Control Concepts for a Decentralized Battery Management System to Optimize Reliability and Battery Operation

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Abstract. Battery systems are used in a wide range of safety-relevant applications, such as electric vehicles, unmanned aerial vehicles and home storage systems. Safety, reliability and availability of the battery system therefore play a key role. In addition, the useful service lifetime of the batteries determines the environmental impact and economic efficiency of the overall system. One possible solution is to give batteries a second life in applications with lower requirements in terms of dynamic behavior or capacity. Heterogeneous battery systems consist of batteries with differences in cell technology, age, capacity, and optimal operating range. To meet the safety, reliability, and availability requirements a scalable, Decentralized Battery Management System (DBMS) based on a distributed control system is proposed. Batteries, generators, and loads have Local Control Units (LCUs) consisting of a microcontroller, a measurement unit, and a DC/DC converter with adjustable voltage and current limits. These LCUs are the basis for the communication-based, cooperative system control and enhance the reliability and scalability of the battery system compared to conventional centralized structures. They record and manage the operating parameters and provide the basis for predictive energy management and battery residual value estimation. As a fallback strategy, a droop-based control of the DC/DC converters is used in addition to the communication-based one. Transition conditions between the control modes are defined and the control methods are compared and differentiated. The performance and the resulting benefits of batteries are determined by the control strategies. In this paper, the requirements for the control strategies for different operating modes, including startup, severe fluctuations of the DC power line voltage, and safe shutdown, are analyzed.

Keywords: Renewable energy sources · battery management system · second life battery · decentralized control · distributed control · control strategies · droop control · battery optimal operation

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1 Introduction

The reduction of fossil energy sources and the integration of renewable energy sources is indispensable in order to reduce the emissions and thus to limit the consequences of the climate crisis in the face of a globally increasing energy demand. The intermittent nature of renewable energy sources and the time difference between energy supply and demand poses a significant challenge. Battery systems offer the possibility to compensate fluctuations and to supply new load types, such as electric vehicles or unmanned aerial vehicles.

Thereby, the service life of the battery system is a key factor regarding the environmental impact and the economic efficiency. Optimal operation of batteries and resource-efficient use of second-life batteries extend the life cycle and thus improve the sustainability [1]. While recycling of raw materials or remanufacturing have been considered as solutions, simply reuse of the battery packs offers tremendous cost benefits [2,3]. Heterogeneous battery systems combine batteries with differences in cell chemistry, nominal capacity, State of Health (SoH), State of Charge (SoC) and age. Integrating new batteries in combination with used batteries, that have been only slightly modified to avoid further development costs, is a challenge [4,5]. A battery state dependent load distribution is necessary for the safe operation of a heterogeneous battery system [6–8].

Furthermore, battery systems are installed in an increasing number of safety-relevant applications such as in electric vehicles, backup power or home energy storage systems. Therefore, the availability and the reliability of the battery system are relevant factors. *Availability* describes the ontime and usability of the battery system in different operating states such as start-up or maintenance. *Reliability* is defined in this context as ensuring availability of the battery system and fault-free operation even in the case of failure of single components.

Another challenge is to ensure *robustness*, which is defined as stability in the presence of disturbances, i.e. correct operation in the event of transients, sensor drifts or abrupt load changes.

Flexibility and *scalability* are further requirements to ensure that the battery system can be used for a variety of different applications. *Scalability* refers to a variable number of components that can change even after initial implementation. *Flexibility* describes the possibility to combine any battery types and to integrate different loads and energy generators.

Appropriate control strategies are required to meet the above objectives in a heterogeneous battery system [9]. The main objectives of the control include maintaining the DC power line voltage V_{DC} at a predefined target value and the energy sharing between the parallel connected components (Figs. 1, 4). The use of several components and thus multiple DC/DC converters increases the difficulty of observability and controllability.

In the following, a theoretical analysis of multi-level collaborative control strategies for a decentralized, heterogeneous battery system is presented (Fig. 1). First, existing control strategies in battery systems are considered. Next, the system for which the control strategies are observed, is proposed. The tasks and objectives of the control are described and the control of the overall system is

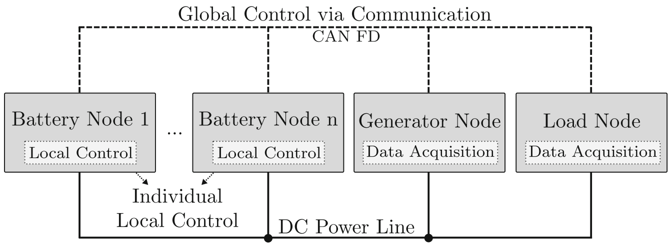

Fig. 1. Decentralized Battery Management (DBMS) system architecture consisting of battery, generator and load nodes. The control is distributed in a local and global level.

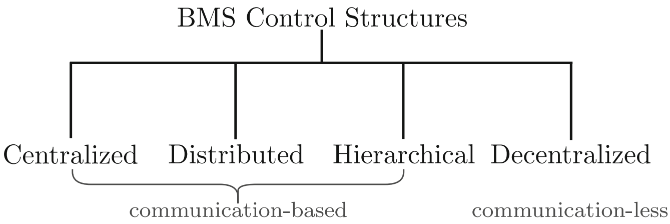

Fig. 2. Centralized, distributed, and hierarchical control strategies require global communication between nodes, while decentralized control operates communication-less.

divided into different levels. Different control strategies for the individual levels as well as their advantages and limitations are discussed. Subsequently, transition conditions between the individual control strategies are defined. Finally, the presented control strategies are put into context with existing ones and an outlook on future measurements and investigations is given.

