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Design of a 100-kW Three-phase Interleaved DC/DC Power Converter for Hybrid Supercapacitor-battery Energy Storage

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Abstract*: *The paper describes the design of a 100-kW three-phase interleaved DC/DC power converter for a hybrid energy storage system based on lithium-ion batteries and supercapacitors. A description of the design and technical solutions of the converter is presented. The design has a minimum length of the connections between elements for lower bulk inductances. The converter uses the SEMIKRON SKiiP IGBT power module with liquid cooling. The control circuit of the converter is shown. The converter operates in buck and boost modes. The results of the simulation of device operation modes are given. The three-phase control scheme allows reducing input current ripple and obtaining the required power.

Index Terms*: *100-kW DC/DC converter, three-phase interleaved converter, design, simulations, hybrid energy storage, lithium-ion batteries, supercapacitors, ultracapacitors.

I. INTRODUCTION

Energy storage systems based on lithium-ion batteries have proven effectiveness in many applications, both in transportation and in electrical networks [1]-[3]. The use of energy storage devices in transport allows reducing fuel consumption by 20-30% and the installed capacity of generator sets by 2-3 times [4]. The introduction of energy storage in energy systems is designed to reduce peak loads, as well as improve the quality and reliability of power supply and the efficiency of the power system as a whole. The existing and potential application areas of energy storage devices in the grid are frequency, voltage and reactive power regulation, optimization of power plant utilization, leveling of daily load schedules and integration of renewable energy sources [5]. The positive effects of the energy storage introduction in the technical connection of remote industrial and infrastructure facilities include reducing investment in the construction of long high-voltage overhead lines, as well as the cost of electricity for consumers by lowering expenses due to daily fluctuations in electricity costs [6].

Among the various types of energy storage devices, lithium batteries are widely distributed. Lithium-iron-phosphate (Li-Fe-Po) batteries are actively used as buffer energy storage devices in autonomous power supply systems using wind generators and solar batteries, as well as in storage technology. Their advantages include high specific energy consumption, large discharge currents up to 20C (where C is numerically equal to the rated battery capacity), minimum self-discharge up to 4-6% per month, wide operating temperature range from -40 to +50 ºC and high efficiency. At the same time, the cyclic life of lithium batteries can reach 5,000 cycles. However, they are also characterized by relatively high cost [7].

Another type of energy storage is supercapacitors. They can provide up to 30 times bigger specific power than batteries and have a much greater cycle lifetime, which is over 500 thousand cycles. However, they have much less specific energy consumption compared to lithium batteries [8].

The combination of different technologies of energy storage allows consolidating their advantages in one device called hybrid energy storage. The use of supercapacitors in conjunction with lithium batteries delivers a smooth increase and decrease of currents of lithium batteries, protecting them from unwanted loads, and thus extending their lifetime and reducing the cost of the energy storage system [9].

II. PROPOSED METHODOLOGY

A. Block Diagram

The scheme of a 100-kW 100-kW·h hybrid energy storage system (HESS) based on lithium-ion batteries and supercapacitors has been previously described [10]. The HESS circuit is shown in Fig. 1. The energy storage device is based on an active hybrid scheme and includes two DC power converters described in this paper, one of which is connected to a lithium battery block and the other one to a supercapacitor block. Both are connected to a bi-directional DC bus of an inverter. This scheme provides separate control of power flows from batteries and supercapacitors for the exchange of electricity with the network and consumers. This scheme was chosen because it enables the control of the charge and discharge currents of each of the energy storage devices separately, regardless of their state of charge.

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In this way, complete utilization of the energy stored in supercapacitors is achieved and, at the same time, a charge-discharge curve of the batteries is formed [11].

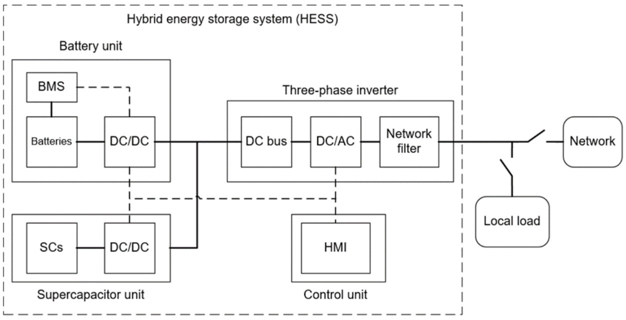

Fig. 1. The hybrid energy storage scheme. BMS – battery management system, SCs – supercapacitors, HMI – human-machine interface.

