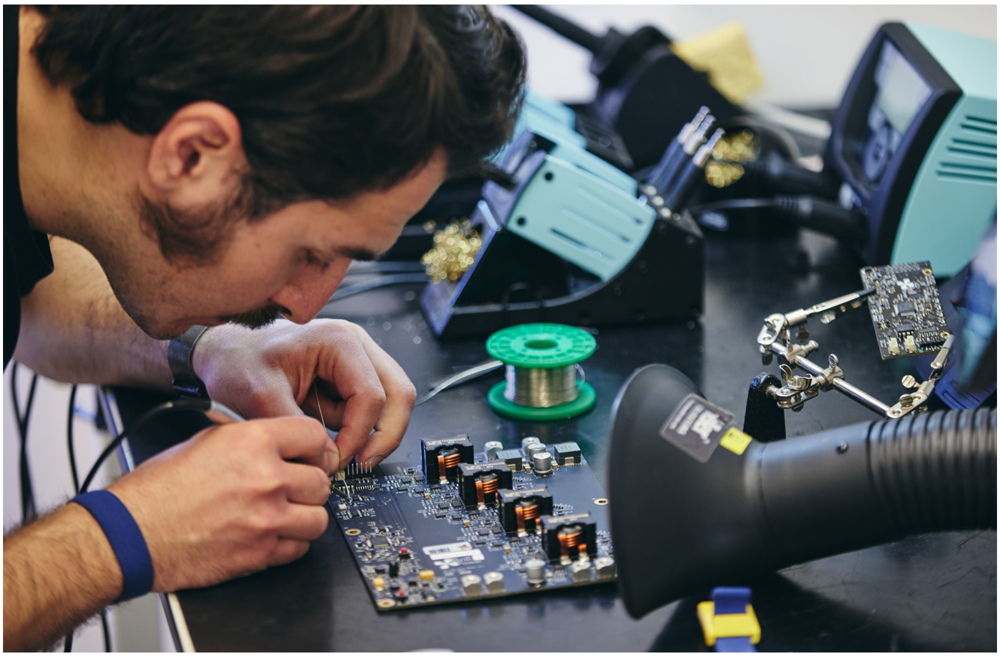
How to design a BMS, the brain of a battery storage system

Battery management | Battery energy storage systems are placed in increasingly demanding market conditions, providing a wide range of applications. Christoph Birkl, Damien Frost and Adrien Bizeray of Brill Power discuss how to build a battery management system (BMS) that ensures long lifetimes, versatility and availability.



Credit: Brill Power

BMS hardware in development.

Every modern battery needs a battery management system (BMS), which is a combination of electronics and software, and acts as the brain of the battery. This article focuses on BMS technology for stationary energy storage systems. The most basic functionalities of the BMS are to make sure that battery cells remain balanced and safe, and important information, such as available energy, is passed on to the user or connected systems.

Balancing is needed because battery systems are made up of hundreds, sometimes thousands of individual cells, which all have slightly different capacities and resistances. These differences increase over time as the cells degrade at different rates. If the cells are not balanced at least occasionally, their voltages will soon drift apart to an extent that the battery capacity becomes unusable.

Safety is ensured by keeping the cells within safe operating limits of voltage, current and temperature, which is particularly important for lithium-ion batteries. If cells get over-charged, charged at very low temperatures, or exposed to excessive currents or temperatures, they could develop faults that may lead to fires or explosions.

Information such as available energy and power cannot be directly measured, which means the BMS must compute it based on measurements of voltage, current and temperature. These computations are called state estimation and the results are passed on to higher-level systems, including user interfaces.

Before we look at BMS design considerations in more detail, it is worth describing the different types of BMS and industry requirements that inform design choices. The balancing approach is typically used to classify BMS types, although other design aspects play important roles, such as different approaches to state estimation and information flows.

Basic Pack Construction

Cells, or electrochemical cells, like lithium-ion cells are the smallest unit of energy storage within a pack. They come in various physical sizes which directly relate to their capacity. The minimum voltage of a Lithium-ion cell can be as low as 2.5V (for LFP cells) and the maximum voltage can be as high as 4.3V for NMC chemistries.

Cells are connected in parallel to increase the maximum current that can be drawn from the pack. A group of parallel connected cells are called a super cell. In general, the cells within a super cell will self-balance and there is no need to manage them further. Exceptions can include novel chemistries like lithium sulfur and chemistries with flat state of charge versus voltage curves operated in extreme C-rate conditions like lithium iron phosphate.

