ANADOLU
STRATEJİ DERGİSİ
Journal of Anadolu Strategy

Battery Management System Architectures For Unmanned Air Vehicles: A Strategic Issue

İnsansız Hava Araçları İçin Batarya Yönetim Sistemi Mimarileri: Stratejik Bir Konu

Asst. Prof. Dr. Melih YILDIZ [*]

Başvuru Tarihi: 20.04.2021
Kabul Tarihi: 01.06.2021
Makale Türü: Araştırma Makalesi

Abstract

Among all of the industrial emissions 3% is produced by aviation. Electric propulsion is a promising option in achieving targets of better environment and sustainability. New concepts of power systems for more electric aircraft (MEA) are being developed, which requires developing demanding battery technologies and other types of energy storage systems. In this roadmap, batteries are strategically critical systems for developing further electric propulsion in aviation. This development also provides benefit to unmanned air vehicles. Using electric propulsion creates more flexible design possibilities for UAVs. Advances in power electronics technologies provide more possibilities for electric power use in UVAs, which also making it possible to use battery technologies. Lithium-ion batteries compared to other electric energy storage systems, provides higher specific energy and energy density. Besides these batteries require to be managed for safe and economic operation. The management function is performed by electronic circuits and systems called battery management systems (BMS). For aviation applications, BMS functions are critical because of the higher safety requirements. Some of the functions can be listed as balancing, over charge/discharge protection, short and overload protection. These functions are related to BMS subsystems which are designed through alternative design architectures. For each specific application, BMS design shall be revisited and BMS subsystems shall be decided according to application specific requirements. While the main focus is safety of the battery or electric energy storage system, reliability is also important for aviation. In this paper, requirements are reviewed for aviation batteries and architecture alternatives and aspects related to BMS design are discussed. It is concluded that, requirement based parametric design of the BMS is essential in aviation battery management applications.

Keywords: Military aviation; UAV battery; battery management system; UAV battery system requirements.

Özet

Elektrikli itki sistemleri, daha çevreci, maliyet etkin, güvenilir, bakım yapılabilir ve sürdürülebilir olma hedeflerine ulaşmada umut verici bir seçenektir. Daha elektrikli uçak (More electric aircraft - MEA) itki sistemleri geliştirilirken, görece daha karmaşık batarya teknolojilerinin ve diğer enerji depolama sistemlerinin geliştirilmesi gerekli olmaktadır. Bu yol haritasında bataryalar, havacılıkta daha fazla elektrikli tahrik geliştirmek için stratejik olarak kritik sistemlerdir. Bu teknolojik ilerleme insansız hava araçları (İHA) açısından da fayda sağlamaktadır. Elektrikli tahrik sistemleri, İHA'lar için daha esnek tasarım olanakları

[*] Faculty of Aviation and Space Sciences, Department of Aeronautical Engineering Girne University, **melih.yildiz@kyrenia.edu.tr**, ORCID: 0000-0002-7546-4462

yaratır. Güç elektroniği teknolojilerindeki gelişmeler, İHA'larda elektrik gücü kullanımı için daha fazla olanak sağlamakta ve bu da batarya teknolojilerinin kullanılmasını mümkün kılmaktadır. Lityum iyon bataryalar, diğer elektrik enerjisi depolama sistemlerine göre daha yüksek özgül enerji ve enerji yoğunluğu sağlar. Ayrıca bu bataryaların güvenli ve ekonomik çalışması için yönetilmesi gerekir. Yönetim işlevi, batarya yönetim sistemleri (BYS) adı verilen elektronik devreler ve sistemler tarafından gerçekleştirilir. Havacılık uygulamaları için, daha yüksek güvenlik gereksinimleri nedeniyle BYS işlevleri kritiktir. Fonksiyonlardan bazıları dengeleme, aşırı şarj/deşarj koruması, kısa devre ve aşırı yük koruması olarak sıralanabilir. Bu işlevler, alternatif tasarım mimarileri ile tasarlanan BYS alt sistemleri ile ilgilidir. Her özel uygulama için BYS tasarımı yeniden gözden geçirilmeli ve BYS alt sistemleri uygulamaya özel gereksinimlere göre geliştirilmelidir. Ana odak batarya veya elektrik enerjisi depolama sisteminin emniyeti iken, havacılık için güvenilirlik (reliability) önemlidir. Bu yazıda, havacılık bataryaları ve BYS tasarımlarının mimari alternatifleri farklı uygulamalar için incelenmiş ve BYS tasarımı ile ilgili hususlar tartışılmıştır. BYS'nin gereksinim tabanlı parametrik tasarımının havacılık batarya yönetimi uygulamalarında önemli olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Askeri Havacılık; İHA; Batarya Yönetim Sistemi; İHA Batarya Sistem Gereksinimleri.