2 Literature Analysis

The integration of different renewable energy sources such as photovoltaic or wind in combination with variable loads and different energy storage devices like super capacitors, fuel cells and batteries complicates the control of the common DC power line voltage (Fig. 4) as well as the energy sharing between the components. Various control techniques, such as centralized, decentralized, distributed, and hierarchical ones, are proposed to ensure safe and reliable operation (Fig. 3) [10] (Fig. 2).

2.1 Centralized Control Strategies

In centralized control strategies, data are sent from multiple, distributed, subordinate units to the central controller over the communication links. The total generation, loads and other operational information such as (SoC) of the batteries are processed in the central control unit and corresponding signals are

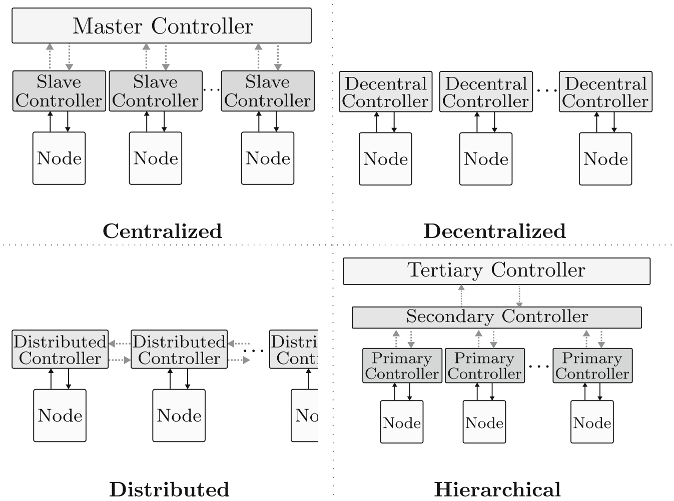

Fig. 3. Existing control strategies can be categorized in centralized **(a)**, decentralized **(b)**, distributed **(c)** and hierarchical **(d)** ones. Common strategies mainly consider battery nodes in the control, while it is also possible to consider load and generation nodes.

sent back. The central unit is functionally different from the subordinate ones [11]. This technique has better observability and controllability. Nevertheless it has lower *reliability* due to the single point of failure and the fixed defined number of inputs to the central control unit is associated with lower *flexibility* and *scalability*.

2.2 Decentralized Control Strategies

Decentralized control strategies are introduced to avoid the single-point failure. The DC/DC converters are adjusted by local controllers, where locally measured signals are the inputs [12]. Droop control is often used, where a virtual droop resistance is used for the battery and a virtual droop capacitance for the super-capacitor [13].

The determination of the droop settings is a challenging task, since current sharing, accuracy and system stability are strongly dependent on the droop settings. Deviations resulting from variations in the measurement resistors are a challenge for the determination of the controller output values [14]. Furthermore, the conventional droop control is problematic at low DC power line voltages in the case of increased output current. For instance, higher droop settings result in a more damped system and higher current sharing accuracy. However, the higher value of droop parameter leads to increased permanent DC voltage deviation on the DC power line. [15,16]

2.3 Distributed Control Strategies

The advantages of centralized and decentralized control are combined in distributed control, where only neighboring units communicate [17,18]. Each DC/DC converter is still steered by a local controller, but the local units additionally exchange information, e.g., the locally own measured DC power line voltage, with neighboring units. The DC power line voltage can be measured differently (Fig. 6), but should be equal in terms of magnitude, taking into account small, permissible measurement errors. The communication between the nodes is helpful to detect defective sensors and deviations.

2.4 Hierarchical Control Strategies

In hierarchical strategies, the control is divided into three levels consisting of primary, secondary and tertiary control [19–23]. The primary controller operates locally and has the shortest response time. It uses locally measured signals to influence the DC power line voltage and is also responsible for energy sharing at the lower level.

The secondary controller has higher response times compared to the primary controller and compensates for the voltage deviation caused or left by the primary controller. Furthermore, it attempts to achieve power balance between the primary controllers with a suitable energy sharing strategy. The secondary controller is needed to compensate for the limits of the primary controller. In particular, the performance of the primary controller is not satisfactory when the line resistance is large. Furthermore, in the case of droop control at the primary level, for example, the permanent control deviation can be compensated. The tertiary controller is the top level controller with the slowest response. It is responsible for maintaining optimal operation, for example, in terms of efficiency with multiple units.

2.5 Comparison of the Reliability and the Control Quality of Existing Control Architectures

In master-slave architecture, the defect of the master board leads to the complete failure of the battery system. The absence of individual slave boards can also lead to safety-critical states, depending on the state of the battery (cell) and whether it can be disconnected from the rest of the system. The control tasks are clearly assigned and the unambiguous specifications of the master based on a uniform database promote control stability.

