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Alessandro De Gloria
Editor

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Preface

Electronics technology has known a very fast development becoming pervasive of everyday life activities. Nowadays, electronics devices are so common that we seldom pay attention to them considering them as usual objects. Electronics devices are often considered a commodity and the attention is toward the application instead of the devices.

Often the prefix "e" is used to technologically qualify a product or a service (E-mail, E-card, E-commerce, E-banking, E-business, E-book, to cite a few) and to communicate that it is new, modern, advanced. Electronics devices have become a part of our life; they are no more a product used in the industrial environment to improve the features of a product. They have changed our life; you only have to think to a smartphone.

The incursion of electronics devices in life has lead to a revision in the electronics engineer's role. It is not enough to be able to design and implement an efficient device. The design has to consider the context in which the device will be used. Factors like human–machine interaction, usability, scalability, reusability must be included into the specification and drive the design of the device.

These considerations lead to put the attention toward the applications and the development of systems that increasingly simplify human activities.

The APPLEPIES conference aims at bringing together researchers and stakeholders, in order to share the state of the art of research and market in the field of applied electronics. The goal is to discuss the most significant trends, to explore the challenges, issues, and opportunities in the research and to debate on visions about the future of the electronics pervading industry, environment, and society.

The conference also includes an exhibition, where industries can highlight their latest products and technological cornerstones for future applications.

APPLEPIES is an annual conference and it is building a scientific community for shaping the future research in the field. This community represents a significant blend of industrial and academic professionals, mainly at Italian level but with an opening over the international audience, committed to the study, development, and deployment of electronics systems in all the main application fields.

Alessandro De Gloria

Contents

Chapter 1
SuperCap-Based Energy Back-up System for Automotive Electronic Control Units

Sergio Saponara, Roberto Saletti, Luca Fanucci, Roberto Roncella, Marco Marlia and Corrado Taviani

Abstract The E-latch is a new automotive mechatronic device that substitutes the door closure mechanical system with electro-actuated parts plus an embedded electronic control unit (ECU) connected to the main vehicle network. Due to severe automotive safety-critical requirements for door closure, an energy back-up system is required. A solution based on supercaps and boost converter is proposed in this work to ensure E-latch operation even in case of main battery failure. An in-depth thermal, electrical and durability characterization of the supercaps proves the reliability of the energy back-up unit for automotive applications. A Components Off the Shelf (COTS) approach has been followed for the E-latch prototype and test phases. A migration towards an Application Specific Integrated Circuit (ASIC) design approach is envisaged for future large volume production.

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1.1 Introduction

A strong tendency in the automotive field is to make the mechanical systems more and more controlled by an Electronic Control Unit (ECU), which properly manages sensors and electro-actuators improves the mechanical system performance and even makes new functions available. Automatic transmission, suspension control, electronic controlled injection in internal combustion engine, brake-by-wire and steer-by-wire systems are just some examples of this consolidated trend [1–6]. As far the door subsystem is concerned window lifter and in some cars also the rear mirror are electronically controlled, while the door open/closure unit is still mechanical, as in [5]. The Advanced Mechatronic Door System (AMDS) project is the framework in which the industry-academic collaboration between Magna Closures and the University of Pisa led to the introduction of a new mechatronic system for door closure called *E-latch*. Several advantages are achieved: reduced weight and size as compared the mechanical-based door closure system; increased flexibility, scalability and re-programmability of the unit to address different vehicle models and vehicle generations; integration of the latch system in the vehicle networks to enable advanced safety features or new comfort functionalities.

The *E-latch* is a new node of the main vehicle network that is connected either through a Local Interconnect Network (LIN) or a Controller Area Network (CAN) bus. It manages all the following functions: reading the car handle and door status by means of Hall sensors or contact sensors; communicating with the car body computer by receiving commands from the users (lock, double lock, child lock, anti theft lock, release) and transmitting the door status or diagnostic info; driving the electric motor actuating the closure/release of the door (operating at 12 V nominal, 8 V minimum, with a current absorption in the order of several amperes); managing the available energy sources, both the main battery and the back-up one (the supercaps and boost converter subsystem proposed in this paper). The widespread adoption of the *E-latch* is strongly challenged by the high level of reliability that is mandatory to achieve, particularly by the energy back-up system. The correct functionality of door release must be guaranteed by the *E-latch* even in case of an accident or a general failure of the main vehicle battery. An energy back-up system with minimum power consumption and weight/size overhead during normal vehicle operation is thus necessary. To overcome this issue a new supercap-based energy back-up system for automotive ECU is proposed in this paper.

