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*PAPERS*

# Battery lifespan calculation and principles of design for low power mode

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This paper addresses the issue concerning the design of battery-powered devices. In particular, it examines aspects affecting both short-term and long-term consumption. The primary focus of the paper is a low-power device powered by miniature batteries. From a broader perspective, it can also prove useful in designing devices powered by high-performance autonomous sources. The paper first identifies the basic design requirements with an emphasis placed on the key parameters of this specific category. The following chapters describe processing and circuit measures aimed at eliminating device consumption. The concluding part sums up the findings and presents some recommendations. The described methodology for the calculation of battery life has been experimentally validated and can be used to determine the battery lifespan in virtually any system.

Keywords: electrochemical sources, galvanic cells, battery, accumulators, low-power mode, reduced-consumption mode, sleep mode, idle mode, interruption

## 1 Introduction

Devices powered by battery sources - be they primary or secondary - should be invariably operated in a special mode. However, this mode will essentially be a compromise between opposing requirements:

- instant response to external stimuli,
- high computing performance,
- low consumption.

The term "low power consumption" is rather very abstract. The majority of contemporary technologies are designed for low-consumption operation - excluding appliances which consume energy principally to maintain their primary operation. These include especially heat sources, high-voltage electromagnetic switches, light sources, *etc.*

The designer of a power system can affect the overall system consumption chiefly by optimizing the circuit design (HW measures) as well as the process design (SW measures).

## 2 Process control in low-power mode

Battery-powered systems, *ie*systems operated in a low-consumption mode, generally process individual operations differently than those in a power supply mode. For the purposes of clarification, the term passive mode refers to a mode wherein an emphasis is placed on low consumption, i.e. a system characterized by permanent inactivity, interrupted only in the event of an urgent processing need. Conversely, the term active mode applies to a system which is in continuous operation, identifying processing requests which it accommodates as required [1].

### *2.1 Processing methods*

In active mode, processes are largely processed *sequentially*. In passive mode, the individual processes are mostly performed *conditionally*. The sequential mode continuously inquires about the necessity and/or possibility to perform specific procedures in cyclic loops. The process of continuous cyclic inquiry of individual procedures as to the possibility of accommodating their requests is also known as *polling*. Figure 1 shows a flow chart of general sequential processing of individual processes or operations. After an initial initialization, the individual processing requests are gradually carried out in an endless loop. Since the active mode is characterized by continuous activity, it is not entirely compatible with systems requiring extremely low energy consumption.

The conditional performance of individual processes corresponds closely to passive mode requirements. The device remains inactive throughout the operation. Whenever required, the device shits from inactivity (idle mode) into a mode with increased consumption and high processing output  an active mode. While in this mode, it carries out the procedure that required its activation and returns to idle mode. In this case, the required procedures are not performed sequentially in cyclic loops, but solely according to specific requirements.

Although the mode of conditional performance guarantees the lowest possible consumption, it is not capable of reaching the full processing output as is the case in terms of sequential processing. The transition from passive to active mode requires interaction with an external object. This is due to the device in idle mode not having enough options to cause an interruption. Wireless com-

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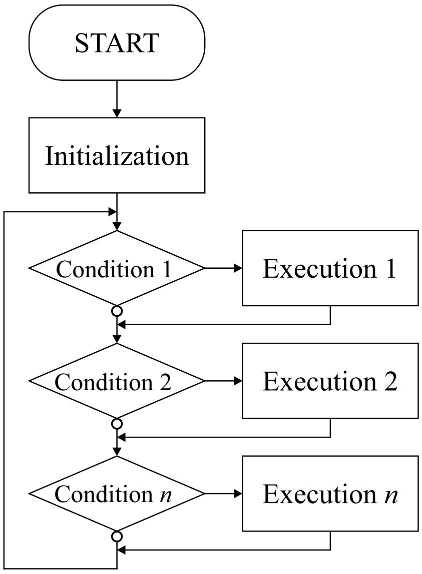


**Fig. 1.** Sequential processing

munication modules are a typical example of this. If the receiver is in low-consumption mode, it cannot recognize incoming data and, in turn, is unable to bring about an interruption that would make it possible to receive and process the data and to respond appropriately. The ways in which the transition from idle to active mode can be facilitated are very limited. They include:

- altering the logic level at the digital output,
- exceeding the voltage level of the comparator,
- RTC module time increment,
- time event via a low-consumption oscillator,
- movement recorded by an accelerometer.