The decentralized architecture also ensures operation of the battery system in the event of single or multiple failed controller boards, but the communicationless concept based on local measurements has drawbacks in terms of control accuracy.

Using distributed control strategies, the failure of single or multiple controllers also does not endanger operation, but the point-to-point communication is interrupted. This can lead to limitations in control accuracy and stability.

With hierarchical control strategies, it depends on which controller type fails. A functioning battery system is possible even if several primary controllers fail. If a failure of the secondary or tertiary controller occurs, the primary controllers do not receive system information and load sharing specifications. The primary controllers can still be used for a short term, e.g., for an emergency stop. The communication between the controllers in the distributed and hierarchical control strategy enhances the data basis for the control decisions and improves the control stability.

The selection of a control strategies leads to a trade-off between *reliability* and control quality.

3 System Description

Existing systems use a single control strategy. In the following, a system is presented that offers the possibility to switch between different control strategies depending on the operating state. With the subsequently proposed hardware setup shown in Fig. 5 and Fig. 6 it is possible to implement centralized, decentralized, distributed and hierarchical control strategies (Fig. 3), as well as mixed forms thereof, and to switch between them only using the corresponding software.

Subsequent control strategies and the switching conditions between them are mainly designed for a Decentralized Battery Management System (DBMS). It consists of renewable energy sources, variable loads and of batteries with differences in cell chemistry, rated capacity, SoC and SoH. Each of these components is equipped with its own Local Control Unit (LCU). The LCU consists of a microcontroller with various communication interfaces, DC/DC or AC/DC converters, voltage, current and temperature sensors, and a relay that can be opened for maintenance or when critical operation states are reached (Fig. 6). For system-wide data consistency, each microcontroller manages all operating data required for the control and sends them via the Controller Area Network with Flexible Data-Rate (CAN FD) line to all the remaining participants. Consequently, each microcontroller has all the data required for system control. For battery-state aware energy sharing, the DC/DC converters have adjustable output voltages and output current limits that can be changed during operation. Each battery output is controlled by a bidirectional DC/DC converter for charging and discharging. Furthermore, the LCUs of the battery nodes manage all battery state-related data and determine the *battery fitness*, a numerical value for system-wide, explicit state evaluation of different batteries. Complex bidirectional controls are required as various battery technologies have differences in energy density, power density, and optimal operating range. The presented architecture in Fig. 5 basically exhibits the characteristics of a distributed, decentralized BMS consisting of several local controllers. The global communication also enables hierarchical control strategies. This architecture improves the *reliability* by eliminating the single point of failure. In addition, the microcontrollers offer increased computing power, which can be used, for example, to calculate optimization strategies faster [24].

In the following, different global and local control strategies are designed. Their advantages and limitations are discussed and they are assigned to operating states. Transfer conditions are defined and the advantages of mixed control strategies are analyzed.

4 Control Objectives, Optimizations and Distribution to Separate Control Levels

The main control objective of the DBMS is to maintain the DC power line voltage V_{DC} at a fixed defined setpoint (Fig. 4).

An additional constraint is, that the batteries must be operated within their permissible operating ranges. The maximum permissible charging or discharging power depends, among other things, on the SoC, the operating temperature, the Open Collector Voltage (OCV) and the internal resistance of the battery. DC/DC converters connected to the batteries limit the output and input power according to the specifications. If there is enough charging and discharging capacity, various optimizations are taken into account in the control strategies of the DBMS in addition to the control objective under the aforementioned constraints (Fig. 7).

Optimal battery operation and the resulting improved safety and service life time is one optimization goal. Various battery technologies result in different optimal operating ranges. For parallel connected batteries, the load current is distributed depending on SoC, remaining nominal capacity, operating temperature and optimal operating range. Furthermore, regarding the battery type and the operating condition, low (dis)charge currents, recovery time, i.e. rest periods between charge and discharge processes, or pulsed (dis)charge can have positive effects on battery aging and safe operation [25–29]. The issue of battery-optimal load current sharing is a separate one and is not considered in more detail in this paper. Only the control strategy *optimal battery operation* is considered. It has priority even at the expense of system efficiency and also partial shutdowns of the loads can be considered.

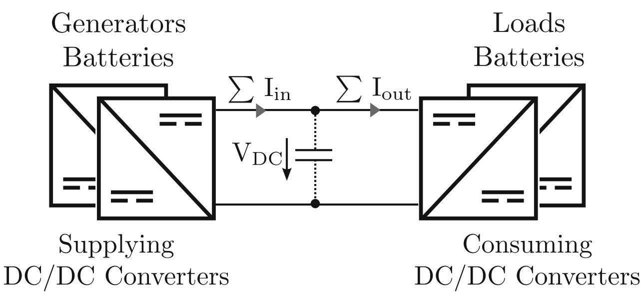

Fig. 4. Simplified representation of the main control objective: maintaining the DC power line voltage at a certain predefined setpoint at a given load and generation by controlling the battery currents.

