# SAVER

## Smart Battery with Active Power Conversion

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***Li-Ion battery for optimized DC network power conversion***

***Final Project Report***

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| **Keyword** | |
| **Abstract** | The Final Project Report: Publishable Summary Report gives on overall view of the SAVER project, its achievements and exploitable results. |

# RECORD OF REVISIONS

| Revisions | Date | Description |
|---|---|---|
| 1-0 | 26/10/2015 | Document creation |
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# GLOSSARY

| | |
|---|---|
| BMS | Battery Management System |
| CfP | Call for Proposal |
| DoW | Description of Work |
| EMI | Electromagnetic Interference |
| HVDC | High Voltage DC |
| LVDC | Low Voltage DC |
| MEA | More Electrical Aircraft |
| SLA | Sealed lead-acid |
| SOC | State of Charge |
| TAES | Thales Avionic Electrical Systems |
| TRU | Transformer Rectifier Unit |
| WP | Work Package |

# 1 EXECUTIVE SUMMARY

SAVER "Smart Battery with Active Power Conversion" was developed as part of the Clean Sky 2 partnership between the European Commission and the European Aeronautical Industry, a partnership which is set up to bring significant innovations regarding the environmental impact of aviation by improving aircraft reliability and efficiency by contributing to the continuous development of More Electrical Aircraft (MEA).

SAVER delivered the $28V_{dc}$ active power conversion/energy storage architecture which is to be employed by the Task Manager, Thales Avionics Electrical Systems (TAES). The multi-disciplinary nature of the project brought together three consortium partners, each with their own specialisation; UPJV (management, power electronics and battery simulation), SGTE (power electronics) and E4V (battery systems).

The main objective of SAVER was the delivery of a $28V_{dc}$ li-ion battery with its battery management system, together with its accompanying DC/DC converter for safe, accurate charging. This is to be used as a platform for developing li-ion technology for aerospace use.

The delivered battery is based on the $LiFePO_4$ chemistry which trades power density for stability, ensuring safe operation - a critical aspect in aerospace use. Configured in 8s2p, the battery delivers 100Ah at $28V_{nom}$.

The DC/DC buck converter powers the LVDC bus from the HVDC whilst also handling the battery charging. It makes use of soft-switching techniques in order to obtain high efficiency whilst keeping EMI at low levels.

Modelling and simulation activities produced high fidelity models of the both the battery and the converter. The battery model employs Kalman filters for state of charge (SOC) and temperature estimation, whilst the converter model aids in the development of control strategies.

SAVER was delivered to Thales AES in April 2016, and is ready to play its vital role in advancing li-ion battery architecture for use in aerospace applications.

*Figure 1-1: The SAVER team*

## 2 SAVER CONTEXT AND OBJECTIVES

The main driver for the existence of SAVER is the development of More Electrical Aircraft, or MEA for short. Decades of development by civil aircraft manufacturers to address economical, ecological, regulatory and technological challenges have caused aircraft systems to become ever more complex, resulting in far from optimal and inefficient architectures which are composed out of four power networks, namely hydraulic, pneumatic, mechanical and electrical. The incompatibility of these four power sources reduces the efficiency and reliability of the whole system.

The trend then is to use electrical power for the sourcing and distribution of all non-propulsive aircraft engine power and this trend is defined as MEA. MEA aims to make aircraft more efficient by making them lighter. This is where li-ion steps in. By having much higher power densities than the traditional sealed lead acid (SLA) battery, li-ion batteries can help save weight. But as these batteries are much more sensitive to overcharge (and thus overvoltage) than their SLA counterparts (which can easily absorb excess charge) they require accurate charging and monitoring.

The LVDC bus used to be powered by AC/DC transformer rectifier units (TRUs), but with the move towards MEA more emphasis is placed on power quality and efficiency, with current TRUs with their passive switching no longer being able to satisfy near future aircraft technical requirements for power quality, EMI/EMC improvements, weight reduction and noise.

The objectives then are to develop a $28V_{dc}$ active power conversion/energy storage architecture which includes li-ion battery constraints in order to achieve:

- weight and volume optimizations;
- improve battery life;
- optimization of operating, maintenance and replacement costs, and
- no break power transfer.

To achieve the above objectives SAVER aims to deliver a $28V_{dc}$ li-ion battery with BMS, together with a buck DC/DC converter utilizing soft-switching techniques. The converter control, in communication with the battery BMS, will execute proper battery charging algorithms.