All of the above-mentioned stimuli can be employed in low-consumption mode, which normally does not exceed 1 $\mu$A. Additional types of external stimuli include

- data reception using a wired receiver,
- data reception using a wireless receiver,
- exceeding of sensor values.

However, these necessitate operation involving higher current consumption, ranging from hundreds of microamperes to several milliamperes. It is imperative that the type of the power supply and its replacement or charging intervals be determined based on operational requirements.

An optimum solution with regard to the operation of a system in low-consumption mode can be achieved by:

- the ability to initiate a transition from inactive to active mode while maintaining minimum current consumption,
- prompt transition to a process-efficient (active) mode,
- performing relevant operations without undue delay and in the shortest time possible,
- setting up the required parameters to enable further activation,
- promptly returning to a low-consumption mode.

The general flow chart of conditional processing presented in Fig. 2 shows an approach adopted to manage relevant sub-processes. This makes it possible to achieve lower consumption than in sequential processing. The system becomes inactive once the initialization is completed. In this mode, only the most essential modules remain active, including the input ports (IO), the low-power oscillator (LPO) and the real-time clock module (RTC) and/or comparator. At the moment of an anticipated asynchronous pulse, the system is activated, sets up the required peripheral, conducts relevant procedures, initiates the parameters needed for reactivation and returns to the idle mode.

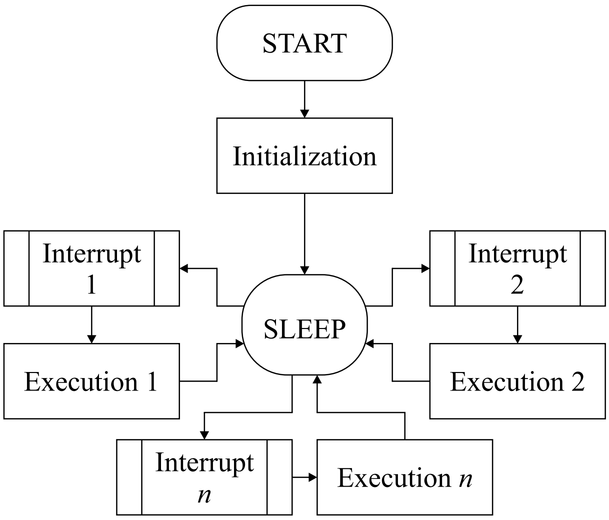


**Fig. 2.** Conditional processing

The process approaches dealt with so far have only identified individual options and their advantages and specified the drawbacks associated with system operation in a particular mode. The following section will deal with the approximate calculation of the battery life and its replacement and/or recharging intervals.

### *2.2 Battery lifespan calculation*

One of the key requirements specified at the very beginning of the assignment concerns the duration of operation before the battery needs to be replaced or recharged. Generally, no designer will be able to proceed effectively without having this information. A qualified estimate of the service life of the power source, *ie* its capacity, should be obtained at the earliest stage of the design. Electric power consumption is affected both by the parameters of components connected to the battery and by the frequency of their use. While some parameters can be calculated with a fair degree of accuracy, the frequency of their use can be best determined based on an empirical estimate obtained via close monitoring of the system operation [2].