The modern level of semiconductor technology allows the use of controlled semiconductor switches designed to withstand a few kA and a few kV. The recovery rate and dynamic characteristics of the switches allow them to be used at switching frequencies of up to tens of kHz [12]. Increasing the switching frequency reduces the output current ripple and decreases the size of the inductor by lowering the required inductance. At the same time, as the frequency and current increase, the amount of power losses leading to overheating of semiconductors also increases. For efficient heat transfer from semiconductors, aluminum radiators with forced air cooling, as well as with waterproof channels for liquid cooling are used [13]. A glycol-water mixture in the ratio of 50%:50% acts as a cooling agent.

B. Algorithm

Due to network equipment operation, the following requirements should be applied to the converter: provision of galvanic isolation between the input and output; the possibility of remote turning on and off; the possibility of parallel operation; maintainability; ensuring quick replacement of blocks or elements in the case of a malfunction, etc. The converter must ensure the stabilization of the electric power parameters within specified limits when there are fluctuations in the quality indicators of electrical energy or changes in the magnitude and nature of the load, as well as provide protection if the specified parameters deviate beyond acceptable limits [14].

For the use in the above-described HESS, a three-phase interleaved DC/DC power converter rated 100 kW and its design was developed. The calculation of the characteristics of the converter and its control system was carried out on simulation models. The following are the details of each of the stages of development of the converter. In order to provide the necessary output power of the DC/DC converter and reduce the total heat loss produced in semiconductor switches, a parallel connection of several semiconductor modules was applied. The circuit is implemented with the SEMIKRON SKiiP power IGBT modules. The circuit of the three-phase power converter is presented in Fig. 2. The SKiiP power module combines a three-phase power bridge, driver and protection scheme in one device. It is made based on IGBT transistors with reverse diodes. Snubber capacitors C10, C11 and C12 are designed to compensate for the distributed inductance of the DC bus and protect the power switches from overvoltage. Capacitors C1-C6 are DC bus capacitors and have a total capacity of 3,400 uF. Parallel to each capacitor, a discharge resistor of 47 kΩ is installed to ensure slow discharge of capacitors and safety during maintenance of the installation. Power inductors L1, L2 and L3 are necessary for the operation of the converter in both buck and boost mode and for smoothing the low side current of the converter. The magnitude of these inductances depends on the current ripple amplitude and the operation mode (continuous or discontinuous current mode), which also affects the control system settings. KM10 and KM11 are the main contactors designed for connecting energy storage. KM20 and KM21 are precharge circuit contactors. R10 and R11 are current-limiting resistors in the precharge mode.

C. Flow Chart

The precharge circuit is necessary to limit the charging currents of capacitors C1-C6 when the power source is connected. To protect the circuit and mainly lithium-ion batteries from overloading, fuses FU10 and FU11 are used.

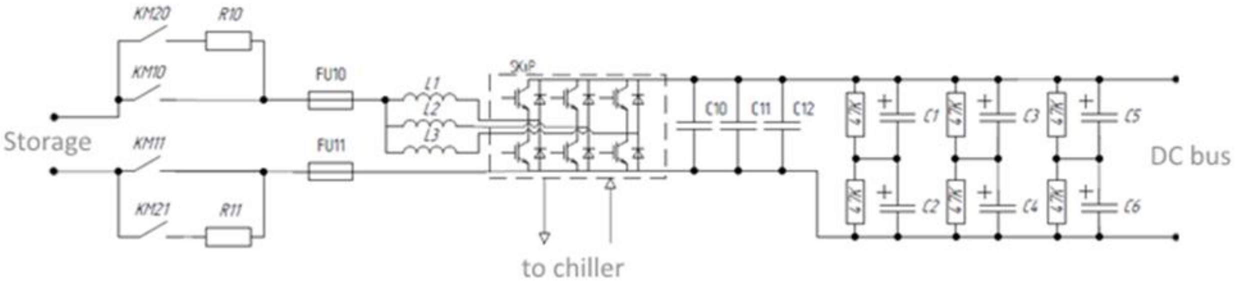

Fig. 2. The electrical circuit of the three-phase interleaved DC/DC power converter.

