Building Digital Battery System via Energy Digitization for Sustainable 5G Power Feeding

Song Ci, Hongjie He, Chongqing Kang, and Yang Yang

Abstract

In the upcoming era of 5G, the number of base stations, edge computing nodes and data centers is believed to be three to five times more than that of 4G. Serious challenges on the deployment and operation of 5G networks and services arise, especially on how to build and maintain battery energy storage systems for sustainable 5G power feeding at low cost for all scenarios. Although battery has long been used as a major backup power in various communications systems, current battery systems essentially are "dumb devices." In the current battery systems, the charging/discharging energy flow is continuous due to the fixed series-parallel cell topology adopted by existing battery systems. The fixed topology also causes the "bucket effect" at the system level due to the fact that it is incapable of handling cell difference in a battery system, leading to a series of system-level problems in terms of power density, energy efficiency, cycle life, reliability, and safety. All these will make it very challenging for sustainable 5G power feeding, which will further affect the cost-effective deployment and operation of 5G networks and services. Thanks to the recent breakthrough of power electronics semiconductors, such as power metal-oxide-semiconductor field-effect transistor (MOSFET), silicon carbide (SiC) and gallium nitride (GaN) with their outstanding material properties, it becomes feasible to carry out digital energy processing operations at high switching speed, high voltage, and feverish temperature. By building a new digital "grid-to-chip" power train using high switching speed power semiconductors, traditional analog battery systems can be transformed into digital battery systems through energy digitization, which will significantly facilitate feasible 5G deployment and operation. In this article, we will propose and describe the basic concept of energy digitization, the design framework of the digital battery system including key components, modeling, and the performance evaluation of the digital battery system. Results of experiments and real-world applications show the effectiveness and efficiency of digital battery system, which offer a promising disruptive approach to sustainable 5G power feeding.

Introduction

With the ongoing commercialization in 2020, 5G and beyond is gathering increasing interest among industries and academia. As shown in Fig.1, the transformation from 2/3/4G to 5G is significant and paradigm-shifting and is expected to be applied in numerous vertical fields, such as telecommunications [1], unmanned aerial vehicles [2], and vehicular networks [3]. But most applications could come to work only after the appropriate 5G deployment and operation. Nowadays, one of the biggest challenges in 5G deployment and operation lies in its much higher requirements on power feeding infrastructure [4] due to 5G millimeter wave communications. First, the existing power feeding infrastructure used for powering mobile base stations and data centers are reaching its maximum capacity, which needs to be expanded for 5G deployment. However, doing so will make us face a new set of problems, such as insufficient space and weight bearing capacity on existing sites. Second, the traditional framework of power feeding does not fully support 5G deployment and operation. For example, the direct current (DC) power feeding for 4G long term evolution (LTE) only provides a short distance of power delivery, which cannot meet the needs of deployment and operation of 5G active antenna units (AAU) with much higher power ratings. Third, it is predicted that by 2025, the entire information and communications technology (ICT) industry will consume 20 percent of the total amount of electricity generated worldwide, imposing severe economic and environmental challenges on the sustainability of 5G deployment and operation.

Battery system has long been used as a vital backup power source to provide uninterrupted power for various ICT systems, ranging from portable devices to backup power systems for mobile base stations and data centers [5]. The typical application scenarios of battery system in 5G deployment and operation are the backup power system for data centers and mobile base stations as well as the energy storage system used for renewable energy penetration in 5G powering [6]. Furthermore, the traditional power feeding solutions cannot meet the requirement of 5G powering because of its low energy efficiency caused by multiple power conversions (AC-DC-AC-DC), which resulting in a huge amount of electricity cost, at least 15 percent of the entire operating expense (OPEX). A great deal of research has been done to improve the conversion efficiency of the backup power system by reducing the length of the grid-to-chip power