# 3 SAVER MAIN TECHNOLOGICAL OUTCOMES

Physically SAVER can be split in two parts: the li-ion battery and the DC/DC converter.

## 3.1 THE BATTERY

The battery was constructed by consortium partner E4V. It is a li-ion battery based on the $LiFePO_4$ chemistry which trades lower power density for inherent stability. The battery is delivered with their battery management system which handles protection of the battery, cell balancing, state of charge calculation and communications via CAN bus (with the converter). The battery consists of 2 parallel groups of 8 series connected cells to give an 8s2p configuration, nominal output voltage of 28V and 100Ah capacity.

In parallel was developed a high fidelity battery model, based on the electrical equivalent circuit in order to easily allow simulations with power electronic circuitry connected to the model. By using parameters extracted from the E4V battery the model was characterised. Through the use of Extended Kalman Filters both the state of charge (SOC) and battery temperature are accurately estimated.

## 3.2 THE DC/DC CONVERTER

The buck DC/DC converter was developed and constructed by consortium partner SGTE. As a DC/DC converter destined for aerospace use it has to adhere to stringent specifications in terms of mass, dimensions (volume), efficiency, power quality and security. It powers the LVDC bus, to which the battery is connected, from the HVDC bus and also handles charging of the battery through the use of appropriate control and charging algorithms.

Its specifications are as follows:

- Input voltage : 250 - 320Vdc
- Output voltage with battery load : 20 - 32Vdc
- Nominal output power : 5kW
- Switching frequency : 100kHz
- Efficiency (at nominal power and voltage
- plateau) : >94%
- Weight : <12kg
- Dimensions max : 300*280*280mm

The converter conforms to the RTCA-DO160G cat. B (§20-2 §21-1) standard. It also delivers a current adapted to the battery and its charging strategy by taking into consideration that the required current must be available on the bus.

# 4 POTENTIAL IMPACT, EXPLOITATION OF RESULTS AND MAIN DISSEMINATION ACTIVITIES

## 4.1 SAVER ECONOMIC AND SOCIETAL IMPACTS

Manufacturers of aircraft are currently finding themselves in a constantly evolving and competitive environment of economical, ecological, regulatory and technological challenges. Another concern for the aircraft industry is the growing public interest in environmental issues such as pollution, noise and climate change. As it stands, the air transport industry only produces 2% of man-made $CO_2$ emissions (and 12% of all transport sources), but this is predicted to increase to 3% by 2050 due to the continuous growth of air traffic.

Another concern for the aircraft industry is the growing public interest in environmental issues such as pollution, noise and climate change. ACARE (Advisory Council for Aeronautics Research in Europe) has also set forth in their Vision 2020 goals of reducing fuel consumption and $CO_2$ emissions by 50% per passenger kilometre, reducing NOx emissions by 80% and reducing perceived noise by 50%. The main contributors to achieving the above targets are efficient aircraft: 20-25%, efficient engines: 15-20% and improved air traffic management: 5-10%.

Already looking beyond 2020, ACARE is targeting a 75% cut in $CO_2$, 90% in NOx and a 65% noise reduction in their Flightpath 2050.

In light of the above, the European Union and its aircraft industry has embarked upon optimization campaigns with the aims being cost reduction, increasing operational reliability and lessening the overall environmental impact of air-transportation systems. Among these campaigns are Power Optimized Aircraft (2002 till 2006), More Open Electrical Technologies (2006 till 2009), Clean Sky (2009-2016) and Clean Sky 2 (2014-2023). All these programs either already have or will facilitate the reaching of these goals. Ready to play its vital role is the SAVER $28V_{dc}$ active power conversion/energy storage platform.

SAVER aims to aid in evaluating li-ion battery technology for use in aerospace conditions by providing a li-ion battery with battery management system (BMS) and an active switching power converter for battery charging algorithm development and validation. This is crucial given the problems experienced with the li-ion battery as used on the Boeing B787 Dreamliner. These events showed that li-ion based energy storage require further testing before final implementation, both for the battery and its associated power conversion.

By taking the above into account it is safe to assume that SAVER, both directly and indirectly:

- aids in ensuring the safe implementation of li-ion battery technology in aircraft, crucial in the move towards MEA as other technologies depend on its higher current capacity;
- will aid in making aircraft lighter by replacing sealed lead-acid batteries with lighter, higher power density li-ion batteries, and replacing heavy, passive switching transformer rectifier units with light and efficient active power converters for battery charging;
- will aid in solving potential li-ion battery related problems in a controlled laboratory environment rather than in-flight where such problems could lead to grounded aircraft, costly delays and repairs, and a potential hazard to the lives of passengers.