The calculation of consumption can be viewed in terms of several degrees of accuracy. Batteries are classified based on their capacity (Ah), supply voltage (V) and internal resistance ($\Omega_{\mathrm{i}}$). These parameters vary depending on the duration of use, on current consumption, on environmental parameters, *etc.* The energy which the battery has available over its lifespan (or cycle) cannot be simply determined by the product of its nominal values, but rather by the integration of its instantaneous power

$$W_B = \int_{U_{\max}}^{U_{\min}} u(t)i(t)\mathrm{d}t\,. \tag{1}$$

The same applies to the load. By activating individual peripherals, the control module modifies the load of the supply battery. The connection is incremental; however, due to the relatively high internal resistance as well as the internal impedance of individual loads, energy consumption is a continuous process which can be determined quite accurately by means of input integration. While using this high-precision approach will allow us to determine the lifespan of the battery with a high degree of accuracy, it won't essentially be possible to obtain an accurate result owing to the relatively large number of unknown modifiers.

In applying the next precision degree of the calculation, the transition lines between individual load switching can be approximated - treated as discontinuous. Once the consumption of individual loads and the size of the internal resistance of the source are determined, the overall power consumption can be calculated as follows

$$W_{\mathrm{B}} = W_{\mathrm{L}} = \sum_{U_{\max}}^{U_{\min}} u_t i_t \Delta t\,. \tag{2}$$

The best result is likely to be achieved by applying the highest abstraction. It is essentially a compromise between the ease of calculation and the degree of influence exerted by external factors. In this calculation, which is to be explained in a more detail below, the supply voltage (being a constant) is excluded and only the equivalence between the charge supplied by the battery and the charge consumed by the system is calculated. The battery charge, defined as capacity (Ah), fluctuating between maximum and minimum voltage, is released into the system gradually over the lifespan of the battery. In this case, the consumed charge will be considered instead of the input with respect to the operated system. This implies that the calculations are not based on energy conservation but rather on charge conservation.

$$Q_{\mathrm{L}} = Q_{\mathrm{B}} = Q_{\mathrm{C}} + \sum Q_{\mathrm{P}} + \sum Q_{\mathrm{A}}\,. \tag{3}$$

In (3), the charge volume of the appliance is divided into categories that are characteristic for system operation. Their classification plays a crucial role in determining the life of battery supply and, as such, should be part of any such commissioning. Operation categories can be divided into:

- $Q_{\mathrm{P}}$ periodic sequence with a known period length,
- $Q_{\mathrm{A}}$ asynchronous sequence with the required number of occurrences,
- $Q_{\mathrm{C}}$ continuous consumption in idle mode.

Battery capacity is denoted as $Q_{\mathrm{L}}$.

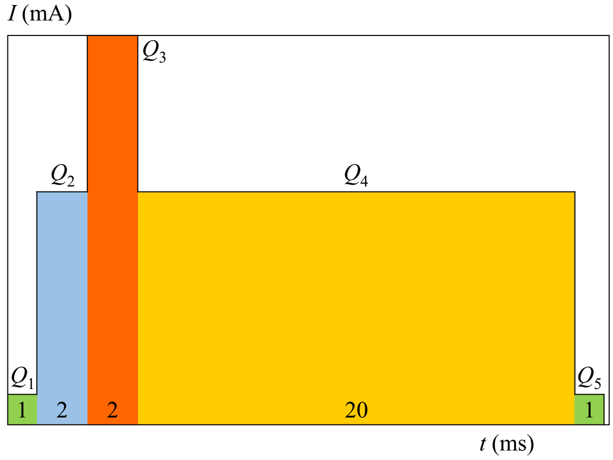


**Fig. 3.** Example of charge consumption in individual sequences

### $Q_{\mathrm{P}}$ *Periodic sequence*

This category includes periodically recurring processes with a known length of period such as system activation by the RTC module. Every second, the system is awakened, modifies the display and returns to sleep mode. Every minute, for example, the system sends data via a wireless module and measures battery consumption at 60-minute intervals. A total of three types of cycles, each with a different period and a different type of load can be summed up. Each cycle can be described by

$$Q_{\mathrm{P}} = \frac{t_{\mathrm{L}}}{T_{\mathrm{p}}} \sum_{n} I_n \Delta t_n \tag{4}$$

where $Q_{\mathrm{P}}$ is the overall charge of one sequence, $I_{\mathrm{n}}$ is current consumption of one sequence section lasting for a period of $\Delta t_{\mathrm{n}}$. The battery lifespan is $t_{\mathrm{L}}$ and $T_{\mathrm{P}}$ is the time of the sequence period.