Super cells are connected in series to form a string. A battery pack usually consists of a single string. Connecting super cells in series increases the voltage of the pack, which is necessary in high power applications to prevent otherwise extremely high operating currents.

When adding cells to a battery pack configuration, the energy capacity increases. Therefore, adding parallel cells to a super cell increases the pack's energy capacity, as does connecting an additional super cell in series.

BMS types

Balancing approach

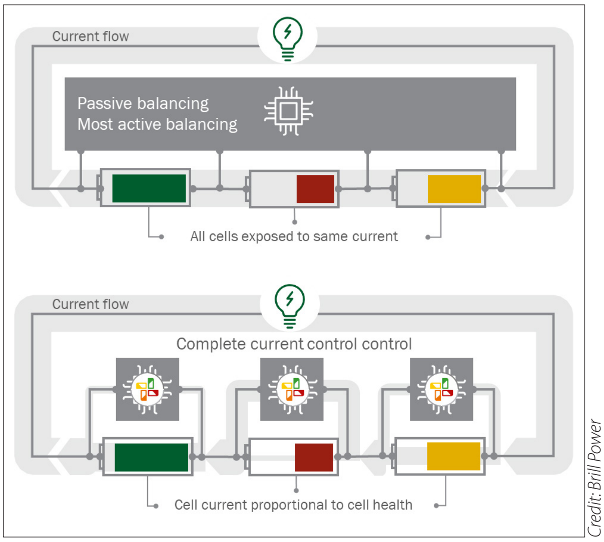
Passive balancing synchronises cell voltages at the end of the charge process by dissipating energy, which would have gone into fully charged cells, as heat via resistors. The advantage of this approach is the low component cost of the electronics. Disadvantages include that all cells are exposed to the same current, which means that the weakest series-connected cells limit the energy, power, lifetime and safety of the whole battery. Cell degradation is accelerated since the current on weaker cells is higher relative to their capacity, which can also cause localised hot spots that may lead to de-rating of battery power or even safety issues. Moreover, energy is wasted during the charging process. The passive BMS can only monitor the pack current and interrupt it via a disconnect switch in the event of a fault. If bi-directional information flow is implemented, system-level parameters such as operational settings may be changed to prioritise either battery lifetime or performance. Lifetime is prioritised by reducing the operational window at the expense of available energy or power, while performance is prioritised by widening the operational window, at the expense of battery life.

Active balancing is typically implemented via low-current bypass circuits, which direct low charging currents to cells that are not yet charged, rather than dissipating the energy as heat. The main benefit of this approach is to improve charging efficiency, which may be important if the available charging energy must be utilised as efficiently as possible. For most applications, however, active balancing does not justify the added component cost for the benefits they yield. Like with passive balancing, cell degradation is accelerated by higher relative currents on weaker cells and hot spots may form.

Complete current control is a novel approach to battery control and management, recently developed and patented by our team at Brill Power, a spin-out company of Oxford University. The current on each super cell (or small super cell string) is continuously regulated in proportion to the health of the cells – weaker cells are exposed to lower currents, stronger cells to higher currents. This ensures that all available energy and power is utilised, no single cell or cell group limits the lifetime of the battery, and degradation on weaker cells is slowed down.

Safety benefits of complete current control include avoiding the formation of hot-spots by reducing the currents on cells with high resistance, and cell-level disconnects to contain any possible faults. This approach also has the benefit of system-level voltage regulation, which enables the direct integration of the battery with DC power sources, such as solar PV, fuel cells and other battery types, as well as with DC loads, such as EV chargers. The component cost of this approach is higher than for a passive balancing BMS, when the BMS is viewed in isolation, but lower when viewed at a system level.

The lower system cost is achieved by reducing battery size for a given performance and avoiding additional hardware such as DC/DC converters or inverters (which are needed to link solar PV and storage, or storage and EV charging). Total cost of ownership is reduced by extending battery lifetime by up to 60%, according to analyses by Brill Power and WSP.



A simplified illustration of different BMS types

Other, niche approaches to BMS technology include cascading cell bypasses and the integration of inverters, but we will not discuss them further here due to their limited applicability.