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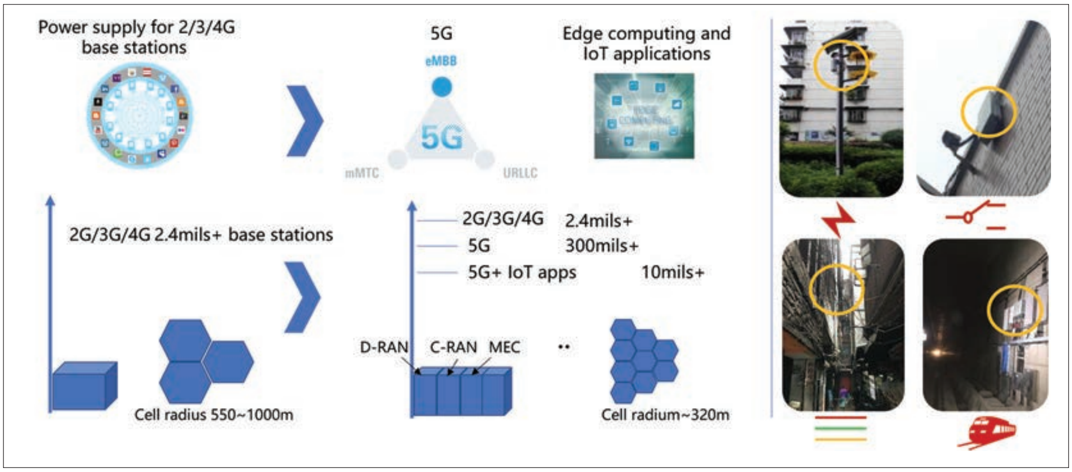

FIGURE 1. The transformation from 2/3/4G to 5G and the related powering feeding problems in 5G deployment. In order to provide uninterrupted services, more than 50 percent 5G base stations require backup battery power systems, which imposing a great challenge to the existing telecommunications infrastructure. The current analog battery power systems cannot support the requirement of 5G network.

train with various DC power distribution methods [7, 8]. However, battery system has been largely ignored by all these works in the literature.

Conventionally, a battery system is typically built with a large number of battery cells interconnected by a fixed (hardwired) series-parallel cell topology. In this sense, the energy flow inside a battery system is essentially an analog signal modulated with various nonlinear electrochemical characteristics, such as cell difference, thermal effect, current effect and recovery effect [9]. Furthermore, the traditional fixed cell topology of battery systems only considers the requirements of desired voltage, current, and power density. But traditional battery systems ignore the fact that every battery cell is different from each other, which leads to a series of severe performance degradation problems, such as low usable capacity, low energy conversion efficiency, cell overcharge or/and overdischarge, low reliability and low safety. Furthermore, it is impossible for us to achieve high energy efficiency at the system level, when interfacing an analog hardwired battery system with a digital computing system, since they are working at different frequencies [10]. Essentially, this is the fundamental performance problem faced by all battery powered ICT devices, such as cell phones, laptops, electric vehicles and other battery backup power systems.

In recent years, with the fast-paced development of power electronics semiconductors, such as Wide Band Gap devices SiC and GaN, as shown in Fig. 2, it has allowed an analog energy flow to be discretized and processed at high switching speed, high voltage and feverish temperature [11]. Thanks to their outstanding material properties, these high switching speed power semiconductors throw a light on digitizing the analog energy flow in traditional backup power systems, where they can be used as "grid-to-chip" I/O interfaces to discretize and digitize up to kilowatt (kW)-level continuous energy flow at MHz level, making the processing of energy digitization feasible, and thus traditional analog backup power systems can be transformed into digital, creating a new method to process and use energy in future mobile base stations and data centers [11].