Within one cycle, different loads of different lengths are connected, as shown, for example, in Fig. 3. Upon cycle initiation (time $t_0$) the system proceeds to process data (consumption of 2 mA, time 1 ms). This is followed by sensor activation (consumption 10 mA, time 2 ms). The data is then sent via a wireless transmitter (consumption 25 mA, time 2 ms). Next, a wireless receiver is switched on to wait for confirmation of the received data (consumption 15 mA, time 20 ms). Once the data is received, it is processed (2 mA, 1 ms) and the system re-enters a low-consumption mode.

### $Q_\mathrm{A}$ *Asynchronous sequence*

This category consists of known processes with random occurrence. In terms of processing, their occurrence may be regarded as stochastic, *ie* asynchronous with respect to the program operation. The minimum number of occurrences could be detailed in the specifications. These are then sequences with a pre-determined minimum number of occurrences. Since the periodicity of occurrences cannot be determined, the conditions are reversed to determine the number of occurrences instead

$$Q_\mathrm{A} = N_\mathrm{A} \sum_n I_n \Delta t_n \tag{5}$$

where $Q_\mathrm{A}$ represents the total charge of one sequence and $I_n$ stands for consumption lasting for a period of $\Delta t_n$, and $N_\mathrm{A}$ indicates the number of occurrences. The process may look similar to that shown in Fig. 3. The difference between the two categories lies in the randomness of occurrences. While the consumption of periodically recurring sequences can be calculated with a fair degree of accuracy, the consumption of stochastically occurring sequences must be supplemented by the anticipated number of occurrences. The client may, for example, require a minimum of 20 thousand sequences to be sent in response to the push of a button on a remote control.

### $Q_\mathrm{C}$ **Sleep-mode consumption**

This crucial category addresses the issue of charge dissipation throughout the lifespan of the battery in idle mode. It includes the consumption of all modules in periods of inactivity. The size can be influenced more effectively by circuit approaches rather than by adopting processing measures

$$Q_\mathrm{C} = I_\mathrm{C} t_\mathrm{L} \,. \tag{6}$$

As could be expected, the charge in (6) is determined in the $Q_\mathrm{C}$ continuous mode as the product of total consumption $I_\mathrm{C}$ over the lifespan of the battery $t_\mathrm{L}$.

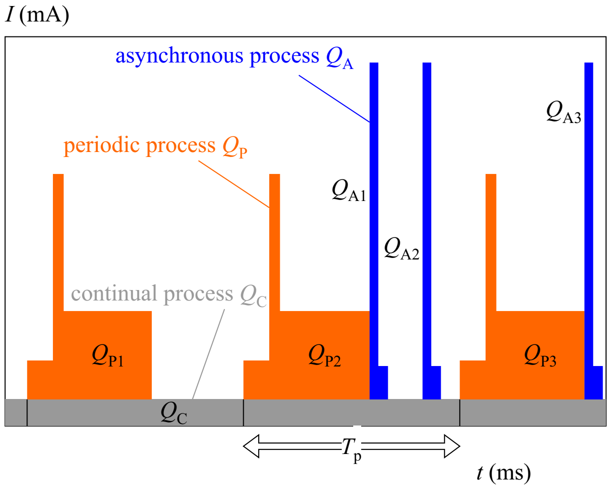


**Fig. 4.** Example of full charge consumption

Figure 4 shows an example of device consumption involving all categories, *ie* periodic, asynchronous and continuous.

Note. At the time of active processing output, *ie* while $Q_\mathrm{P}$ or $Q_\mathrm{A}$ is active, the $Q_\mathrm{P}$ charge is not likely to be consumed and should, therefore, be deducted in all occurrences. Since its size is expected to be approximately a thousand times smaller than the consumption during active operation, further and more complex mathematical modifications would be insignificant.