Although applied to the E-latch ECU, the proposed energy-back up subsystem is general enough to be applied to any automotive ECU. Hereafter Sect. 1.2 describes the E-latch architecture while Sect. 1.3 deals with the architecture of the energy back-up system. Section 1.4 discusses the thermal, electrical and life-cycle characterization of the new proposed energy back-up system. Conclusions are drawn in Sect. 1.5.

1.2 The New E-latch Electronic Control Unit

Figure 1.1a shows the modular architecture of the *E-Latch*, which is divided in two main units (Latch and Cinch). Each unit includes: (1) a micro-controller with LIN connectivity and multiple PWM output channels, (2) a high-voltage protection circuit for the direct connection to a 12 V power supply, (3) an integrated H-bridge power MOS motor driver to drive an electrical motor, (4) electrical motor and Hall sensors to carry on the door lock/release and monitor the door status, respectively. The Latch sub-unit, the detailed architecture of which is shown in Fig. 1.1b, is generally used in all the vehicles, since it manages the basic door locking and release (with special child-lock or double lock or anti-theft lock functionalities), whereas the Cinch is a special function, which automatically and gently closes the door when the door is leaved ajar by the user, to be installed in premium vehicles only.

The Latch sub-unit is connected to the body computer through a LIN port, while the Cinch module, when present, is a slave of the Latch one. The operating temperature of the *E-latch* spans from −40 to 80°C, and thousands of open/lock cycles are expected in its lifetime. The electronics must also withstand temperatures up to 130°C during the repainting process of a vehicle door. The micro-controller and the protection circuitry are realized by a System-on-a-Package (SIP) device with TQFP48 package, the Quest from Freescale [7], which integrates in the same package a digital chip (a 16-b S12 CPU with 20 MHz clock frequency, several kB of FLASH and RAM memory, 16-b timer) and an analog chip sustaining up to 18 V with on-chip temperature sensor, integrated low-drop out 2.5 V/5 V voltage regulator, 10-b ADC, multi-channel PWM module for high/low-side drivers, Hall sensor front-end, GPIO pins.

The integrated motor driver, from STMicroelectronics [8], is provided in a MultiPowerSO-30 package. It contains a dual monolithic high-side driver and two low side switches, with Power MOSFET and intelligent signal/protection circuitry. all It is able to sustain PWM motor control up to 20 kHz with 40 and 30 A voltage and current maximum values, well above the requirements of the Latch or Cinch modules.

The *E-latch* can work in two power modes: full power mode, where all the sub-units are working; power-down mode, where all the devices are off and the ECU is ready to be waken-up by the watchdog timer or an external interrupt. The residual current consumption in this mode useful when the vehicle is parked is a few microampere. The *E-latch* complies with the paradigm of the safety-critical electronic design as dictated by ISO/DIS 26262 [9].

As the E-latch future market volumes are foreseen in millions of pieces, an envisaged evolution of the proposed architecture consists in partitioning the Latch and Cinch units, currently realized via hardware, via software, by adopting a single 32-bit automotive microcontroller, with a 64 pin package at least. Such kind of devices, which represents the next generation of automotive processors [10–12] from different vendors (e.g. TX03 family by Toshiba, SPC56 family by STMicroelectronics, Tricore family by Infineon, Fado and Bolero families by Freescale), are often