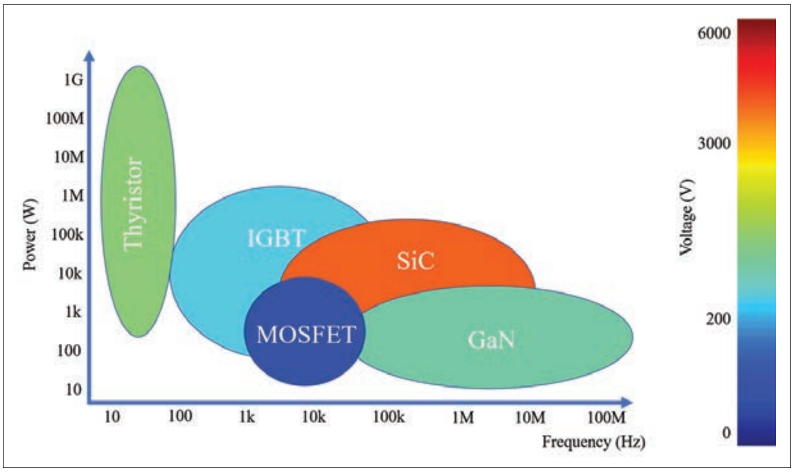

FIGURE 2. An overview of power electronic semiconductors [11]. With the fast development of power electronic semiconductors, building a digital battery system with energy digitization become possible.

In this article, we focus on building digital battery systems through energy digitization toward sustainable power feeding for efficient and effective 5G deployment and operation. Without losing generality, we take the battery backup power system in mobile base stations and data centers as an example to illustrate the design methodology of a digital battery system. We will present the basic concept of energy digitization and the proposed design framework of a digital battery system. The system behavior of a digital battery system will be analyzed in detail. Experimental results and use cases in mobile base stations and data centers will be discussed to show the feasibility of energy digitization as well as the effectiveness and efficiency of digital battery system.

The rest of this article is organized as follows. The basic concept of energy digitization under the context of backup battery system is presented in the following section. We then focus on key components, modeling, and performance evaluation of digital battery system. Corresponding experimental results are discussed then, followed by real-world use cases of digital battery systems built for 5G deployment under the contexts of

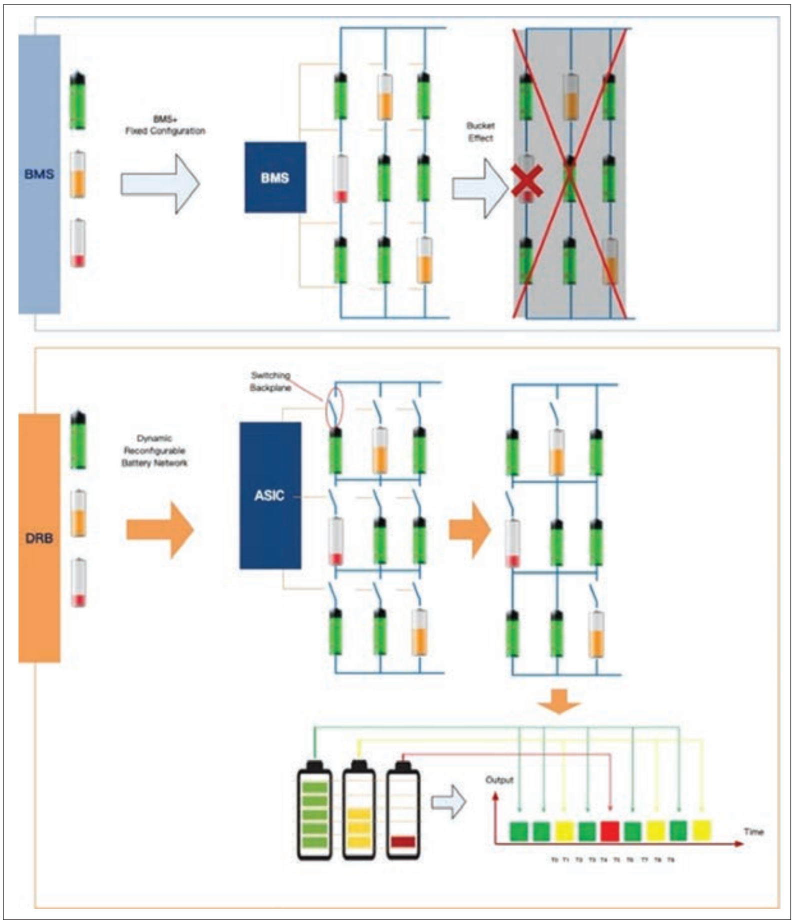

FIGURE 3. The schematic diagram of the energy digitization processing. In traditional battery systems, energy flow is analog and continuous, which mismatching the difference of individual battery cells, leading to single-point failure, efficiency and safety issues. With leveraging high frequency power electronics, analog energy flow can be discretized and digitized, making battery cell difference transparent to various applications.