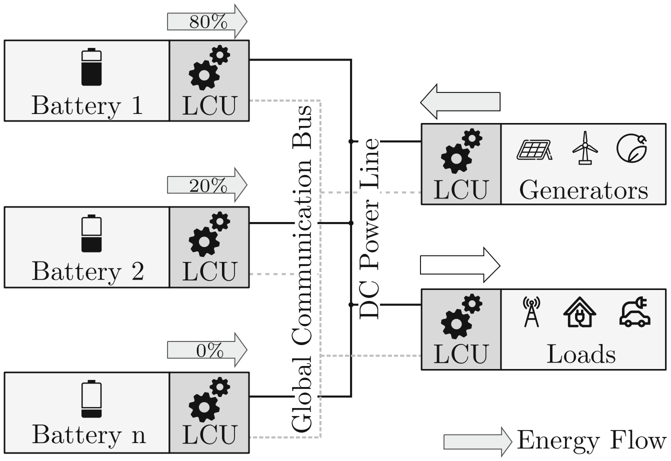

Fig. 5. Overview of the decentralized battery management system with battery state-aware load distribution: The local control units are the basis for distributed control and battery state-dependent load sharing.

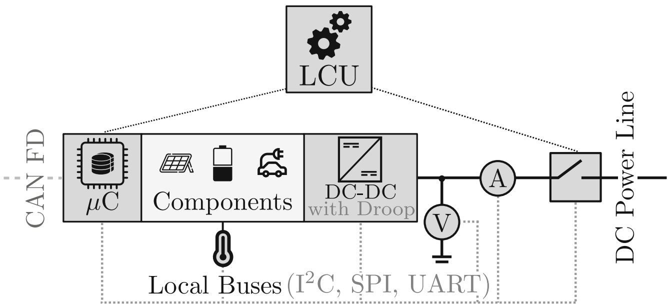

Fig. 6. The Local Control Units (LCUs) consist of microcontrollers, current, voltage and temperature sensors and relays. The operating parameters are recorded and managed by the LCUs. This allows to apply predictive energy management strategies and helps to estimate the residual value of the batteries.

Alternatively, the system can be optimized for *maximum efficiency*. The focus here is primarily on the optimum efficiency range of the DC/DC converters. At low power ranges, switching losses lead to an overall low efficiency of the DC/DC converter [30]. As a result, when pursuing the optimization goal of *maximum efficiency* at low consumption powers, individual battery nodes can be completely deactivated. Consequently, the remaining battery nodes deliver higher output powers and their DC/DC converters operate in a higher efficiency range. In addition, supercapacitors can be integrated for balancing low load and generation peaks. They exhibit high efficiencies at low energy density.

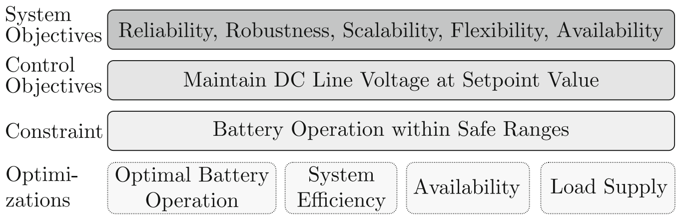

Fig. 7. The system objectives, the control objective, and the constraints mandatorily affect each control strategy, while the optimizations are optionally considered.

Another optimization goal is *system availability* over the longest possible operating time, e.g. range optimization, supply of mobile applications or stand-alone grids. The intention in this case is to maximize the operating time and to safely supply the consumer at least partially for as long as possible. The approach is that in such scenarios, the batteries also operate outside their optimal operating range. System efficiency with temporary deactivation of individual battery nodes to optimize overall efficiency remains a focus, as does partial shutdown of loads.

Ensuring the load supply even when the batteries leave their optimal range or the DC/DC converters operate outside their maximum system efficiency ranges is a further optimization goal. Use cases include emergency stop in vehicles, safe landing of an unmanned aerial vehicle or placing an emergency call on a mobile phone.

Besides the control objective and the optimization strategies, the higher-level system objectives of *robustness, reliability, scalability, flexibility* and *availability* also have to be considered (Fig. 7).

In order to meet the requirements, different distributed and hierarchical control strategies are presented, among which switching takes place depending on the operating state. For a defined separation of tasks and a specified assignment of responsibilities, the system control is divided into two levels: a global and a local control level.

5 Global Control Level Strategies

The global control layer is responsible for system-level control decisions. Its tasks include the decision on the applied global and local control states as well as the verification of the transition conditions between them and the implementation of the optimization strategies. At the global level, there are two control states.

1) Decentralized, Droop-Based Control Strategy: The fully decentralized, droop-based control takes into account local measurements of the nodes and operates without a global communication between the components. In this case, stored droop characteristics determine the virtual droop resistance and thus realize the load sharing between the components and the voltage control of the DC power line (Fig. 8).

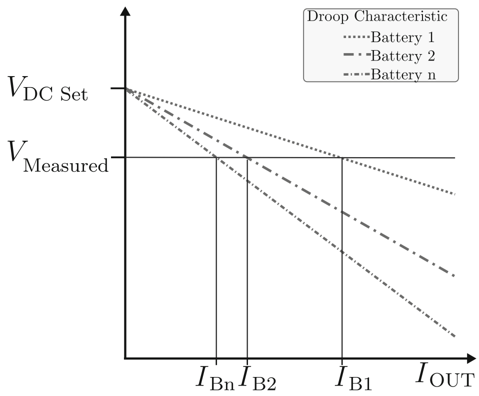

Fig. 8. The slope of the droop curves and thus the value of the virtual internal resistance determine the discharge current and are adjusted according to the battery state. In local measurements, the actual DC power line voltage is acquired and compared with the stored droop characteristic to specify the output current. In this scenario, Battery 1 supplies the majority of the required power.