To determine the lifespan of the battery, it was essential to first categorize individual types of consumption, which now makes it possible to establish an equation based on the presented relations. Below is a summary of individual categories

$$\sum Q_\mathrm{P} = t_\mathrm{L} \sum_n \frac{\sum I_{nx} \Delta t_{nx}}{T_{\mathrm{P}x}} \,, \tag{7}$$

$$\sum Q_\mathrm{A} = \sum N_{\mathrm{A}x} \sum_n I_{nx} \Delta t_{nx} \,, \tag{8}$$

$$Q_\mathrm{C} = t_\mathrm{L} \sum I_{\mathrm{C}x} \,. \tag{9}$$

As the relations indicate, each category can include several types of sequences. Substitution into (3) results in the following equation

$$\begin{aligned} Q_\mathrm{L} = t_\mathrm{L} \sum \frac{\sum_n I_{nx} \Delta t_{nx}}{T_{\mathrm{P}x}} + \\ \sum N_{\mathrm{A}x} \sum_n I_{nx} \Delta t_{nx} + t_\mathrm{L} \sum I_{\mathrm{C}x} \end{aligned} \tag{10}$$

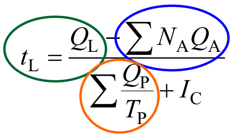
which can be used to express the life of the battery

$$t_\mathrm{L} = \frac{Q_\mathrm{L} - \sum N_{\mathrm{A}x} \sum_n I_{nx} \Delta t_{nx}}{\sum \frac{\sum_n I_{nx} \Delta t_{nx}}{T_{\mathrm{P}x}} + \sum I_{\mathrm{C}x}} \,. \tag{11}$$

From (11) one may also be expressed verbally as follows: Battery life is determined by the proportion of battery capacity, reduced by the given number of asynchronous sequences, to the sum of periodic sequences divided by the period of occurrence, increased by consumption in idle mode

$$t_\mathrm{L} = \frac{Q_\mathrm{L} - \sum N_\mathrm{A} Q_\mathrm{A}}{\sum \frac{Q_\mathrm{P}}{T_\mathrm{P}} + I_\mathrm{C}} \,. \tag{12}$$

For the purposes of convenience, (11) may be further simplified by re-substituting individual charges to obtain a general expression of the battery lifespan. Even though the presented relations express the battery charge dissipation only approximately, they are sufficient with respect to the volume of limiting factors and will reliably determine the result.



$$t_L = \frac{Q_L - \sum N_A Q_A}{\sum \frac{Q_P}{T_P} + I_C}$$

**Fig. 5.** Graphical classification of parameters in (12)

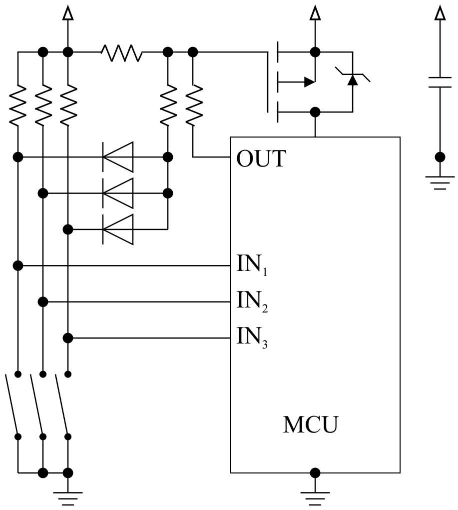


**Fig. 6.** Random button power switching

Figure 5 reflects the color coding used (12). The battery parameters - its lifespan and rated capacity - are highlighted in green, the sum of all asynchronous sequences in blue, the sum of all symmetric sequences in orange, and the amount of current in a reduced-consumption mode over the lifetime of the battery is highlighted in gray.

All of the presented relations have been derived from generally accepted theories. They were experimentally validated in component applications as well as via long-term operation in cycle testing machines. Due to the relatively high degree of leeway applied to the calculations and the fact that mostly minimum circuit parameters were taken into account, the actual battery life was found to be almost invariably longer than when calculated. However, this in not in conflict with system requirements as the emphasis is mostly placed on minimum battery life.