data center and mobile base station. The final section concludes this article.

The Basic Concept of Energy Digitization

In this section, we will present the basic concept of energy digitization under the context of backup battery systems. The vital processing part of energy digitization is to "format" the analog energy flow into "energy slices" over time by adopting high-speed power switching semiconductors, and then to schedule "energy slices" of each battery cell by dynamically connecting them into the charge/discharge circuit to form a dispatchable energy flow for the load, as illustrated in Fig. 3.

Before going further to discuss the basic concept of energy digitization, let us briefly review major drawbacks of all traditional battery systems. Since the battery was invented 200 years ago, a practical battery system is built upon a large number of small-capacity battery cells with a fixed series-parallel cell topology (connection). However, this hardwired cell connection overlooks the fact that every battery cell is different from each other due to the highly dynamic and nonlinear nature of electrochemistry. As a result, the maximum usable capacity of each cell varies largely, leading to unbalanced charging or discharging behaviors observed at the system level [12]. Furthermore, the usable capacity of a battery cell is a highly nonlinear function of its working conditions, such as temperature, charging/discharging current rate and the state of health (SOH) [13], which may further enlarge cell difference in a traditional hardwired battery system. Last but not least, any faulty battery cell in the traditional hardwired battery system will lead to serious performance degradation, making the entire battery system suffering "single point failure." As shown in the upper half of Fig. 3, traditional battery systems adopt fixed cell topology; under this circumstance, if any battery cell fails, the entire series with that faulty cell will have to be shut down. As a conclusion, the fundamental problem of traditional battery systems is the mismatch between the cell difference and the fixed cell topology, leading to the "Liebig's Barrel" effect, in which the weakest cell decides the performance of the entire battery system and causes a series of performance issues at the system level, such as usable capacity, cost, reliability and safety.

Therefore, energy digitization is proposed to overcome the major drawbacks of traditional hardwired battery systems by transforming the analog energy flow into fine-grained "energy slices" by high-speed energy switching array fabricated by power semiconductors and controlled by scheduling software. In this article, we treat energy flow as an analog variable. Energy discretization discretizes the fixed energy flow of the traditional hardwired battery system into the flexible "energy slices" of the battery cells in the dynamic reconfigurable battery network. The quantity of the "energy slices" is a continuous variable and there is no minimum unit of power which is common in the digital field. Through this program-controlled dynamic reconfigurable battery network, digital battery system can be built to eliminate all major drawbacks as observed in traditional analog battery systems [14]. Thanks to the technological advancement in the field of power electronics, the digital processing of an analog energy flow can be performed at up to MHz level, which is much faster than the nonlinearity of battery electrochemistry. Therefore, the nonlinear battery effects can be largely eliminated by energy digitization. Fig.3 shows the schematic diagram of energy digitization processing, where each battery cell is connected to a high-speed switching array of power electronics semiconductors, thus a dynamic configurable battery network will be formed. By dynamically controlling the state of each switch on the switching array, the analog energy flow of each battery cell will be discretized into a pulse train of "energy slices," which then can be quantized based on the sampled values. In this way, the analog energy flow can be discretized and digitized at fine tempo-spatial resolutions. Here, an application specific integrated circuit (ASIC) is needed to calculate the optimal selection of the subset of battery cells to be physically connected into the charge/discharge circuit under the current adaptation time interval. This adaptation time interval could be long or short based on the power demands of electric load, which is adaptive in the time length. During this adaptation time interval the battery system would reconfigure to achieve optimal scheduling just like a self-adaptive power backup system. The optimal scheduling algorithm will be designed with considerations of the output voltage and current, the states of battery cells, the load profile, and the environmental conditions. Once the cell selection is made, the ASIC will control the switching array to provide a dispatchable energy flow to power up the electric load.