Introduction

Introduction of More Electric Aircraft (MEA) and All Electric Aircraft (AEA) concepts, made the industry to be able to develop aircraft with lower emission and lower operating costs (Abdelhafez & Forsyth, 2009; Mcloughlin, 2009; Technology, 2001). Industry has already achieved high efficiency gains for large civil aircraft using MEA concept (Wheeler & Bozhko, 2014). Introduction of MEA and AEA, requires the use of higher capacity batteries, compared to conventional aircraft.

Virtually all aviation platforms use batteries to store electric energy on board. Whatever the air vehicle, even it is a single engine propeller or satellite, batteries are required as an electric energy storage device. Air platforms are required to carry all of the energy for the mission and shall turn back without fully using it. Every mission has its specific requirements and thus, contrary to lead acid battery technology, batteries shall be designed for each other mission of the air vehicle (Borthomieu, 2014).

There are many kinds of lithium-ion battery cells in the market with different electrochemistry thus different thermal and energetic properties. Battery cells are also provided in several different forms and structures. Some examples are cylindrical cells with sizes 18650, 26650, pouch cells and prismatic cells.

Batteries for aviation applications have high capacity and thus large number of cells in series and parallel are used. Lithium-ion cells have relatively small capacity. Cells are integrated into battery modules and modules forms the battery system. For high capacity applications, battery systems contain one or more battery modules. The integrated battery system at the end may consist of hundreds of cells (Lu et al., 2013). The large number of cells used in batteries expose the problems of safety, cost and reliability. For this reason, battery management system (BMS) is needed for safe operation. BMS shall be efficient and also safe itself, in order to keep battery system ready to operate whenever and wherever needed (Rahn. D. & Wang, 2013).

Weight and size of the batteries mainly depend on the electrochemistry which is defined in the specific energy and energy density figures. Besides, management system itself adds additional weight and volume to the total of the battery system.

In this work, possible battery management system (BMS) architecture alternatives are investigated depending on the requirements of military aviation applications. Methodologies for collecting aviation BMS design is analyzed and BMS design considerations by means of technology and topology are defined. For aviation BMS applications, it is critical to design every battery system for each mission and platform specific requirements.

Battery Requirements in Aviation

Aviation battery requirements can be summarized in four titles. The battery systems shall be; (Reid, 2015; Vutetakis, 2013);

a) Safe
b) Lightweight (high specific energy)
c) Compact (high energy density)
d) Reliable, (meeting mission requirements by means of energy and power capacities)

Safety is a major factor for aviation, especially after battery accident took place in 2013 when battery of a large civil aircraft got fires. Depending on the survey, authorities reported that thermal management of the battery is required for every battery system for aviation (Williard et al., 2013).

BMS and also battery systems have to be lightweight without compromising the safety. Aviation is very sensitive to the system weight and every requirement shall be fulfilled in acceptable weight and size. All subsystems including cells, thermal management, balancing, structural components etc shall be compact as possible. BMS also have to consume as low energy as possible, as any additional consumption decreases the efficiency of the overall battery system.