## 3 Circuit design principles in low-power mode

A circuit design is equally important in optimizing the overall device consumption and thereby extending the battery life. Whereas the process design consists of optimizing individual processes, the circuit design is responsible for instant consumption in both idle and active modes. Accordingly, the designer must painstakingly select components which are suitable with respect to consumption both during operation and when the system is inactive. Modern electronic components feature increasingly low consumption. Moreover, this trend is quickly becoming part of the marketing strategy. Different manufacturers use different names to identify their products suitable for battery-powered operation. The terms consumers are likely to come across include: “nanoWatt technology”, “ultra-low-power-mode”, “LowPower” or “eXtremeLowPower” to name just a few; however, numerous older types of integrated circuits with substantially worse electrical properties, and thus less favorable in terms of their design, remain available on the market to ensure product compatibility and sustainability. For the sake of comparison, allow me to highlight some of the differences between several microcontrollers and integrated circuits.

**Table 1.** Comparison of consumption parameters in selected microcontrollers

| MCU | $U$ (V) | $I$ (32 kHz) ($\mu$A) | $I$ (16 MHz) (mA) |
|---|---|---|---|
| PIC16F84 [3] | 2 | 15-45 | 10-20 |
| PIC16LF18324 [4] | 1.8 | 0.5 | 1.3-1.5 |
| MSP430FR5969 [5] | 1.8 | 0.45 | $> 2$ |

**Table 2.** Comparison of consumption parameters in selected EEPROM memory units

| EEPROM | $I_{\text{read}}$ (mA) | $I_{\text{write}}$ (mA) | $I_{\text{standby}}$ ($\mu$A) |
|---|---|---|---|
| CAT24M01 [6] | 1 | 4 | 2 |
| 25LC160 [7] | 5 | 5 | 10 |
| 24AA1025 [8] | 0.45 | 5 | 5 |

As tables 1 and 2 suggest, designers have a wide range of options at their disposal to affect the overall consumption of the respective device. Extreme values have been excluded; the tables only give an example of comparison between several types of integrated circuits. While these are not, admittedly, the most important parameters in terms of the design, each category can be optimized to select the most suitable integrated circuit.

### *3.1 Module power supply*

With regard to battery-powered systems, it is essential to factor in a greater amplitude, or rather a reduction in the rated supply. In mains-powered applications, a drop of 10 % in supply voltage is not uncommon. This value is determined by a rectifier and its actual decrease is often even lower. Conversely, if a system is battery-powered, the voltage can drop by as much as 30 to 40 % and still maintain a functioning system, provided the designer modifies the circuit as required. For example, a CR2032 lithium battery is capable of supplying a current of several milliamperes even though its voltage is just below 2 V. In this case, its internal resistance is quite substantial, meaning that it is unable to power larger appliances, but it will still reliably maintain the operation of the microcontroller and all of its modules. It is therefore necessary that the minimum supply voltage of all required appliances remains at *the lower operating threshold* of the supply battery.

In circumstances where accurate time is not of the essence, *ie* the device does not need to be powered on a continuous basis, it will be possible to use the circuit presented in Fig. 6. The microcontroller (MCU) can independently connect to / disconnect from the battery. If any button is pressed, the PMOS transistor will become active and will proceed to connect the MCU to the power supply. The transistor will switch off again once the button is released; however, during power-on reset (POR) the microcontroller will take over the transistor arbiter, which remains active event after the button is released. As soon as the system completes the required operation, the transistor is released to interrupt power supply to the microcontroller and to the other peripherals.

Both solutions are rather radical alternatives applied either to obsolete components or to accommodate demanding requirements to minimize consumption in passive mode.

### *3.2 Battery measurement*

The option to measure the status of the supply voltage should be a matter of course in battery-powered systems. Users should always be able to keep track of the amount of the available “fuel” and be duly notified of the approaching end of the battery life or the need for it to be recharged. There are a couple of issues involved in measuring battery voltage. The progress of decreasing voltage is not linear with respect to the amount of charge released from the battery. If the battery voltage is measured in no-load mode, there will be virtually no decrease in voltage. Even though the battery resistance decreases in proportion to the amount of released charge, there won’t be any significant voltage loss if a small amount of current is flowing through it. This may, at times, lead to an incorrect interpretation of the measured values.