Thus, by using q dynamic reconfigurable battery network, energy digitization can fundamentally solve the major drawbacks of traditional battery systems. As a result, the overall performance of a battery system can be significantly enhanced. Another advantage of energy digitization is that the power source can be fine-tuned to follow up the dynamics of the electric load, leading to a highly efficient energy use.

The Proposed Design Framework of a Digital Battery System

Key Components

A digital battery system requires cooperation and coordination among multiple system components, each performing a set of key system functions. In this section, we will discuss each system component in detail.

Analog-to-Digital Conversion of Analog Energy Flow: In the field of digital signal processing, analog-to-digital (A/D) converters are pervasively adopted to convert analog signals into digital signals. Similarly, in a digital battery system, high-speed power electronics switching array is essential for discretization and digitization of an analog energy flow. By performing energy digitization, the characteristics of the analog energy flow of each battery cell can be well captured over time, which will be further scheduled and dispatched by leveraging the fine-resolution processing capability of a computing system.

Reconfigurable Battery Network: Each battery cell will need to be connected with at least one high-speed power switch in order to form a reconfigurable battery network. In this way, the battery cell topology can be dynamically reconfigured according to the output voltage and current, the states of charge of each battery cell, the load profile and environmental conditions. Therefore, a digital battery system is essentially built upon the chassis of a reconfigurable battery network for various digital energy processing operations in the charge/discharge process.

Controller: A control unit is crucial for a digital battery system to coordinate interactions among all system components toward the overall system efficiency, reliability, and stability. Since a digital battery system is a complex system, a considerable amount of computational intelligence is needed in the control unit to handle all kinds of system operations.

Design Challenges

The major design challenges of a digital battery system can be generalized in two folds, which are the design of a high-speed power switching array for energy digitization, and the design of a reconfigurable battery network controller. Thanks to the rapid development of the power electronics semiconductor industry, a high-speed power switching array can be accomplished through the adoption of high switching frequency power electronics circuitry, which can discretize and digitize the energy flow over each sampling interval of nanoseconds. On the other hand, the battery network controller design is challenging due to the real-time processing and control nature of energy digitization and energy dispatching. Essentially, a digital battery system is a cyber-physical energy system (CPES), which is full of interactions and interdependencies among critical functions, such as hardware operations, behavior modeling, state estimation and performance optimization, mixed with the electrochemical nonlinearities and the dynamics of load.

Digital Battery System Modeling

Generally speaking, a digital battery system consists of a group of battery cells represented by a set of system design variables, including cell topology, states of battery cells, load profiles, and environmental conditions. Assume that a digital battery system is built on top of a $k \times l$ switching array, and we define T_i as a logic matrix that stands for the topology of the switching array at the ith adaptation time interval. The state of each switch is expressed as S_{mn}, which is 1 when a battery cell at mth row and nth column is online, and 0 if offline. The states of all switches are combined as T_i. We let L_i denote the matrix of capacity loss of each single battery cell in the entire digital battery system. The capacity loss of each cell under arbitrary topology over an adaptation interval is expressed by l_{mn}. Furthermore, R_i is a matrix describing the amount of recovered capacity at the system level, and r_{mn} is the amount of recovered capacity of the battery cell. In the end, we define t_i as the length of the ith adaptation interval, Γ_i as the total capacity loss of the battery system for the corresponding operational scenario. Thus, the capacity loss of receiving power generated by renewable energy over an adaptive interval can be expressed as a Hadamard product, given as [12]

$$\Gamma_i = L_i \circ T_i + R_i \circ \overline{T}_i \tag{1}$$

where the symbol ° is the Hadamard product operator. It is worth noting that the formulation above is based on the behaviors of the digital battery system over one given adaptation time interval. The overall capacity loss through operational period equals the sum of capacity loss over each adaptation interval, which can be expressed as:

$$\Gamma = \Sigma_{i=1}^{N} \{L_i \circ T_i + R_i \circ \overline{T}_i\} \tag{2}$$