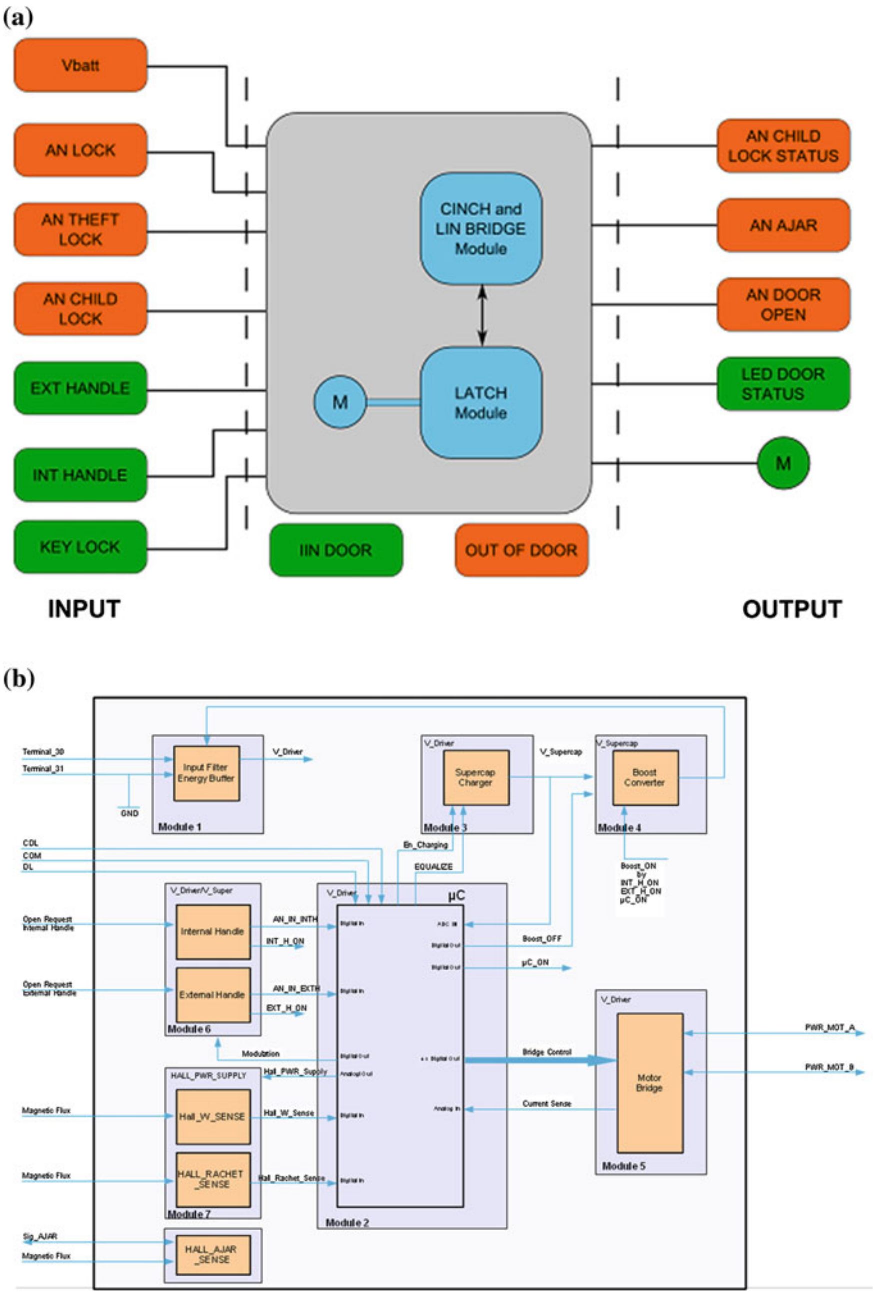

Fig. 1.1 **a** E-latch block diagram with Latch and Cinch functions. **b** Schematic of the E-latch unit

equipped with a double core thus increasing redundancy and hence fault-robustness. This way, the Cinch function or other advanced tasks can be added/removed by simply changing the firmware while the hardware of the E-latch ECU remains the same. The microcontroller 12 V protection/power managing circuitry (currently integrated in the single-package Quest device), the integrated motor drivers and the sparse glue logic could be realized single-chip as a custom ASIC, thus reducing the size and assembly cost of the E-latch. This new architecture can be the revolutionary approach to a completely new door system that, beside the E-latch, currently includes other two ECUs, the window lifter (integrating intelligent functionalities as the anti-pinch software) and the mirror control. A single 32-bit powerful automotive microcontroller could manage all the software tasks and the communication with the car body computer, while distributing multiple applications specific ICs for sensor interfacing and motor driving, one for each function (mirror, window lifter, latch/cinch), instead of having 3 different ECUs.