The DC line voltage is measured by each battery node and the respective droop characteristic is used to determine the output current accordingly. For battery state dependent load sharing, the slope of the droop characteristic can be changed depending on e.g., the *battery fitness*.

Droop control offers increased *robustness*, fail-safety and *reliability* due to its communication-less operation based on local measurements. Determining the droop characteristics and subsequently the droop settings is critical for safe battery operation, accurate DC power line voltage control and fair energy sharing. In this context, the selection of the droop characteristics represents a compromise between optimal energy sharing and optimal voltage regulation. In addition, the selection of inappropriate droop settings in nodes may lead to voltage fluctuations at the DC power line and a mismatch in current sharing. The droop parameter is the gain factor of a P-controller, i.e. the overall system is a parallel connection of several P-controllers with different gain factors. [31,32]

As a result, a permanent control deviation remains. In summary, droop control offers improved *robustness* and *reliability* with limited control accuracy and a permanent control deviation.

2) Hierarchical, Communication-Based Control Strategy: A further control strategy on the global level is the communication-based hierarchical control, where a functioning communication between all nodes is a prerequisite. All components, including the generators and loads, send their operating parameters via a global bus line (CAN FD) and manage the received operating data of all remaining participants. Consequently, each microcontroller has available all the data required for system control.

In principle, all battery nodes are able to autonomously control the system by consuming or supplying surplus power according to the DC power line voltage measurement. This leads to a system of distributed autonomous nodes. The clocks of the distributed nodes cannot be perfectly synchronized, resulting in nodes operating to local clocks with small drifts and offsets. The clock drifts can be reduced, but not fully eliminated. To design the control for a system consisting of asynchronous operating nodes, all possible state transitions between the different nodes must be defined, which is a non-trivial task.

Therefore, a hierarchical control consisting of two domains, the *regulating domain* and the *actuating domain*, is proposed, which still fulfills the system goals *reliability, robustness, scalability, flexibility*.

The tasks of the *regulating domain* include the specification of the control parameters of all batteries and thus a battery state-dependent adaptive load sharing to balance the battery states, the synchronization of the nodes, the management of the (de)activation of participating nodes and the implementation of the selected optimization strategy. One of the battery nodes is elected as the temporary leader, performing strategic and regulatory tasks. The temporary leader takes into account the battery states and the current load and generation data (Fig. 9). In addition to this, the temporary leader compensates for the permanent control deviation. For this reason, only a battery node can be elected. The remaining battery nodes operate as actuators according to the specifications of the temporary leader and form the *actuating domain*.

For the hierarchical, communication-based control, error-free communication between all participating nodes is a prerequisite. Compared to droop-based control, this strategy is more costly in terms of computing power and energy consumption of the microcontrollers. Communication between components, data management and monitoring as well as repeated calculation of the actuating variables depending on the operating parameters is required. The message exchange

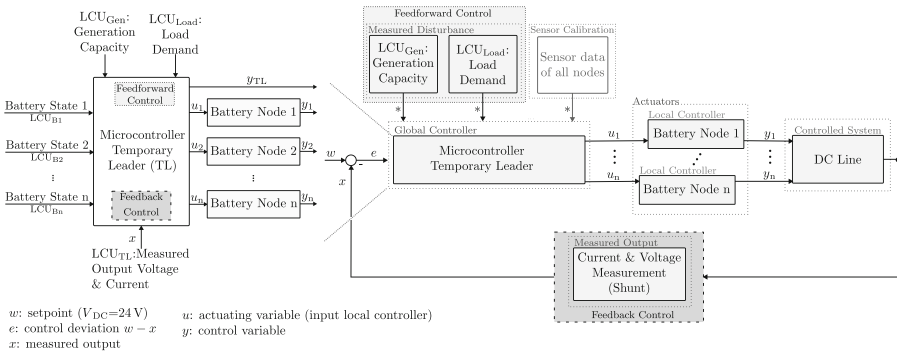

Fig. 9. The cascaded control of the DBMS consists of an outer, global control loop and several inner, local control loops (Fig. 1). The microcontroller of the temporary leader is the global controller and it takes into account the battery states, the measured generation and power consumption as measured disturbances (feedforward control) and the measured actual values (feedback control) for the specification of the actuating variables. Furthermore the temporary leader steers its own DC/DC converter to adjust the remaining control deviation. (*Data are sent to all LCUs, but only the temporary leader processes them.)

allows the generation and load values to be directly included in the feedforward control loop as measured disturbance. This improves control dynamics by eliminating the wait for effects of current generation and consumption on the DC power line voltage and its measurement and processing in the feedback control.

In summary, the battery state dependent load sharing and optimization strategies can be realized more precisely by direct specifications via the temporary leader compared to the adjustment of the droop characteristics. Furthermore, no permanent control deviation is required to determine the output values, which improves the control accuracy.

The droop-based and communication-based control strategies at the global control level exhibit different characteristics (Fig. 11) and requirements and, accordingly, are suitable for different operating states. Figure 10 shows the state diagram of the control at global level.