Battery performance is also shown to be a function of the temperature of the cells (Pals & Newman, 1995; Pesaran, 2001). In order to achieve longer and efficient battery and cell life, all the cells shall operate at the same temperature level (Pesaran et al., 1997). For reliable operation of battery systems, thermal management is required both at system level and battery level as defined in literature and accident investigation reports (Pesaran et al., 1999; Rahn. D. & Wang, 2013).

Specifications and Functions of BMS

Batteries are used in every mobile electronic device from watch to satellites. Every application has its own mission requirement. Even batteries used in different sections of the aircraft can have distinct requirements. BMS can be designed in a broad functionality range from having a simple monitoring function up to complex electromechanical system. The difference depends only in the system where it is integrated. This characteristic makes the lithium-ion battery different from its ancestor, the lead acid battery. Lithium-ion battery shall be tailored for aviation applications in order to have enough safety and reliability in cost and energy effective manner.

BMS is responsible for controlling the charging and discharging of the battery (Rahn. D. & Wang, 2013). BMS is a real-time electronic system for sensing/controlling/deciding and reporting about the battery status in order to provide (i) safe and reliable operation of the battery system (ii) ensure that the cells are balanced, (iii) charge and discharge currents are limited. Generally, it is integrated into the battery case for prompt prediction of failure and prevention.

Battery system and BMS design are already studied in depth for the automobile industry. BMS for aviation applications have to be designed for more strict safety and maintainability considerations in addition to battery system requirements. The aviation industry is showing progress from a simple lead-acid battery to energizing the aircraft with the lithium-ion battery. In this period, deploying a careful design methodology is required due to high energy capacity required air vehicle.

In this work, only safety and maintainability is discussed briefly. In design cases besides of this two reliability, availability, integrity and dependability shall also be assessed as design considerations.

Safety

BMS is an electronic system which includes electronic components and software in most of the applications. Safety of the BMS is discussed in the literature for electric vehicles (Hauser & Kuhn, 2015a). Procedures are similar in both industries, and as the process includes comprehensive risk management methodology, it can be easily adapted to the aviation. EVs require the compliance to the ISO 26262 standard which compromises both hardware and software part as subsystems. For aviation in addition to ISO 26262, compliance to DO178 for software and DO254 (or ED80) for hardware development is required for achieving acceptable means of safety.

Battery is considered as an avionic for the aviation industry. As a specific avionic battery system and specifically BMS design is a safety oriented process which starts in the concept phase. At this step Hazard Analysis and Risk Assessment (HARA) is conducted in order to define possible hazards and malfunctions, using techniques as brainstorming, FMEA etc (Bozzano & Villafiorita, 2011). Every possible hazard is graded according to its severity, exposure and controllability. System level effects of the hazard are also considered. After the hazard and malfunctions are listed and graded, safety goals for the system are listed. For example, prevention of deep discharge of the cells is a sample safety goal for BMS. The listed Safety Goals (SG) are converted to Functional Safety Requirement (FSR) to determine the measures to be implemented. The FSRs are detailed requirements in order to make it possible to get to the Technical Safety Requirements which act as an input for system design. At the system design phase, preliminary system architecture is developed to include detailed design.
Another challenge of BMS design is the secure power supply for BMS itself. Most of the BMs uses the battery power in order to drive itself. This causes a deficit of in case of any battery or cell failure, BMS power supply cannot be secured in order to perform the expected safety measures.

One of the critical challenges in BMS design is the answer to the classical question such as if the BMS shall allow the current draw from the battery even if the battery has reached the critical level of discharge. Shall the BMS sacrifice the battery against the loss of the energy supplied to the aircraft? For an application of more electric aircraft, it cannot be a big deal but in case of an all-electric aircraft, it requires to be decided in the first step.

Maintainability
For civil transport aircraft, maintenance costs can be as high as 30% of the total operating costs (ICAO 2017). Batteries having a useful life, need to be maintained especially near to the end of their life. Cell voltages and State of Health (SoH) and BMS functions shall be validated.