Whichever architecture is adopted, a key issue for door ECUs is guaranteeing the correct behaviour when the main battery fails: a supercapacitor-based energy back-up system has been designed to this aim, and characterized in terms of electrical, thermal and durability performance.

1.3 Architecture of the Energy Back-up Unit for Automotive ECU

The energy back-up system of an automotive door systems must operate from −40 to 80°C, and withstand up to 130°C in case of door repainting. The energy back-up unit is kept charged by the main vehicle battery in normal conditions, so that it can provide enough energy (tens of joule in short bursts of about 100 ms, for about 100 W in power, 8–12 V in voltage and 6–10 A in current) to ensure several door releases in case of main battery failure. The energy back-up unit should be close to the ECU, robust to wiring failures, with minimum overhead in terms of cost, size and weight. Supercapacitor based energy storage systems are used in cars, but mainly for higher energy/power levels (tens of kWh/kW) [13–17]. Energy back-up solutions for low-power embedded systems are found in the literature mainly for ICT or consumer applications, not meeting the harsh environment requirements of vehicles. Our choice was exploring the use of super-capacitors as storage devices in the E-latch application, because of the large temperature range and the high power density needed. Lithium batteries, widely adopted [13, 14] for automotive electric or hybrid propulsion, would provide better energy density; however, a burst release of power is needed in the E-latch application when the emergency release is activated (supercapacitors provide better power density [15–21]) and the required temperature range is not covered by Lithium-based rechargeable batteries, typically limited up to 60°C. There are Lithium batteries (3.6 V Li-$SOCl_2$) that operate up to 150°C, but they are non rechargeable and with high series resistance. Hence, these batteries seem more suited as very long-term energy storage devices, useful to keep the energy backup system charged during the winter parking of cabriolet cars or every time the main battery is disconnected for a long time. In conclusion, Electric Double Layer Capacitors (EDLC) with 2.5 V supply and tens of Farads, available from several vendors such as Elna, Nichicon, Cooper-Bussmann, Maxwell, were selected as energy storage devices for the energy back-up system of the E-latch.

Since the electric motor of the Latch or Cinch needs a minimum drive of 8 V, and considering also redundancy issues, the back-up system includes: two EDLC supercapacitors (2.5 V nominal) connected in series plus an on-board x2 boost converter. This solution provides a nominal voltage of 10 V and a minimum of 8 V when the supercapacitors are not completely charged. As an example, two 2.5 V 10 F supercapacitors connected in series provide up to 62.5 J, an energy sufficient for 10 door releases in case of main battery failure. In fact, each release typically requires 10 V and 6 A for 100 ms.

The switching architecture of the boost converter provides a high power efficiency in the voltage doubling. The PWM controller is realized with the TI TL5001A IC and small external RC components in the feedback loop, mounted on the same PCB. The *E-latch* micro-controller properly drives as open the boost converter switch SW1 and the feedback switch SW2 of Fig. 1.2, when the main battery voltage is present.

The boost converter is thus normally off, the super-capacitors maintain their backup energy and the resistors of the converter feedback do not waste power. When the main battery fails, the micro-controller is supplied by the two supercapacitors in series (5 V), and the switches SW1 and SW2 are now turned on, so that the door latch electric motor can be supplied by the supercapacitors.

The switches SW1 and SW2 are realized with low-resistance MOS to maximize power efficiency. The main inductor also has a series resistance of few milliohms. The feedback is realized with a divider of the output voltage realized with two resistors of 30 and 330 kΩ. Since a complete characterization of supercapacitors of few farads for energy back-up in automotive ECU is missing in the literature, the devices to be used in the *E-latch* have been chosen after a thorough characterization campaign of 2.5 V EDLC supercapacitors in the range 10–25 F, provided from the above cited vendors. Given the available space, not all the experimental data are reported. Instead, the characterization tests are described in Sect. 1.4 and the results obtained for the selected device, the 18 F Nichicon device with $V_{nom} = 2.5$ V and $V_{max} = 2.7$ V, are showed.