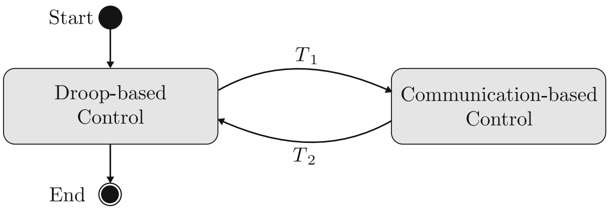

Fig. 10. State diagram of the global control level with state transitions T_1 and T_2 (Eqs. 1, 2.)

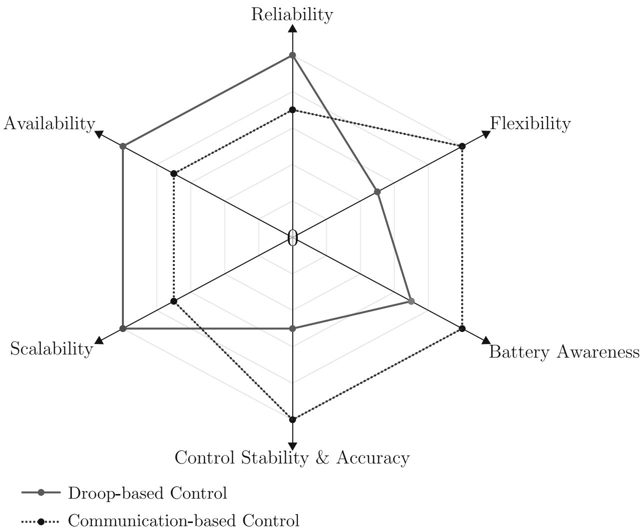

Fig. 11. Characteristics of the control strategies at the global control level: The droop-based control is characterized mainly by *robustness* and lower system requirements, while the communication-based control strategy provides more precise setpoint specifications and takes battery conditions into account more effectively.

The state-transitions are defined by the Eqs. 1, 2.

A_1: *The temporary leader is elected and operational.*
A_2: *The global communication between all participating nodes and the leader is error-free.*
A_3: *The deviation of the measured DC power line voltage from the setpoint voltage is less than* $\pm 20\%$
A_4: *A software update is performed.*
A_5: *Components are added, removed or temporarily deactivated.*
A_6: *System start-up or shut-down is performed.*

$$T_1 = A_1 \wedge A_2 \wedge A_3 \wedge \overline{A_4} \wedge \overline{A_5} \wedge \overline{A_6} \quad (1)$$

$$T_2 = \overline{T_1} = \overline{A_1} \vee \overline{A_2} \vee \overline{A_3} \vee A_4 \vee A_5 \vee A_6 \quad (2)$$

6 Local Control Level Strategies

The global control level specifies the setpoints for the local control loops of each battery node (Fig. 12). In droop-based control, characteristics for the virtual internal resistance are determined for every battery node. These characteristics are compared to locally acquired measurement values and the intersection defines the current setpoint.

In communication-based control, the temporary leader directly specifies and sends the setpoints via the communication line. The local control loop is a feedback control. The current and voltage sensors record the actual values and are part of the feedback control. The actual values are sent to the microcontroller, which monitors them and considers them in the control to the setpoints.

The LCUs of the loads and generators also capture the actual current values and send them to all participating nodes via the global communication line. This information is taken into account as a measured disturbance in the feedforward control section. Control stability and control dynamics are improved since the

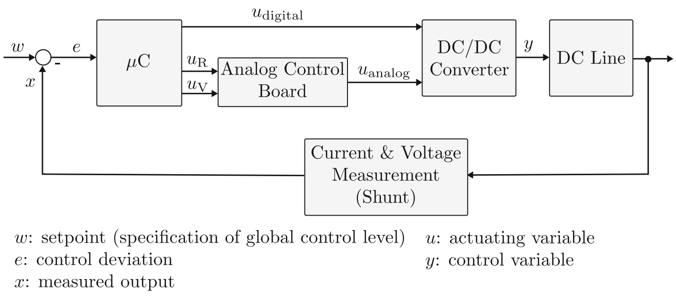

Fig. 12. The task of the local control loop is to control to the setpoint w specified by the global control level (Fig. 9). The actuator is the DC/DC converter whose control variable y is specified using either a digital or analog controller.

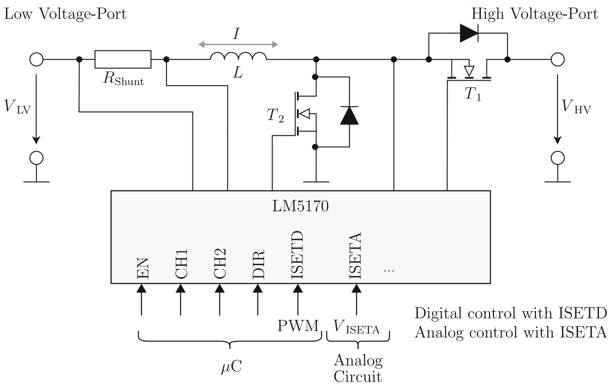

Fig. 13. Bidirectional half bridge connected to one of the two channels of the analog (`ISETA`) and digital (`ISETD`) controllable current controller: In buck mode MOSFET T1 realizes the switch and MOSFET T2 is permanently disabled and vice versa for the boost mode [34].

manipulated variables are adjusted directly instead of reacting to a change of the DC power line voltage due to excess or missing power.