Batteries generally have high voltage electric which makes the maintenance a special process. Handling during maintenance needs special care for the poles. During the design, maintenance process shall be considered and required measures such as disconnecting the poles shall be placed. Also, BMS shall have the short protection for not only maintenance but also for normal use and handling.

Embedded software and human interfaces are also needed to be developed in order to ease the maintenance process. Embedded software is also subject to cyber security threats, which shall be considered for maintenance procedures.

BMS functions
BMS functions are performed via an electronic circuit which includes subsystems with specific functions. The functions listed in the literature can be grouped under 9 main function groups.

1- Measurement and Battery parameters detection
   a. Thermal monitoring
   b. Cell voltage monitoring
   c. Current monitoring
   d. Power monitoring
2- Evaluation and Calculation/estimation of battery states
   a. SoC calculation/estimation
      i. Voltage based
      ii. Coulomb counting
   b. SoH calculation/estimation
   c. SoF calculation/estimation
3- Management and Safety control and measures
   a. Over charge protection
   b. Over discharge protection
   c. External short protection

   d. Over current protection
   e. Thermal protection
   f. Switching
4- Battery balancing
   a. Active balancing
   b. Resistive balancing
5- Thermal management
   a. Active thermal management
   b. Heating only
   c. Passive thermal management
   d. Protection only (thermal fuse)
6- Communication
   a. Dedicated analog wire
   b. Digital
   c. Data link
7- Logging and Data storage
8- On-board diagnosis
9- Power supply

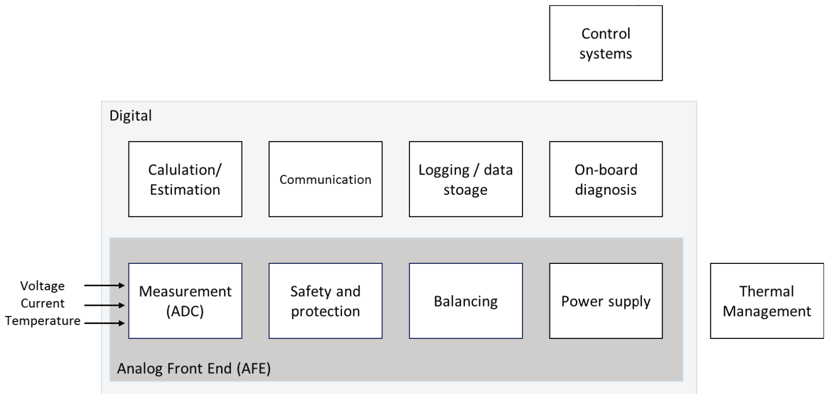

Figure 1 Schematic of the functions of the BMS

BMS functions needed for safe battery operation is listed above and given in Figure 1. In this figure, the analog front end and digital part functions are shown. Also, some functions like control systems and thermal management are shown out of the PCB as they consist contactors, fuses, and auxiliary thermal management systems like water pump, pipes, heat exchangers etc.

BMS Technology Alternatives
Battery Management is required in any electric and electronic system where a battery is used. Battery management can be a simple protection circuit or even a complex electronic system. The system complexity depends on the requirements of the system design.

BMS is a printed circuit board (PCB) with electronic components on it. Every BMS have an analog part which is called analog front end (AFE). This sub part is required in order to read cell voltages, current and it provides balancing circuit and has some safety measures like fuses etc. If the BMS processes the cell voltages with analog circuitry, the BMS is called analog (Andrea, 2010). Similarly, BMS that processed the cell voltages digitally are called digital BMS. Digital BMS have micro controllers which run algorithms for the required function of the BMS.

Analog BMS
Analog BMS capabilities are limited but yet useful and provide enough level of safety for most of the applications. For example, the battery pack for floor washing machines with 7 kWh capacity is developed with

analog BMS given in Figure 3, tested in a real environment. In analog architecture, BMS does not know which cell voltage is higher or lower but just knows if there is a higher voltage cell. But this information is enough in order to shut off the pack for protection.