In the boost mode, the lower switches are operated, and in the buck mode, the upper switches are operated, as in conventional power converter circuits. The switches are controlled by supplying pulses to IGBT switches with a necessary pulse-width modulation (PWM) duty cycle with a phase shift of 120º between them. An additional advantage of this circuit is that a smoother current can be obtained at the input of the converter and the inductance of the inductors, providing the required level of current ripples, can be less than in the case of a single phase. Fig. 3 shows the plots of the inductors currents of each phase of a three-phase converter in rated operation.

The amplitude of the total current ripple Isc at the input of the converter is significantly less than the amplitude of the current ripple in each of the inductors Isc1, Isc2 and Isc3.

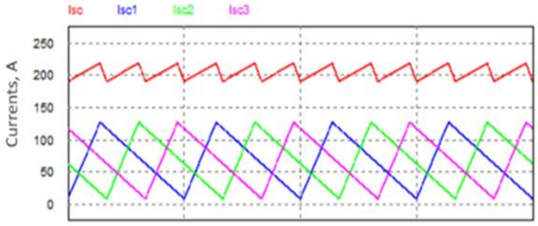

Fig. 3. Inductors current of the three-phase interleaved DC/DC power converter and the total current at 120º phase shift.

Measured values of currents and voltages, as well as the state of the power module, are transmitted from the driver to the control unit, which performs the calculations and generates control signals in accordance with the specified control mode. The control unit also monitors the device operation parameters and controls the main contactor and the precharge circuit contactor. The control unit receives the setpoint according to the operating mode and transmits data about the state of the device by sending messages via the CAN data bus.

Thus, the circuit allows the device to be used in the bidirectional mode for fast charge and discharge of energy storage devices, such as lithium-ion batteries or supercapacitors, and provides small ripple input current.

III. RESULT ANALYSIS

D. Design of the Converter

The developed three-phase DC/DC converter is designed as a single unit, all elements of which are fixed on the mounting platform. Due to this, compactness and a minimal length of connection lines are achieved. Positive and negative busbars are made as monolithic copper plates with holes for connecting capacitors and insulators between them. DC bus capacitors are mounted on the heat sink plate and fixed to it. Snubber capacitors are installed as close as possible to the positive and negative inputs of the power module. Power inductors are connected to the u, v and w terminals of the power module, which is also connected with a common copper bus at the connection point to the energy storage device. The control board is placed on a metal base fixed above the power module. The connection of the liquid cooling circuit is made on the sides of the cooling plate of the power module.

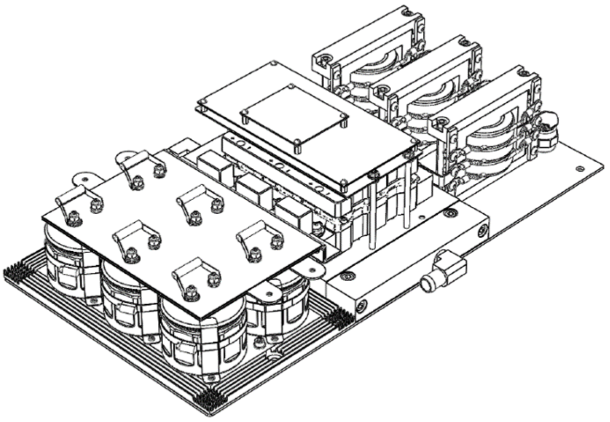

Fig. 4. Design of the power converter.

Power inductors are made of ferrite cores, which provide high inductance and low losses at high frequencies. Coils are sectioned to improve the heat dissipation. When choosing a winding wire, the current skin effect at high switching frequencies was taken into account. Each inductor is designed for the current of 100 A and has an inductance of 600 μH.