State estimation

Estimation of the State of Charge (SoC) and State of Health (SoH) is based on a combination of battery models and estimation algorithms. The level of sophistication and accuracy that is possible for state estimation and underlying battery models strongly depends on the hardware, which we use here to differentiate different approaches.

Integrated circuits (IC) are used in most conventional BMSs for state estimation, which are often referred to as 'fuel gauge'. ICs are 'hardwired' with chemistry-specific battery models and state estimation algorithms. The advantage of ICs is that they are low cost. The disadvantages include limited system design flexibility and accuracy. The latter tends to get worse over time. Design flexibility is limited because ICs are typically created for a particular battery chemistry with particular specifications.

If the battery chemistry or specifications change, the IC also needs to be changed and the design adapted. The reasons for the limited and deteriorating accuracy are (i) state estimation on ICs is based on generalised representations of the battery chemistry and doesn't capture the nuanced thermodynamic and dynamic properties of cells, which can vary between manufacturers, formats and batches, even for the same chemistry (ii) limited computing power on ICs constrains the complexity and fidelity of state estimation algorithms and underlying battery models, and (iii) cell characteristics change over time, which cannot be captured by hardwired IC algorithms, leading to increasing inaccuracy over time.

Microprocessors can be programmed with more complex, higher-fidelity battery models and state estimation algorithms, which can be fine-tuned to account for particular cell characteristics and specifications. The changing cell characteristics can be accommodated by updating the parameters of the state estimation algorithms and battery models, which keeps outputs more accurate over time. The same hardware can be used for any type of battery chemistry or manufacturer, allowing for ultimate design flexibility. The disadvantage can be higher component cost, depending on the required functionality and computational power.

Information flow

Uni-directional information flow is common in most battery systems: information flows from the BMS to higher-level systems and user interfaces. If the BMS is provided by the cell maker, less low-level information tends to be available, as this information can be considered sensitive. The most important information is safety and performance related and includes metrics such as SoC and SoH.

Bi-directional information flow is possible if the BMS can process inputs, such as changes to operational settings (for example maximal and minimal allowable cell voltage or SoC), or even updates to battery models or state estimation algorithms to maintain their accuracy, if microcontrollers are used.

Industry requirements

The selection of the appropriate BMS type is hugely important in creating the optimal battery system for a given application. However, all too often it is not up to the battery system manufacturers, developers or operators to select the appropriate BMS. The dominant cell manufacturers tend to impose their own BMS solutions for three obvious reasons:

- Revenues – can be increased by selling their own BMS
- Control and warranties – the BMS can be programmed with conservative settings,

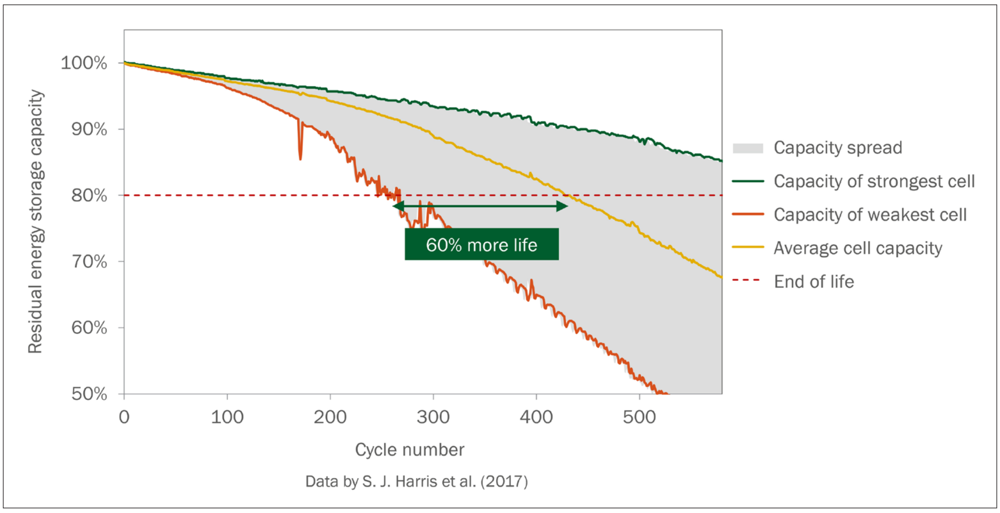
not visible to the battery developer or user, that ensure that warranty cases are minimised. These settings may even be updated by the cell supplier or OEM over time to counter faster-than-expected degradation.
- Confidentiality – the BMS is the gatekeeper to cell-level data, which some cell manufacturers prefer not to make available to their customers.