1.4 Thermal, Electrical and Lifecycle Characterization of Supercap for Energy Back-up

Let us define C as the supercap capacitance, V_{nom} the nominal voltage, V_{max} the maximum allowed voltage, $V_{ref} = 0.9 * V_{max} = 2.43$ V and $I_{ref} = C * V_{ref}/30 = 1.62$ A. The following tests have been carried out.

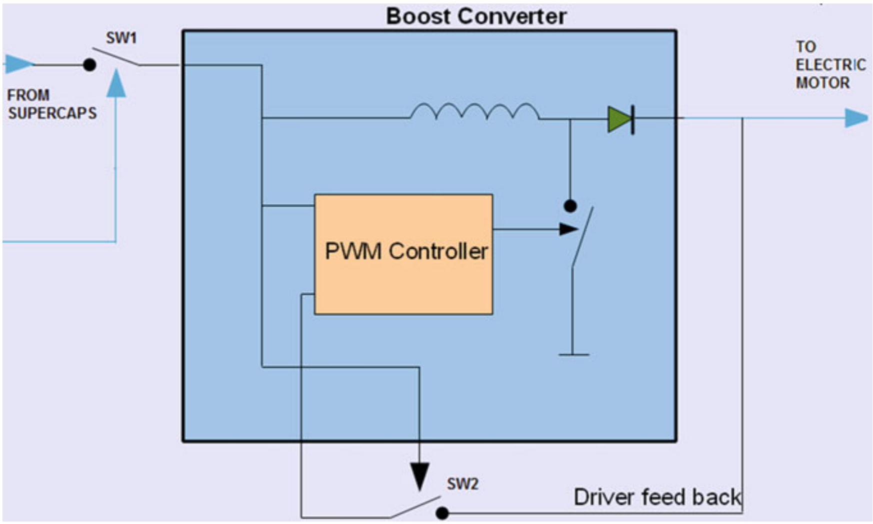

Fig. 1.2 Schematic of the boost-converter used in the back-up energy unit

Constant-current charge/discharge capacitance test: the device is charged at 23°C for 3 cycles at a constant current $I_{test} = I_{ref}/4 = 0.405$ A up to V_{ref}, then it is kept at this constant voltage for 10 ms and then is completely discharged at constant current $I_{ref}/4$; the 3-cycle test is repeated with current values of $I_{ref}/2 = 0.81$ A and $2I_{ref} = 3.24$ A. The supercap capacitance in charge and in discharge modes is calculated as $C = I_{test} * T_{test}/V_{ref}$.

Constant-current ESR test: the supercap series resistance (ESR) has a visible effect during the above described charge/discharge tests at the start of the discharge phase, where the current step determines a voltage drop. Dividing the voltage drop by the constant discharge current gives the ESR value.

Leakage test: the supercap tends to loose charge because of the auto-discharge; this phenomenon is modeled as a parallel time-variant leakage resistance. The supercapacitor is charged from 0 to V_{ref} at 23°C and is kept at such voltage value for 3 h. The capacitor current I_{leak} needed to hold the constant voltage value during this time interval is the leakage current. The parallel resistance R_p is the ratio V_{ref}/I_{leak} and it is calculated after 30 min, 1, 2 and 3 h. This test is usually repeated at different temperatures and for different durations.

Technology spreading and thermal tests: the leakage, ESR and capacitance tests are repeated using different samples of the same device to evaluate the technology spreading. The tests are also repeated on the same super-capacitor at different temperatures to determine the temperature dependence of capacitance, ESR and leakage.

Durability-temperature test: after 10 charge/discharge training cycles at 1 A, the supercap is characterized at 23°C using the above described procedures. This is the starting point of a durability test. A loop of 52 cycles is repeated. The loop consists of a first charge from $V_{max}/2$ to 0.9 V_{max}; 50 charge/slow discharge cycles between

90 and 80 % of V_{max} with a charging current of $I_{ref}/20 = 80$ mA and a discharge current of 10 mA follow; 1 last charge/fast discharge cycle between 90 and 70 % of V_{max} with a charge current of 80 mA and a discharge of $I_{ref}/2 = 800$ mA completes the loop. The entire loop is then repeated 60 times. Such tests are repeated at 25, −40 and 80°C for a total of around 10,000 cycles. The basic ESR-capacitance-leakage characterization at 23°C is carried out after each temperature value, to analyze degradations caused by the durability test.