SAVER thus, by contributing to the validation and evaluation processes of li-ion battery technologies, aids in keeping the European aerospace sector competitive by shortening the delivery to market time of new, innovative and essential aircraft technologies and help airframers in meeting societal requirements for security and environmental impacts on global climate change by making air transport more reliable and less polluting.

### 4.2 EXPLOITABLE RESULTS

SAVER resulted in two commercially exploitable and marketable artefacts: the li-ion battery and the DC/DC power converter.

The use of the li-ion battery, developed by consortium partner E4V, with its stable chemistry, high power density and battery management system (BMS) is not just constrained to aerospace use, but can also be adapted to power electrical vehicles and even be used as a household energy storage system in conjunction with other renewable energy sources.

As with the battery, the DC/DC buck converter, as developed by consortium partner SGTE, is also not just constrained to aerospace use, but can also make its way into electrical vehicles and home-based energy storage units where it can fulfil tasks such as battery charging.

Other, scientifically exploitable results include the models of the battery and the converter as developed by consortium partner UPJV. These models can be used to better understand the behavior of the battery under various operating conditions, even those which are not recreatable on a physical test bench. The converter model can be used to develop and pre-validate various control and battery charging strategies before testing on a test bench, whilst at the same time giving insight into various converter parameters such as losses and EMI.

### 4.3 DISSEMINATION ACTIVITIES

#### 4.3.1 PICARDY REGION RESEARCH AND INNOVATION WEEK: 2014/11/25-28

A poster presentation giving the general overview of SAVER and its role within the development of More Electrical Aircraft was made at the 2014 Picardy Region Research and Innovation Week, France, which took place between the 25th and the 28th of November 2014. It is the region's biggest academic and industrial showcase and an important dissemination platform for the Picardie Region, linking industry and academic research.

An audience which included industrial and public participants from France and other European countries were reached.

#### 4.3.2 SAVER WORKSHOP 2015/04/14

An informative workshop was held at the electrical engineering school ESIEE-Amiens, France, on the 14$^{th}$ of April 2015. The aim of the workshop was to inform master and doctoral level students, and academics, from both ESIEE-Amiens and UPJV (University of Picardy Jules Verne) about the concept of More Electrical Aircraft (MEA) as well the development of SAVER and the role it plays in MEA. In-depth discussions included high-performance bi-directional DC-DC converters for aerospace use together with their modelling and control. The important topic of lithium-ion battery technology for aerospace applications was also thoroughly covered, together with advances in battery modelling techniques and battery state of charge estimation.

Presentations were made by:

- G. Allain, F. Abdesselam, T. Bensalah, R. Bouzourene, (Thales TAES): *Context and Systems for Green Operations Integrated Technology Demonstrator - SAVER PROJECT*
- Prepared by J. Deniaud (SGTE-Power) and presented by the Project Coordinator : *High Performance Bidirectional DC/DC Converter for Aerospace Applications*
- J. Bester, A. Mpanda, A. El Hajjaji (MIS - UPJV): *More Electrical Aircraft: test bench and simulation*
- S. Talbi, A. Mpanda, A. El Hajjaji (MIS - UPJV): *Modelling and Control of Bidirectional DAB Converter with Storage System for Aerospace Applications*
- M. Vanbutsel, M.P. Bichat (E4V): *Battery Li-Ion Technology for Aerospace applications*

- Alejandro Franco (LRCS - UPJV): *Boosting rechargeable batteries R&D from multiscale modeling and in silico experimentation*
- E. Khatib, A. Mpanda, A. El Hajjaji (MIS - UPJV): *Real Time Modelling and Parameter Estimation of Li-Ion Battery*

An audience size of 40 was achieved which included academic researchers and both master and doctoral level students from France.

Included are some photos capturing the spirit of the workshop, the presentations, exchanges and the SAVER team.

*Figure 4-1: SAVER workshop photos*

### 4.3.3 PARIS AIRSHOW AT LE BOURGET: 2015/06/15-21

Another poster presentation was made at the 2015 Paris Air Show at Le Bourget. Being one of the prime events on the aerospace calendar it provided an essential opportunity for diffusing SAVER within both professional industrial circles and the public arena. The poster focused on the dual active bridge converter as developed for the project, putting on display simulation results of its switching behaviour and control.

An international audience of industrial and public participants were reached.