The world's leading cell makers can take this approach because they control cell supply and can choose to not sell their cells without their own BMS. The preferred BMS approach of cell manufacturers is passive balancing with ICs for state estimation and unidirectional information, which can help undercut the competition on capex for battery modules and packs.

Cell manufacturers obviously strive to sell as many cells as possible, which means they are incentivised to limit battery lifetime to the minimal acceptable duration – a fact that must be considered when selecting integrated solutions of cells plus BMS from cell suppliers. Obvious advantages of this offering for battery system developers are the low capex of modules and packs, as well as the simplicity of purchasing fully integrated solutions. One suitable application for this BMS approach is backup power for businesses and industry, where cycle life is of little concern, provided that short to medium term warranties are sufficient.

A low-cost, low-functionality BMS may also be the preferred choice for energy storage deployments, which are scheduled to be augmented in the future once the system has lost too much capacity to operate. The rationale being future technology may be lower cost than today. The risks of this business model are that battery costs may not continue to decrease, not least because of bottlenecks in materials supply, the technical difficulties and 'unknowns' of integrating future and past battery technology, and additional maintenance cost due to high system complexity and downtime caused by failing battery modules or racks.

Suitable applications for active balancing are ones where charging energy is in short supply and must be used as efficiently as possible, such as solar power integrated onboard vehicles on land, air and sea. Active balancing may also be used for harvesting very small amounts of energy via small batteries for isolated systems in remote locations.



Credit: Brill Power

Growing concerns over the sustainability of batteries and their lifecycle, increasing knowledge of battery technology and system economics by developers and operators, as well as the fast pace of development in battery materials and chemistry are leading to increasing interest and demand for complete current control as a BMS approach. Applications that are particularly suitable for the complete current control BMS approach include ones that are sensitive to total cost of ownership or system capex, require high reliability and long cycle life, or that need particular flexibility regarding the integration of future battery chemistries. Examples include grid support with demanding use cases and high system cost, co-located solar and storage, storage projects needing to achieve lifespans of greater than 8-10 years, as well as mission-critical energy storage with maximal reliability.

The lifetime of the battery system can be improved if the battery is not limited by its weakest cell

BMS design and development

Once the appropriate BMS type has been identified, design and development can begin. The single most important factor in BMS design is the team and its expertise. Traditionally, BMS design has been the domain of electrical engineers, who are indeed best placed to design the circuitry, but don't typically have much knowledge of the inner workings of batteries. Designing the perfect BMS requires knowledge and expertise in electrochemistry, physics, electrical and electronic engineering, firmware development and data science.

With the right team in place, the first considerations should go to compliance with regulation and industry standards, since this has implications on both hardware and software design. Regulations and standards are typically specific to regions. Although most regulation and standards apply to the battery system as a whole, some regulations apply to all electronic components and includes hazardous substance regulation, such as the RoHS and REACH directives in Europe. Relevant industry standards strongly depend on application and system specifications. Typical differentiators are residential vs industrial energy storage, and low vs high voltage.

The most relevant standards for industrial storage include IEC62619, UL1973, UL9549 and VDE-AR-E 2510-50. Product and functional safety are the most important aspect of these standards. Although the BMS is not required to be certified as a stand-alone component, it must not prevent the battery system from being certified. Testing and evaluation of prospective standard compliance by independent test and certification organisations, such as DNV, is therefore highly recommended.

Hardware

Hardware design is heavily influenced by system-level specifications and requirements, which include battery module, pack and system specifications (such as current, voltage and capacity), system architecture (common dc link, load profiles, peak loads, peak charging currents), physical dimensions and resulting constraints, safety (thermal management, isolation, contactors), communication and connections. The above aspects inform BMS architecture (master/module arrangements, number of cells per modules and balancing connections), circuit board form factors, component selection, and interfaces.

These high-level specifications form the foundation for the development of electrical design concepts, which strongly depend on the selected approaches to balancing, state estimation and information flow. The simplest hardware design concepts can be realised for passive and some active balancing topologies, since virtually all complex components are available as off-the-shelf building blocks, including ICs for cell balancing and state estimation, which typically come with recommended balancing circuit topologies.