Repainting test: It consists of 15 min test at 130°C followed by 60 min at 110°C. The supercap is characterized at 23°C (ESR, leakage, capacitance) before/after the test, to evaluate possible performance degradations due to the repainting cycle. All the thermal tests are carried out in Binder MK53 thermal chamber.

The above described tests have been applied to several EDLC supercapacitors from different vendors, with 2.5 V nominal voltage and capacitance ranging from 10 to 25 F. We report here the main results obtained for the selected device, a 18 F Nichicon EDLC, that demonstrates the suitability of the supercap to solve the energy back-up issue of the *E-latch*. The capacitance and ESR tests at 23°C shows a measured capacitance and resistance of 17.69 F and 39.42 mΩ, respectively, at 0.405 A. Values of 18.47 F and 18.92 mΩ are found at 3.24 A. The measured capacitance differs less than 2.6 % from the nominal value of 18 F; the series resistance is well below 100 mΩ. The time-variant parallel resistance extracted from the leakage test at 23°C is in the order of some kiloohm after 30 min and rises up to hundreds of kiloohm after 3 h. Repeating the tests on different samples of the same super-capacitor gives a spreading of the results limited to few percent, showing a good repeatability of the device characteristics. A limited mismatch of the samples makes negligible the equalization problem that arises when two units are mounted in series, as it happens in the *E-latch* circuit. Instead, a higher dependence of the parameters on the temperature has been found, as expected from theory and from results presented in the literature for much larger size supercapacitors (up to of thousands of Farad) [15–21]. As an example, Fig. 1.3a shows the ESR measured with a $I_{test} = I_{ref}/2 = 0.81$ A in a temperature range from −40 to 100°C. The ESR value increases when the temperature decreases, but the series resistance remains always below 100 mΩ.

Since the capacitance value changes as a function of temperature, the voltage slope of the charge/discharge test changes in its turn, as it is demonstrated in Fig. 1.3b, where 0.81 A constant current tests at different temperatures are reported. While the ESR behavior is monotonic with the temperature and there is a large variation at low temperatures (Fig. 1.3a), the voltage slope value is instead weakly dependent on the temperature between −40°C and room temperature (Fig. 1.3b). A difference in the time slope in Fig. 1.3b and hence in the capacitance is noticeable when going from room temperature to 100°C.

The slope and hence the capacitance increases with the temperature when going from −40 to 80°C; instead, the capacitance decreases going from 80 to 100°C. This behavior agrees with the results published in the literature over larger supercapacitors (thousands of Farad), in which a non-linear behaviour of the capacitance with the voltage is found. In fact, the capacitance is composed of a fixed part C_0,

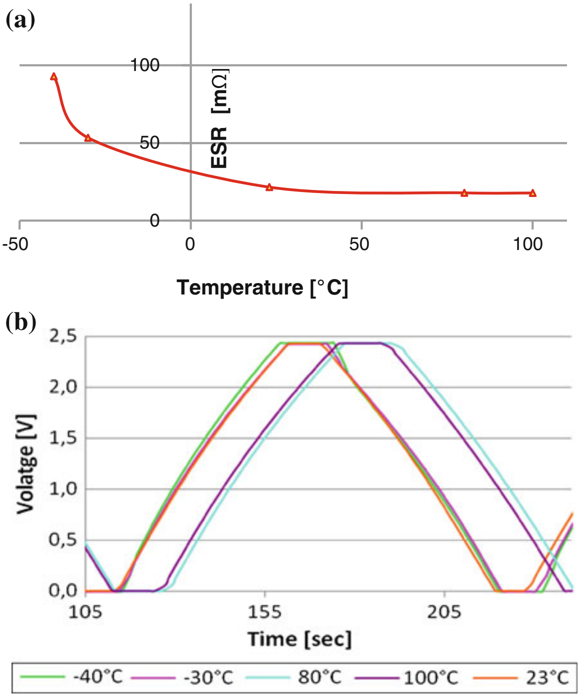

Fig. 1.3 **a** Thermal dependance of the ESR in the charge-discharge test, $I_{test} = 0.81$ A. **b** Thermal dependance of the voltage slope in the charge-discharge test, $I_{test} = 0.81$ A

that increases with the temperature, and a voltage dependent part, C_v(V), that instead decreases when temperature increases.