As indicated in the formulation above, each cell in a digital battery system can be independently controlled, which makes it possible to transform battery energy flow from analog energy flow into digital energy slices. Specifically, during each adaptation interval, energy slices from different battery cells are selected based on their state of charges (SOC) and the load profile through dynamic reconfiguration at the cell level via the power switching array. Thus, the output of a digital battery system at each time interval is the sum of all selected energy slices from the corresponding battery cells. In other words, energy slices from different battery cells are orchestrated to form a dispatchable energy flow,

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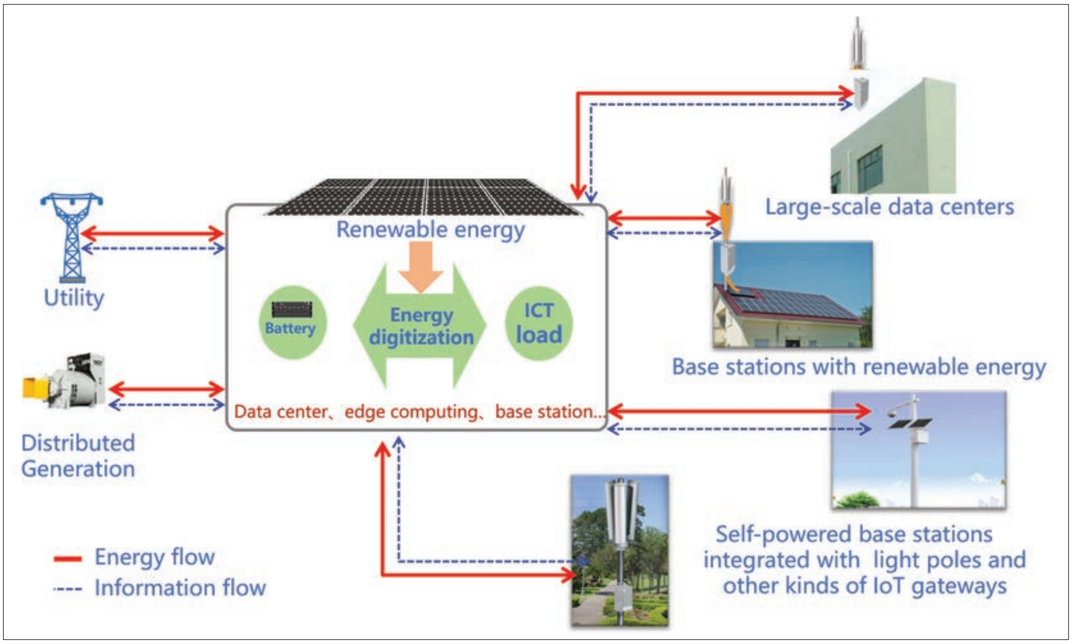

FIGURE 4. Application scenarios of digital battery system in 5G deployment and operation. From the stand of point of sustainable ICT, future 5G needs to increase renewable energy penetration, which is to be seamlessly integrated with battery energy systems.

FIGURE 5. Digital battery systems for 5G data centers and edge computing nodes.

thus achieving better system performance in terms of the energy conversion efficiency and the system reliability.