The only material differences in the various implementations of passive and most active balancing BMS designs are down to system-level specifications, such as system voltage and current, circuit board dimensions, communication requirements, and the number of cells that are balanced in each module (which is a segment of the battery pack).

The picture gets more complicated for some active balancing topologies and complete current control, since these concepts cannot be implemented purely with off-the-shelf building blocks and more sophisticated electrical designs are required. Some active balancing circuits require the integration and control of additional switches to bypass cells or cell groups. These switches interact with system-level control and balancing circuits and must be operated accordingly, which is primarily a firmware challenge.

Complete current control requires the integration of power electronics into the battery pack via a novel circuit topology that is capable of dynamically controlling the current on cells or cell groups in proportion to their state of health. This concept can be implemented with or without a voltage boost capability, meaning that cell voltage can be boosted by up two times the rated cell voltage.

Given the complex topology, new BMS designs are typically simulated as a first step to optimise system functionality and efficiency. Microcontrollers and MOSFETs are used at module-level to implement both state estimation and resulting dynamic current control. Complete current control ensures that cells are continuously balanced, meaning that no separate balancing circuit or balancing step is required. Communication channels between modules are important for this approach due to the speed and amount of data required to flow between modules. Brill Power's patent pending communications bus offers a low cost, low-complexity solution to this challenge by replacing separate communication links to each battery module with one communication bus.

Software

The BMS relies on and interacts with various types of software, which can be broadly categorised into on-board software (embedded on the BMS hardware) and off-line software (hosted on computers and servers that interact intermittently with the BMS).

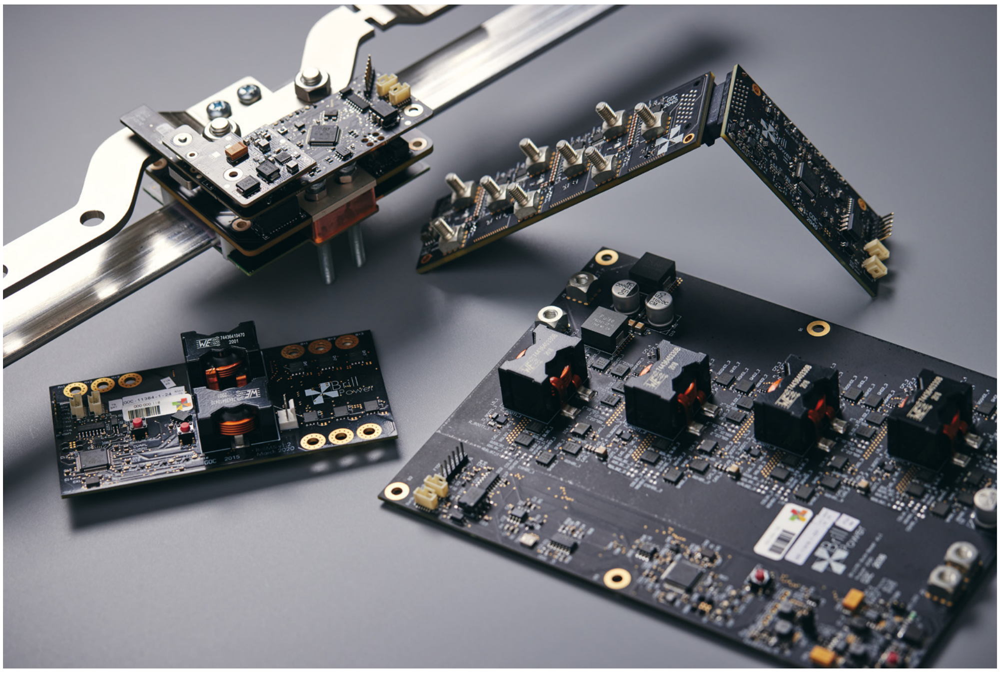
Embedded software includes algorithms for state estimation (such as battery models and estimation algorithms) and balancing, as well as safety settings, which typically initiate safe shutdown procedures when triggered. Safety settings depend on the battery chemistry and manufacturer specifications and are either 'hardwired' on ICs or set when using microcontrollers.

Accurate measures of SoC and SoH are not only important to establish what the battery can and cannot do at any given point in time, but also to determine whether any warranty conditions have been triggered. Since the SoC and SoH of battery cells cannot be measured directly, mathematical models are needed to calculate them based on the parameters that can be measured, including voltage, current and temperature. These models and measurements are never perfectly accurate, which is why they need to be combined with so-called estimation algorithms that continuously compare the model outputs with measurable quantities (typically voltage), using the computed errors to adjust model outputs and improve the accuracy of SoC and SoH estimates.