The majority of modern microcontrollers are designed to enable voltage measurement. However, this feature can only be used if the battery is connected directly to the microcontroller, *ie* without an integrated stabilizer. The voltage measuring module must be equipped with a voltage reference as well as a voltage divider inserted between the supply terminals. The voltage measured on the divider must be referenced by an exact voltage. However, this convenient solution will not guarantee sufficient loading of the source. As a matter of fact, the result will correspond to a no-load battery measurement. In this case, it would help to connect some relevant load for the duration of the measurement that would imitate an actual decrease in battery voltage. For example, the existing LED could be utilized as their brief flashing for no more than several hundreds of microseconds would be negligible. Alternatively, some other existing load whose short-term activation would not cause a processing error could also be used.

$$R_\mathrm{i} = \frac{U_\mathrm{nom} - U_\mathrm{meas}\frac{R_1+R_2}{R_2}}{I_\mathrm{load} + \frac{1}{R_2}U_\mathrm{meas}} \tag{13}$$

Formula (13) solves the relations between the battery voltage drop and its internal resistance on Fig. 7. Its decrease determines the decrease residual battery charge. $R_\mathrm{i}$ is internal resistance of the battery, $U_\mathrm{nom}$ is a nominal battery voltage, $U_\mathrm{meas}$ is the measured voltage, and $I_\mathrm{load}$ is a current of a defined load.

If the control module does not allow for battery measurement, a circuit that would do so could be designed based on Fig. 7, for example. What is required is a divider (R1 and R2) through which a relevant current of useful size will flow. At the same time, any such divider must be disconnectable to ensure that no current is used up in reduced-consumption mode. Its division ratio must be such that the maximum source voltage it divides is lower than the voltage reference. The voltage reference could be either part of the microcontroller or provided externally.

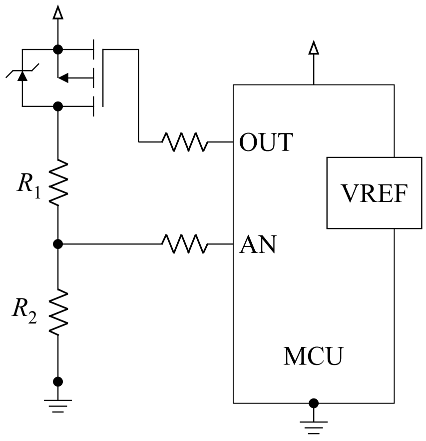


**Fig. 7.** Example of battery voltage measurement

All of the recommendations presented above presume a meticulous selection of components. The best solution hinges on finding components which meet all requirements of an optimum design and which will not need to be subsequently supplemented with supporting circuits (Figs. 6, 7). However, if the situation calls for it and the price and/or density requirements allow, discrete components could also be used. The design of any equipment or device is essentially a compromise between customer requirements on the one hand and physical or technological limitations on the other, with due consideration given to any budget constraints.

In any event, the designer must carry out a thorough analysis of all components connected to the supply bus both in passive and active mode. It is important to keep a good track of the duration of their connection, as well as the manner in which they can affect overall consumption. The same applies to auxiliary components such as pull-up/pull-down resistors, LED circuits and any other artificial loads. Although the effect on instantaneous consumption produced by each of the components may be marginal, it will go a long way towards extending the lifespan of the battery.

## 4 Conclusion

The paper addressed some of the principles involved in designing battery-powered devices. First, the issues associated with battery-powered systems were outlined in comparison with mains-powered devices. This included the specification of design principles, key factors and any drawbacks that one might expect to encounter when pursuing this subject matter. The next section looked at some of the available software and hardware options for circuit optimization with a view to achieving the best possible consumption results. The principal objective of this paper was not to present an all-purpose guide for developing an optimum design of a battery-powered device, but rather to highlight the difficulties this may entail and to outline the potential design solutions.

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