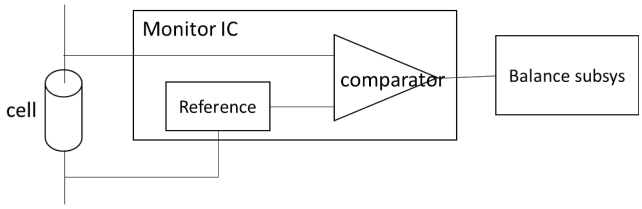

Figure 2 Analog BMS example circuit (Andrea, 2010)

Analog BMS is called simple in the literature and SoC calculation is not provided in analog BMSs. Main items of an analog BMS are the voltage reference and a comparator for comparing the cell voltage (Figure 2). The result of this comparison is used to cut off or open the battery charge/discharge and cell balancing resistance. The Analog BMS used in Figure 3 is given in Figure 4.

Figure 3 An experimental battery pack of 24V, 7kWh with analog BMS

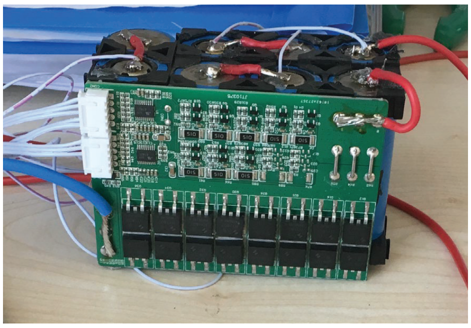

Figure 4 An analog BMS

Digital BMS

Although BMS architecture using a micro controller is called digital, every BMS shall use an analog front end (AFE) in order to read and control the cells in the battery. In the AFE, an analog/digital converter measures each cell voltage and reports it to a microprocessor (Figure 5). Microprocessor runs a software which has algorithms for specific functions like SoC calculation/estimation, safety control etc. Microprocessor reports the results of the calculations and/or estimation together with requested information via display or communication line.

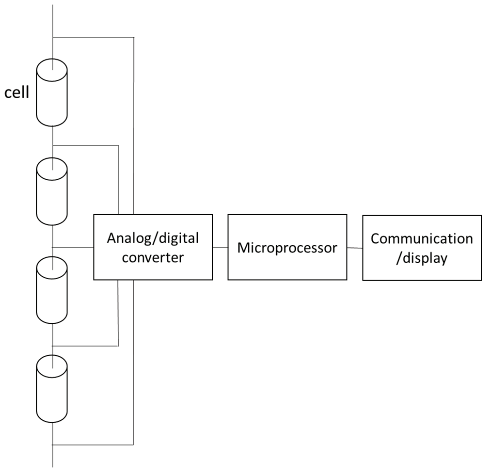

Figure 5 Digital BMS measurement function (Andrea, 2010)

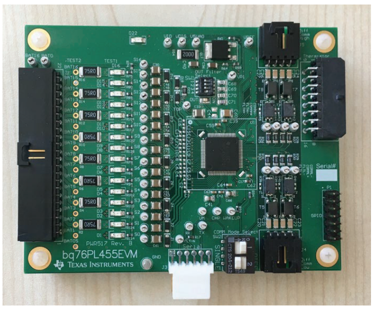

Figure 6 Digital BMS

In Figure 6 a sample digital BMS product is shown. This digital BMS includes a comprehensive analog-digital converter for 16 cell voltage detection at the same time. The PCB also includes balancing and communication subsystems. On this sample, there is no processor as it is connected to a personal computer. The shown BMS has also CANBUS connection capability in order to connect more BMSs in series.