The two greatest challenges in producing accurate SoC and SoH estimates are

Firmware development and testing

Credit: Brill Power



Credit: Brill Power

(i) battery behaviour can vary significantly between different manufacturers and formats, even if the chemistry is the same, and (ii) battery behaviour changes over time and models become increasingly inaccurate if they are not updated. These challenges are mainly a concern if ICs are used, which are 'hardwired' with representative battery models and don't adjust the models over time. When using microcontrollers, battery models can be adjusted to accurately represent the exact cell in use by extracting the model parameters from cell test data. These parameters can be updated throughout the lifetime of the battery to ensure continued accuracy.

Cell balancing algorithms for passive and most active balancing BMS types simply determine upper cell voltage limits and trigger the balancing circuit switches, until all cells have reached the same voltage. Complete current control incorporates cell balancing in its main current control algorithm – charge and discharge cell currents are proportional to SoC and SoH such that all cells are continuously balanced.

Off-line software that may interact with the BMS includes battery monitoring, analytic and predictive software, which helps the user keep the battery safe, flag any faults, determine important performance characteristics (such as available energy and power), schedule any maintenance, estimate the remaining useful lifetime, and even determine residual asset value of the battery system.

At a minimum, the BMS must pass high-level information to off-line software programmes, such as SoC, SoH, battery voltage, current and temperature, which is then displayed to the user and, potentially, used to perform more complex computations to anticipate pending faults, determine how much battery life is left and how are performance characteristics likely to change (in case this is not computed onboard the BMS). More sophisticated embedded BMS software may be able to take inputs from offline software, such as adjusted operating limits and battery model parameters. Clever utilisation of offline software can increase the overall computational power available to optimise battery operation, as well as to minimise component cost by reducing the computational load onboard the BMS itself.

Future trends

As with any technology, it is very difficult to predict the course or timescale of developments in BMS technology. However, a few macro trends in the battery industry are likely to influence the choice of BMS technology and its future developments.

- **Sustainability**

Increasing awareness and concerns about environmental and social impacts of the manufacture of battery technology is already influencing expectations regarding battery quality and life cycle. Therefore, BMS technology capable of maximising battery lifetime and minimising battery waste will likely grow in popularity.

- **Co-location with solar and wind**

Energy storage is increasingly co-located with solar and wind power projects to reduce local effects of intermittency of renewables and to maximise system efficiency. Batteries used for such applications will be expected to reach the same lifespan as solar PV and wind turbines. BMS technology that can maximise lifetime while minimising system complexity and lifetime cost will be favourable for such projects.

- **Future-proofing of storage**

Battery technology changes rapidly; new cell products are introduced every year and entirely new chemistries are under development, such as sodium-ion and solid-state batteries. For developers of battery systems, it is important to be able to quickly adapt to new chemistries, which is enabled by a flexible BMS approach. The same argument holds for energy storage projects that are scheduled for augmentation with future technology, which must be compatible with older batteries.

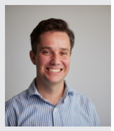
- **Product differentiation**

The battery cell and system market is dominated by a small number of high-volume manufacturers, whose low cell and pack costs can undercut most smaller developers and manufacturers of battery systems. BMS technology can be used by the smaller players to gain a competitive edge in product quality and lifetime.

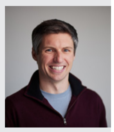
Unlike innovation in battery cells, BMS technology does not rely on fundamental scientific advances, and can bring step-change improvements to today's battery technology. The innovation potential in BMS technology has been largely overlooked in battery system development but we believe it will play a crucial role in the battery systems of the future.

Authors

Christoph Birkl, DPhil, CEO and co-founder of Brill Power, has seven years' experience in battery and fuel cell R&D and was recipient of the Royal Academy of Engineering's SME Leaders Programme.



Damien Frost, DPhil, CTO and Co-founder of Brill Power, is a power electronics engineer with nine years' experience developing products for high-tech start-ups.



Adrien Bizeray, DPhil, chief data scientist and co-founder of Brill Power, holds an MSc degree from Imperial College London and his PhD was funded by Samsung for the development of physics-based battery models.