The processing of the setpoints, i.e. the control according to those setpoints, is the task of the local control level. The actuator of the local control loop is the DC/DC converter. For the DBMS, multiphase DC/DC converters combining a buck and a boost converter with a current controller are used [33]. Two separate half bridges are connected and controlled by a phase shifted signal. The use of two half-bridges divides the current by two and thus leads to lower current ripples, reduced losses and increased efficiency. The current controller is either analog or digital controllable (Figs. 12, 13). According to the setpoint current, the MOSFETs are controlled in such a way that the current measured via the shunt resistor corresponds to half of the setpoint current. The output voltage is not taken into account.

It is possible to switch between analog, hardware-based control and the digital control at the local control level (Fig. 12).

1) Analog Control: For analog control, an additional control board was developed which implements a current controller and a higher-level voltage controller. Further information is given in previous work [34].

Figure 14 shows the analog circuit with control elements adjustable via the microcontroller using the I^2C interface and the digital analog converter. The two actuators V_{REF} and R_{POT} combined realize a DC/DC converter with a digitally adjustable output current and output voltage (Fig. 15). Using the droop-based control strategy at the global control level, R_{POT} defines the droop resistance and thus determines the slope of the droop characteristic as well as the current setpoint. The slope of the droop curve, which can be changed via the resistance value, enables load sharing between the battery nodes depending on the battery state.

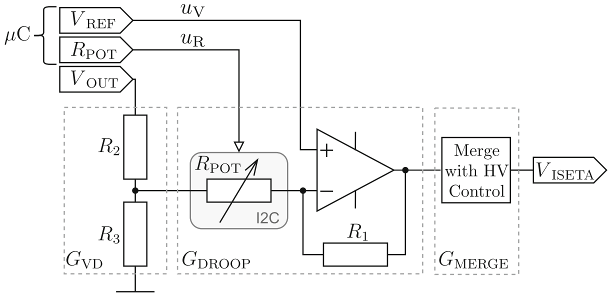

Fig. 14. The analog control board implements a digitally parameterizable droop control. By changing the reference voltage V_{REF} a change of the output reference voltage is realized. The resistor value R_{POT} corresponds to the slope of the droop characteristic. Together with the output voltage V_{OUT} this results in the reference voltage V_{ISETA} for the analog control of the current controller (Fig. 13).

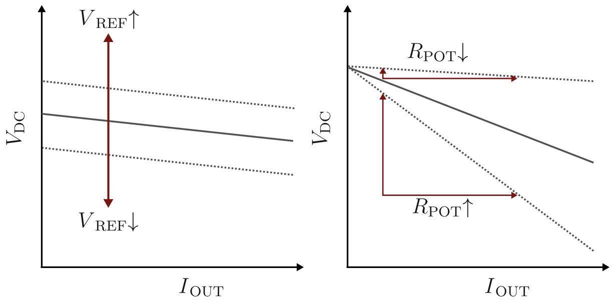

Fig. 15. Operation of the manipulated variables V_{REF} and R_{POT} of the analog control board [34]: R_{POT} changes the slope of the droop characteristic, while V_{REF} defines the voltage setpoint.

For communication-based control at global level, the R_{POT} values can be stored as a look-up table for the setpoint current values at a given output voltage. Consequently, the corresponding R_{POT} value is set directly according to the received specifications from the temporary leader. The output voltage of the analog control circuit is the feedback reference voltage V_{ISETA} of the current controller [33]. Analog control at the local control level offers increased *robustness* with higher losses and thus lower efficiency. Furthermore, it offers only limited control possibilities, since the circuit is fixed and corresponds to a P-controller with a variable gain factor.

2) Digital Adaptive Control: In digital control, a Pulse Width Modulated (PWM) signal can be generated directly by the microcontroller and functions as a reference signal (ISETD) for the current controller (Fig. 12). In this case the controller is not realized analog with operational amplifier and the respective hardware components but fully digital implemented on the microcontroller. This provides more *flexibility* and the ability to use adaptive control.

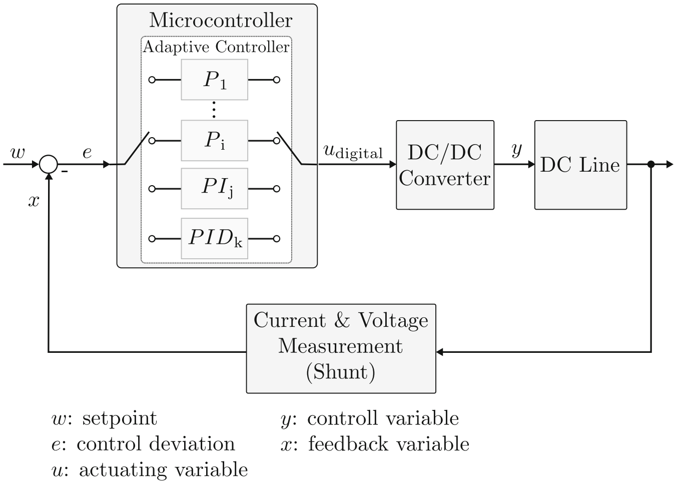

Fig. 16. The digital adaptive controller changes not only the value of the control parameters, but also the type (P, PI or PID) of the controller.