Performance Optimization

In a digital battery system, the input analog energy flow is manipulated in a fully digital fashion through real-time operations of battery network controlling by switching array to achieve an optimized system performance. Thus, the scheduling algorithm of a battery network controller is the core of system performance, where battery characteristics, load profile, and environmental conditions have to be jointly considered. At the cell level, it is important to find the optimal trade-offs among multiple nonlinear capacity effects, particularly rate-capacity effect and recovery effect. At the battery network level, the cell to cell balance issue is critical to the overall system performance. Therefore, the optimization problem can be formulated and solved by dynamic programming, where the operations of the digital battery system over one adaption interval with a given cell topology can be represented by a node. We interconnect the nodes with weighted edges, and the value of a weighted edge is calculated according to the capacity loss of the chosen cell topology. Since nodes are associated with adaptation intervals, no loop will exist on the node graph. As a result, the collection of nodes and edges form a directed acyclic graph (DAG) and can be solved through the shortest path algorithm [15].

To demonstrate the performance gained from digital battery systems, an extensive experimental study has been carried out based on a real-world digital battery system testbed, composed of 64 used lithium-ion battery cells, which can be configured as a traditional analog battery system and a digital battery system, respectively. The performance comparison of the digital battery system and traditional battery system has been extensively conducted. It can be observed that under various charging and discharging conditions, the usable capacity of the digital battery system has been significantly improved by more than 20 percent under all testing settings. In addition, the digital battery system is able to online detect and automatically isolate fault cells, which can greatly enhance the reliability and safety of a battery system.

Application Scenarios of Digital Battery Systems

In order to facilitate 5G deployment and operation, we have proposed a sustainable 5G powering framework, as shown in Fig. 4. As the core of the sustainable power feeding solution, the digital battery system will be used to coordinate and distribute energy flows among various power feeding sources and loads. On the power supply side, the energy flow coming from utility, distributed gas turbine and/or renewable energy will be digitized and integrated with the digital battery system. On the power demand side, the digital battery system will interact with various ICT loads, such as data centers, mobile base stations and the Internet of Things (IoT) gateways. Compared with today's battery backup power systems, the interaction between power supply and power load will

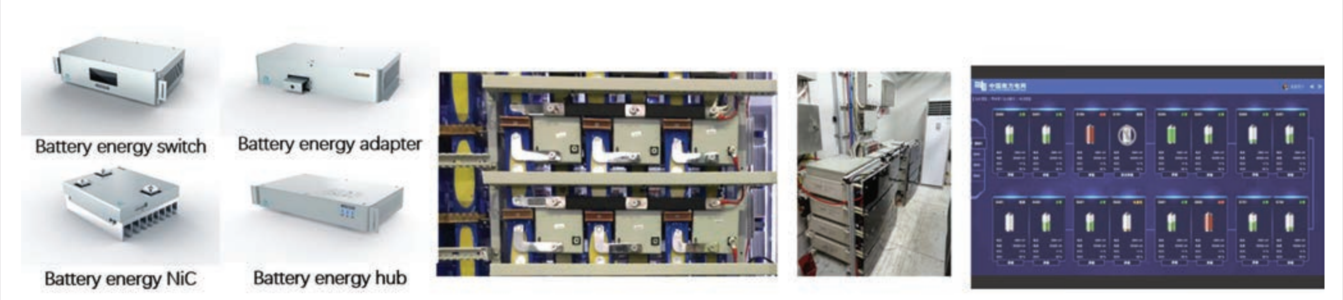

FIGURE 6. Digital battery systems for 5G mobile base stations.

be carried out on both energy flow and information flow at a much finer resolution.

To demonstrate the advantages of a digital battery system, next we will illustrate how a digital battery system can facilitate 5G deployment and operation under major application scenarios, such as data centers and mobile base stations.

Digital Battery System for Data Centers and Edge Computing Nodes

Due to the cloud nature of 5G networks, a large number of data centers and edge computing nodes is expected to be built with high power density. In addition, as application scenarios and deployment schemes may be many, the capacity of a backup power supply system will be different accordingly. Therefore, a customizable, maintenance-free backup power system is highly desirable for effective and efficient 5G deployment and operation.