# 5 WEBSITE AND CONTACT DETAILS

## 5.1 SAVER WEBSITE

The SAVER website contains information on the project scope and objectives, information concerning the project time schedule, the activities undertaken and the remaining activities to be implemented. It also contains public documents (reports, working papers, published papers, announcements, etc.) produced during the project, the agenda of prospective dissemination activities such as seminars, meetings and conferences. Links to other sites of scientific and technological interest, including other EU-funded projects in related fields, are also presented.

The website can be readily accessed at the following URL:

http://www.saver-h2020.eu

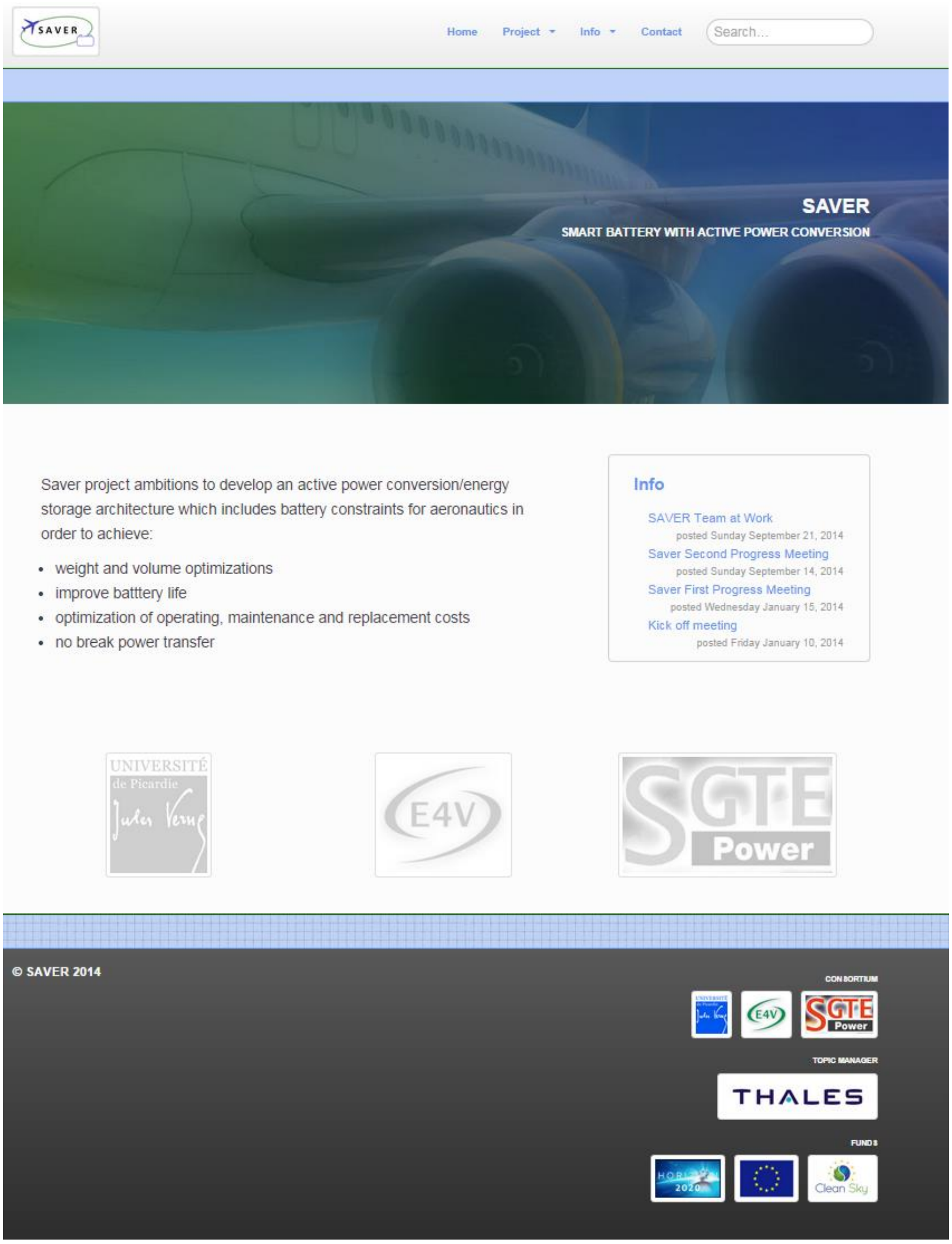


*Figure 5-1: Home page of the SAVER website*

### 5.2 CONTACT DETAILS

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