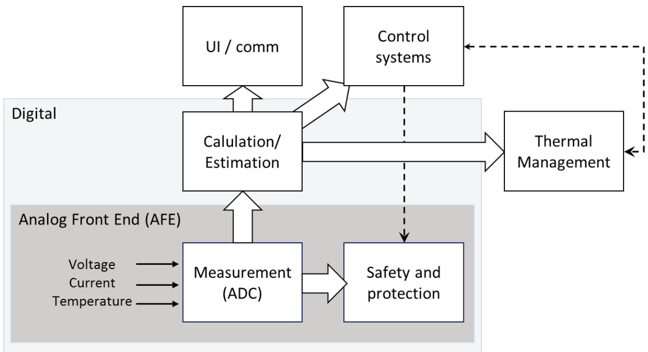

Figure 7 Digital BMS functional schematic

Technology Comparison

Analog and digital BMS technologies have their own advantages for different applications. For lower energy levels and less critical applications analog technology seems more advantageous where digital BMS is preferred on more precise and high energy batteries. Also in an application where energy level estimation of a battery is performed by BMS, digital BMS with a microcontroller is needed to run the estimation algorithm.

Table 1 Functions availability, based on BMS technologies comparison

Function	Analog BMS	Digital BMS
Measurement and Battery parameters detection		
a. Thermal monitoring	X	X
b. Cell voltage monitoring	X	X
c. Current monitoring		X
d. Power monitoring		X
Evaluation and Calculation/estimation of battery states		
a. SoC calculation/estimation		X
b. SoH calculation/estimation		X
c. SoF calculation/estimation		X
Management and Safety control and measures		
a. Over charge protection	X	X
b. Over discharge protection	X	X
c. External short protection	X	X
d. Over current protection	X	X
e. Thermal protection	X	X
f. Switching	X	X
Battery balancing		
a. Active balancing		X
b. Resistive balancing	X	X
c. algorithm based balancing		X
Thermal management		
a. Active thermal management (heating/cooling)		X
b. Heating only		X
c. Passive thermal management (fins only)	X	X
Communication		
a. Dedicated analog wire	X	X
b. Digital		X
c. Data link		X
Logging and Data storage		X
On-board diagnosis		X
Power supply		
a. Dedicated		X
b. From battery	X	X

Function level comparison of the analog and digital BMS technologies are given in Table 1. In this table, the functions are listed and a possibility of application of the function is marked as “X” in the analog or digital column. It can be seen that analog BMS can perform most of the functionalities where digital BMS can provide calculation based functions.

As an example, analog BMS can perform balancing depending on cell voltage comparison, besides the digital BMS can perform it by using more comprehensive algorithms or even using more complex dependencies like internal resistance, status of the battery etc.

BMS Topology Selection
In order to achieve a designed level of performance, reliability and maintenance and production ease BMS hardware can be produced in alternative topologies. Among the BMS samples on the market, four different topologies are discussed. Every topology has its own advantages and may be selected according to the application it is used. (Hauser & Kuhn, 2015b).

Most referred four topologies are centralized, modular, master-slave and distributed topologies. They are named mainly according to their digital and analog parts' proximity to the cells. It can be seen that the closer the electronic part to the source, the more cleanly the signal and read efficiency is. On the other hand, especially in large batteries with a high amount of cells, BMS placement become trickier as the harness and cable lengths increase.

Selection of appropriate topology is critical by means of production cost, maintainability and reliability. In order to be able to select the optimal topology, four alternative topologies are presented and discussed.

Centralized
In this topology (Figure 8), BMS is a single PCB wired directly to the cells. This topology provides more compact and cost effective solution. Besides, it can be easier to maintain and produce if the pack consists a small number of cells. This topology is more suitable and preferred for analog BMS applications.

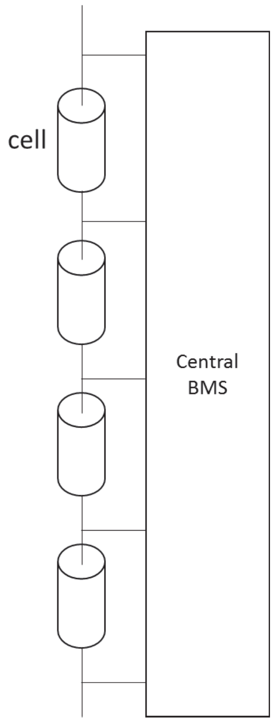

Figure 8 Topology of a centralized BMS

Modular
In case the battery is made up of several packs with a large number of cells in parallel (Figure 9), it may be advantageous to split the BMS. This topology is similar to centralized BMS, which are connected in series. In this topology, a communication link exists between the modules and one of the BMS modules is selected as the master which communicates the reference values with other BMSs and system.