To meet the aforementioned demands on data centers and edge computing nodes, we have designed and developed digital battery systems, as shown in Fig. 5. The digital battery backup power system is seamlessly integrated with the existing ICT ecosystem, transforming traditional analog battery backup power systems into a new kind of ICT equipment. This novel digital battery system consists of several rack-mounted low-voltage DC backup power units, called Digital Battery Blade (DBB), as shown in Fig. 5. In this new system, the digital battery system takes the same form factor as the standard server blade to achieve a compact, scalable, highly efficient backup power system.

DBB is a digital device instead of its traditional analog counterpart by utilizing reconfigurable battery network. Compared with the existing analog backup power systems, DBB can achieve considerable electricity saving and usable space saving in data centers due to its shorter grid-to-chip power train and the replacement of the centralized uninterruptible power supply (UPS) and battery system by distributed vertical battery deployment in the rack. The digital battery systems have been extensively tested in data centers and edge computing nodes and well received by users. In that case, our digital battery system approach can outperform the traditional solution by at least 10 percent electricity saving and 20 percent usable space saving.

Digital Battery System for Mobile Base Stations

In order to provide quality of service to end users in 5G, a large number of mobile base stations will be built, which is believed to be three to five times more than the number of 4G, reaching to hundreds of millions, and all of them will be equipped with backup power systems for reliable operations. However, it is impossible for us to keep using the current manual maintenance code on battery backup systems, such as monthly manual charge/discharge tests and replace the entire pack if there is a faulty cell in a battery pack.

To solve this painful problem, we have developed a distributed digital battery system dedicated for 5G deployment in mobile base stations, and then building a "battery energy cloud" platform to enable online real-time operation and maintenance on such a large number of backup battery systems in mobile base stations, including battery status sensing and analysis, battery operation and maintenance, faulty cell detection and isolation, as shown in Fig. 6. The platform can allow us to monitor and control backup battery systems at a much finer resolution at cell level within milliseconds.

As shown in Fig. 6, the hardware components of the distributed digital battery system are battery energy switch, battery energy adapter, battery energy network interface card and battery energy hub. The battery energy network interface card is a module that supports energy digitization as well as the physical connection between battery cells. The battery energy hub is a module that uses embedded sensors to collect the key status data of battery cells. The battery energy switch is a module to collect battery information from battery energy hubs. The battery energy adapter is a module to interface with the power load. A digital battery system realizes the reconfigurable cell topology through the battery energy network interface cards, battery energy hubs, and battery energy switch. The battery energy adapter empowers interactions among power load, power supply and utility grid. So far, we have deployed 100 sets of digital battery systems in 100 mobile base stations managed by China Tower in Guangzhou, China, which form a cloud-based digital battery system and collectively manage 2.88 MWh battery capacity, as shown in Fig. 6. In this case, the cloud-based digital battery system can be used to interact with the local utility company to provide ancillary services to the power grid, which leads to a new source of revenue for the telecommunications service providers, while piggybacking the battery maintenance in ancillary services, and then prolong the battery lifespan by fine-resolution cell balancing with no additional cost.

Conclusion

In this article, we have proposed a new concept of energy digitization based on the fast-paced high-speed power electronics semiconductors for sustainable 5G power feeding, and then

Results from both experimental studies and the real-world field tests have proven that there will be significant performance enhancement when we transform the traditional analog battery system into its digital dual, implying this paradigm-shifting technology can be further applied in many other application scenarios where battery is used as the main power source.

discussed how to build digital battery systems through energy digitization to facilitate 5G deployment and operation. Real-world applications of digital battery systems under the context of 5G deployment and operation in data centers, edge computing nodes and mobile base stations have been presented and discussed to show the feasibility and effectiveness of the proposed concept and system framework. To our best knowledge, this is the first of its kind digital battery system to have been developed and deployed. Results from both experimental studies and the real-world field tests have proven that there will be significant performance enhancement when we transform the traditional analog battery system into its digital dual, implying this paradigm-shifting technology can be further applied in many other application scenarios where battery is used as the main power source, such as electric vehicles, various energy storage systems, portable electronics and other battery powered smart embedded devices.

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