Adaptive controllers can change their behavior in response to changes in the dynamics of the system and disturbances (Fig. 16). In contrast to the ordinary feedback control with constant gain, adaptive controllers change the gain or even the controller type according to the operating conditions [35].

Ordinary linear feedback with constant gain can work properly under a certain operating condition. However, difficulties may arise when the operating conditions change. A more sophisticated, adaptive controller offers the possibility to work in a variety of operating conditions.

One scenario in digital adaptive control is that all normal battery nodes operate with a P-behavior using gain factors, whose magnitude depends on the battery state, and only the temporary leader operates with the behavior of a PI-controller. The remaining control deviation is reduced compared to a system only consisting of P-controllers and the control stability is improved.

In addition, it is possible to change the controller type of some or all of the battery nodes, e.g. to a PD controller or PID controller for specific operating conditions such as system startup, severe fluctuations, or for predictable or previously announced load/generation changes. In this case it is also possible to vary the size of the corresponding controller components.

In summary, digital adaptive control offers more *flexibility* and the possibility to improve control dynamics and stability over a variety of different operating conditions. The selection of the type of the adaptive controller, the determination of the controller types as well as the controller coefficients and the assignment to the operating conditions with definition of the transition conditions are challenging tasks. Compared to the droop control, the computational effort is higher, but the losses caused by the hardware components are eliminated, positively affecting the efficiency of the system.

7 Assignment of the Control Strategies to the Operating States

The different operating states pursue various control goals and therefore it can be helpful to change the chosen control strategy. Figure 17 shows the different operating states that can occur in the DBMS.

In the operating states with high requirements for *robustness* and at the same time lower requirements for battery-optimal operation and control stability, the droop-based control strategy is used (Table 1). Advantageous in this case is that less system requirements have to be fulfilled, i.e. no communication between the nodes is necessary and no leader has to be selected. If possible, i.e. if there is enough battery capacity, if the communication works and if the leader is elected, the communication based control is enabled and more sophisticated and system oriented modes of operation become available (Table 1).

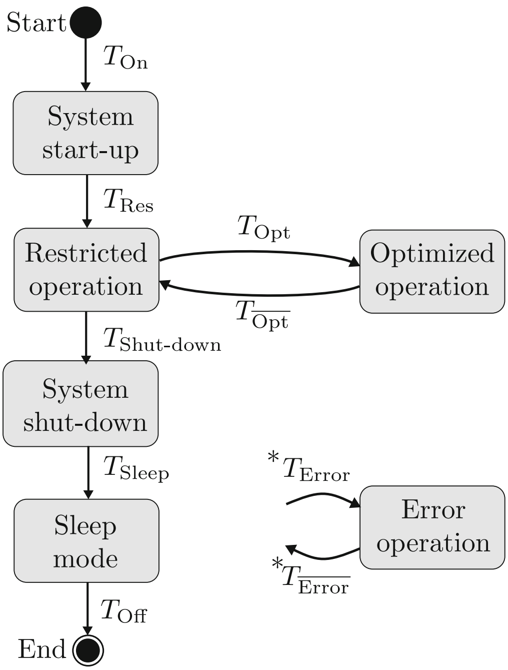

Fig. 17. Operating states of the DBMS and the respective transfer conditions, which are defined in Table 1. (* Transfer to the state *error operation* is possible from all operating states)

Table 1. Description of the transfer conditions and assignment of the control strategies to the different operating states

Operating State	Transfer	Transfer Condition	Global Control	Local Control
System start-up	T_{On}	Activation signal	droop-based	analog
Restricted operation	T_{Res}	Leader is elected and the deviation of the DC power line voltage from the setpoint is $\leq 20\%$	communication-based	analog in combination with digital
Optimized operation	T_{Opt}	Sufficient (dis)charge capacity available	communication-based	analog in combination with digital
Error operation	T_{Error}	Error occurrence such as interruption of communication or failure of leader	droop-based	analog
System shut-down	T_{Shut}	Deactivation signal	droop-based	analog
Sleep mode	T_{Sleep}	DC power line is potential-free	communication-based*	digital[a]

[a] Inactive - except for recharging processes

8 Conclusion and Outlook

In this paper, the control concepts of a decentralized battery management system were discussed. A battery management system was presented which can implement centralized, decentralized, distributed and hierarchical control strategies without hardware changes. The characteristics of different control strategies were evaluated considering the *reliability* and the control accuracy. Instead of using a single control strategy throughout the operation of the DBMS, the system switches between different control strategies as various operating states also exhibit different properties. The control was divided into a global and local control level and two different strategies per each level were presented. The operating states were defined and a first assignment of the control strategies was made. This assignment is the basis for the future implementation and further investigations regarding the *scalability* and *robustness* of the system. Furthermore, a method for switching between the control strategies based on the bumpless transfer [36,37] will be developed in further work, so that the change of the control strategies only minimally influences the control stability. Related future investigations include analyzing the control stability of the system depending on the number of nodes and comparing the control strategies in terms of energy efficiency.

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