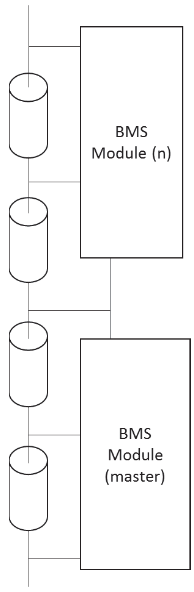

Figure 9 Schematic of a modular BMS topology

Modular topology provides the ease for the harness. Also, it is easier to extend the battery by just adding a pack with modular BMS. An addition of dedicated communication line between the modules may add some cost and additional wiring. Also, there is a possibility that the unused functions exist on the slave modules which are dedicated for master functions.

Master-Slave

Master-slave topology includes two different subsystem configurations. One is the slave module which includes the AFE and directly connected to cells, the other is the master module who communicates with slave modules and user (Figure 10). The master module performs the calculations, estimations and control of the system. In this way, it is different from the modular topology.

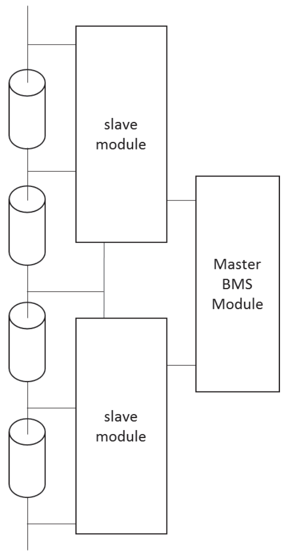

Figure 10 Master-slave topology schematic

It may be cost effective to keep the analog circuits on the slave modules and remove the digital part to the master module. By means of reliability, maintainability and cost efficiency, this topology is mostly preferred especially for high voltage battery systems with a large number of cells. In this topology, it is also easy to extend the battery with an addition of slave module connected pack.

Distributed
In this topology, relatively small circuits are connected directly on the cell tabs which communicate with each other and the last module is connected to a controller (Figure 11). BMS controller controls the communication and performs the calculations and controls. This topology can be useful in large format prismatic cells where long cables and complex harness is required.

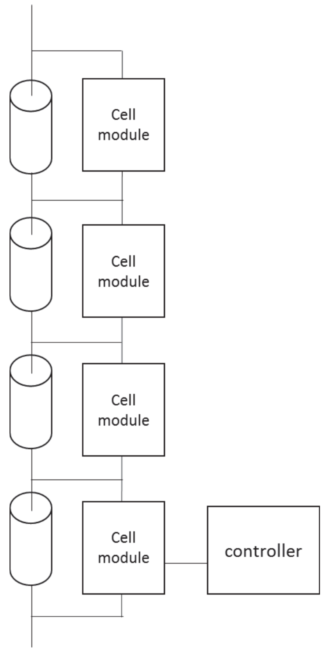

Figure 11 Schematic of distributed BMS topology

Conclusion
Military application of the electricifcation of the UAVs will enable those parties with these capabilities to have a more competent fighting machines. In terms of economy, stealth, durability and maintainability.

Battery design for aviation applications has many criteria, especially on safety, maintainability, cost and reliability. A battery design process need careful analysis of the technology and topology alternatives of the BMS. It is obvious that every specific mission for every air platform needs specific battery systems. Therefore there is no one solution for each aviation application. There are analog and digital technological solutions for BMS design where for high voltage and critical battery systems digital technology or even a hybrid design seems appropriate. Selecting a topology for BMS depends highly on electrochemistry and the cell type selected for the BMS. There are numerous topologies with advantages and disadvantages and each shall be considered for every application requirement.

