedure of the MPU, resulting in a shorter UPS system uptime t_{UPS} when running on U2. To prolong the running time of the UPS system in U2 backup mode, more batteries can be added in parallel, with the condition to be technically identical, properly balanced and to respect the maximum working current rating of the IC2 and F1. O course, in this case the charging time from IC1 will be longer according to relation (1).

Also the IC4 converter did not exhibit excessive heating or overcurrent protection problems when operating in U1 external power supply mode, at the maximum input and output current draw, because of the higher input voltage value.

Another thing to be taken into consideration is the U2 voltage recovery value, after an exploitation session. Thus a smarter algorithm in the MCU logic can be developed in order to identify the recovery voltage level interval of U2, and only allow the next power-up of the MPU when a superior voltage or a maximum 4.2 V_{DC} voltage level of the U2 is reached through charging. As a result, exploiting the 18650 Li-Ion batteries around the nominal voltage value (3.6 V or 3.7 V depending on the manufacturer), their total charge/discharge cycles can be increased, prolonging their work life.

In conclusion, through the evaluation of the proposed UPS prototype, it has been demonstrated that with minor upgrades, such as forced cooling or raising the battery pack low voltage threshold for the emergency shutdown procedure in the MCU algorithm, the system can provide the expected results for a decent runtime at the maximum current load of 3 A or of 1.4 A.

As a result, the use of the proposed UPS system can be extended for civilian, medical or military, critical portable devices, home protection and surveillance systems, research equipment data loggers, or as a kit for learning purposes in electronics classes.

Further research and upgrades are possible, such as power path management and battery information display with adjustable system voltage settings, in order to develop a better, safer and more energy efficient, UPS system version.

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