The repainting test up to 130°C does not seem to affect the supercap performance. Indeed, the ESR, leakage current and capacitance values measured after the repainting thermal cycle shows that the capacitance and ESR are 17.61 F and 27.58 mΩ respectively at 0.405 A, and 17.85 F and 20.11 mΩ respectively, at 3.24 A. The leakage resistance varies from 2 to 105 kΩ from 30 min to 3 h. Such values are acceptable for the normal use of a super-capacitor in the *E-latch*. Similar findings are obtained after the durability tests, see Table 1.1. The durability test consists of 10,000 cycles at temperatures from −40 to 80°C. It is found that the ESR only increases of a few percent and the capacitance decrease also is limited to a maximum of 10 %. These values are well acceptable for the application and demonstrate the suitability of the supercaps as energy back-up sources also after thousands of operating cycles. A major effect is instead noticed on the leakage current: the 3 h leakage value increases from 2 to 50 μA after the durability test. It means that after 10,000 cycles the investigated supercapacitor is completely autodischarged in about 10^6 s, i.e. around 11 days, if it is not recharged. This is not a problem when the main battery is working and it is continuously charging the supercapacitors (boost converter off). Should a

Table 1.1 Performance derating after durability test

	ESR (mΩ)		Capacitance (F)		Leakage current
	0.405 A	1.62 A	0.405 A	1.62 A	–
Initial	26.52	19.27	17.52	17.85	2 μA
Max. derating	27.35	19.47	16.04	16	50 μA
Change	3.03 %	1.03 %	8.45 %	10.36 %	–

main battery failure occur, the supercapacitors backup energy source is needed to actuate the door release (e.g. to escape the car after a road accident) and hence 11 days before the autodischarge are still a long time considering the typical *E-latch* application.

1.5 Conclusions

A new generation of ECU where the mechanical door closure system is actuated by a motor controlled by an electronic system is showing up on the car market. The *E-latch* brings advantages in system modularity, scalability, cost, size and weight. Due to the severe automotive safety-critical requirements, an energy back-up solution is needed to ensure door release/closure also in case of main battery failure, e.g. after a road accident when the emergency release must be guaranteed. An energy back-up solution based on small-size super-capacitors and a boost converter is proposed to this aim. An in-depth thermal, electrical and durability characterization of the supercaps proves their applicability as energy back-up and the reliability of the energy back-up unit for any automotive small energy back-up applications. The critical point is the right selection of the energy storage device. A thorough test and measurement campaign demonstrates that the selected EDLC supercaps allow for the required energy storage capability, with extended operating temperature range from −40°C up to (non continuous) 130°C, low series resistance and leakage current, and low performance degradation even after 10,000-cycle durability test.

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Chapter 2
CH_4 Monitoring with Ultra-Low Power Wireless Sensor Network

Davide Brunelli and Maurizio Rossi

Abstract We propose a novel method to reveal and measure natural gas presence in air, using commercial off-the-self available MOX gas sensors in wireless sensor network applications. This technique reduces the power consumed by the catalytic sensors of a factor 10×, by an analysis on a reduced sampled period and thus extending the autonomy of battery operated systems. The information about the gas concentration is extracted from the sensor transient response through a discrete cosine transform (DCT) analysis and permits to immediately discriminate between clean-air and hazardous situations. The characterization of the sensing device has been conducted using a wide range of humidity and environmental conditions to demonstrate the effectiveness of the approach and a detailed comparison with the standard usage has been performed. Finally, the technique has been implemented in a Wireless Sensor Network designed specifically to measure air-quality in a large area and to share information over the internet.

2.1 Introduction

The detection of volatile chemicals is an essential to assess the air quality and the safety of indoor environments, because together with surveillance techniques [1], it guarantees to keep the environment safe and secure. Catalytic gas sensors are widely used in environmental monitoring applications because of their low cost, and are available for many kind of chemicals. Moreover, they are more robust with very low maintenance, they exhibit long life time with respect to electrochemical sensors

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