For aviation applications, BMS certifications require DO178 and DO256 for embedded software and electronics hardware simultaneously. Because of the high reliability and safety requirements, digital BMS technology is a must for aviation. Besides for redundancy analog BMS technology may be considered in cooperation with digital structure.

BMS topology for aviation can be selected for every design, but shorter balancing and signal cabling must be considered for reliability and safety, thus master-slave topology seems more applicable as it provides both shorter cabling and failure tracking ability for embedded software in the master module.

References

Abdelhafez, A., & Forsyth, A. J. (2009). A Review of More-Electric Aircraft. *Aerospace Sciences & Aviation Technology*, 1–13.

Andrea, D. (2010). *Battery Management Systems for Large Lithium-ion Battery Packs*. Artech House.

Borthomieu, Y. (2014). Satellite Lithium-Ion Batteries. In *Lithium-Ion Batteries* (pp. 311–344). Elsevier. https://doi.org/10.1016/B978-0-444-59513-3.00014-5

Bozzano, M., & Villafiorita, A. (2011). *Design and safety assessment of critical systems*. Auerbach Publications.

Hauser, A., & Kuhn, R. (2015a). Cell balancing, battery state estimation, and safety aspects of battery management systems for electric vehicles. In *Advances in Battery Technologies for Electric Vehicles* (Vol. 26262, pp. 283–326). Elsevier. https://doi.org/10.1016/B978-1-78242-377-5.00012-1

Hauser, A., & Kuhn, R. (2015b). High-voltage battery management systems (BMS) for electric vehicles. In *Advances in Battery Technologies for Electric Vehicles* (pp. 265–282). Elsevier. https://doi.org/10.1016/B978-1-78242-377-5.00011-X

Lu, L., Han, X., Li, J., Hua, J., & Ouyang, M. (2013). A review on the key issues for lithium-ion battery management in electric vehicles. *Journal of Power Sources*, *226*, 272–288. https://doi.org/10.1016/j.jpowsour.2012.10.060

Mcloughlin, A. (2009). More Electric – Ready for take off ? *13th European Conference on Power Electronics and Applications*, 1–7.

Pals, C. R., & Newman, J. (1995). Thermal Modeling of the Lithium/Polymer Battery I. Discharge Behavior of a Single Cell. *Journal of The Electrochemical Society*, *142*(10), 3282. https://doi.org/10.1149/1.2049975

Pesaran, A. (2001). Battery Thermal Management in EVs and HEVs : Issues and Solutions. *Advanced Automotive Battery Conference*, 10.

Pesaran, A., Burch, S. D., & Keyser, M. (1999). An approach for designing thermal management systems for electric and hybrid vehicle battery packs. *Fourth Vehicle Thermal Management Systems Conference and Exhibition*. http://www.nrel.gov/docs/fy99osti/25992.pdf

Pesaran, A., Vlahinos, A., & Burch, S. D. (1997). Thermal Performance of EV and HEV Battery Modules and Packs. *Fourteenth International Electric Vehicle Symposium*.

Rahn. D., C., & Wang, C.-Y. (2013). *Battery Systems Engineering*. Wiley.

Reid, C. M. (2015). Batteries at NASA – Today and Beyond. *Undergraduate Seminar for Xavier University of New Orleans*.

Technology, A. (2001). Advances in more-electric aircraft technologies. *Aircraft Engineering and Aerospace Technology*, *73*(3).

Vutetakis, D. (2013). Applications - Transportation | Aviation: Battery. In *Reference Module in Chemistry, Molecular Sciences and Chemical Engineering*. https://doi.org/10.1016/B978-0-12-409547-2.01114-8

Wheeler, P., & Bozhko, S. (2014). The More Electric Aircraft: Technology and challenges. *IEEE Electrification Magazine*, *2*(4), 6–12. https://doi.org/10.1109/MELE.2014.2360720

Williard, N., He, W., Hendricks, C., & Pecht, M. (2013). Lessons learned from the 787 dreamliner issue on Lithium-Ion Battery reliability. *Energies*, *6*(9), 4682–4695. https://doi.org/10.3390/en6094682