In the converter design, aspects of effective heat removal, as well as electromagnetic compatibility, were taken into account. Minimum lengths of communication lines allow obtaining low values of distributed inductances, which reduces the level of transient overvoltage and of electromagnetic emission. Good thermal coupling of the elements increases the reliability of the protection system. The device is designed to be installed inside an electrical cabinet and provides modularity to easily increase the output power of the end device.

E. Simulations

To calculate the operating modes and select the optimal number of modules, a mathematical simulation model of a multi-phase DC/DC converter was developed and applied. The model of a three-phase DC/DC converter is presented in Fig. 5.

The three-phase DC/DC converter is operating in current control mode in buck mode and boost mode. The external control loop is designed to maintain the output voltage. Three internal control loops (each circuit for a separate phase) are used to evenly distribute the currents between each of the three phases. In each of the phases, the inductors L1, L2 and L3 with the same parameters are included, taking into account the active resistance of the windings. Current and voltage feedbacks are measures with the appropriate sensors depending on the converter mode of operation.

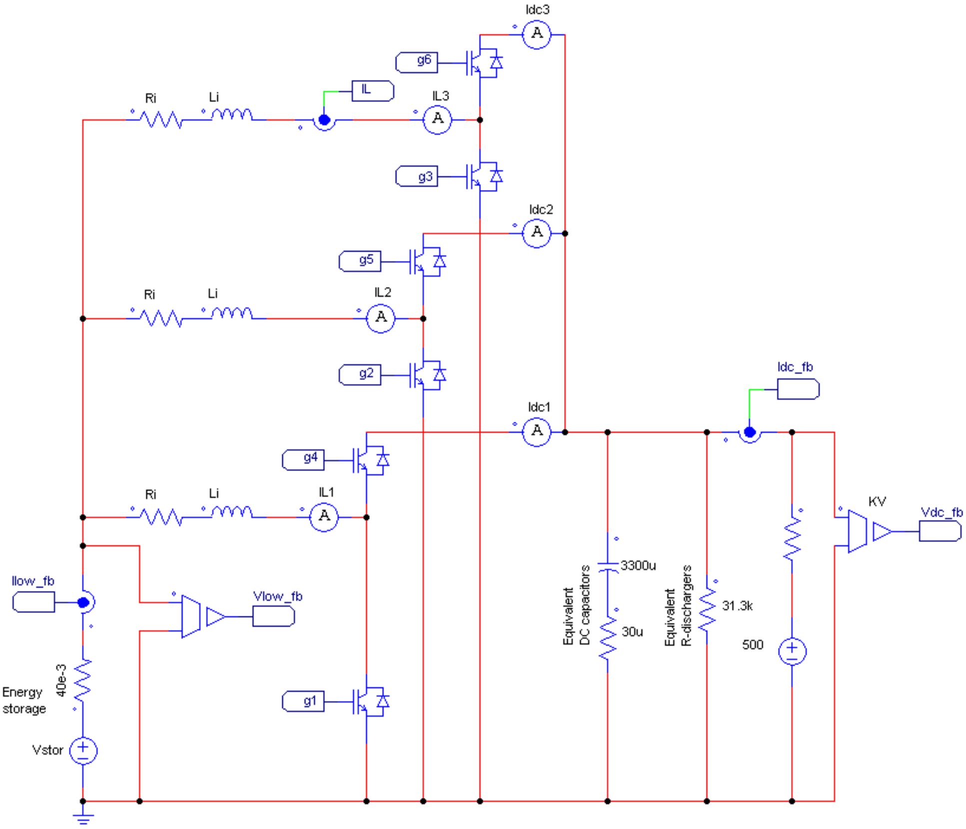

Fig. 5. Simulation model of the three-phase DC/DC power converter.

Fig. 6 shows the control loop of the three-phase DC/DC converter in boost mode. The external current control loop sets the reference value for the voltage control loop of each of the three parallel branches of the converter. At the input of the internal loop, a voltage limit of 900 V is set. The maintenance of the set values is performed by a proportional-integral controller in the z-domain PI(z). Operation of the switches of each branch is carried out with a phase shift of 120°. In this mode, the DC bus current is maintained according to the value set by the operator or according to the schedule. The model implements a digital control system close to the operation of a microprocessor device. Model data is discretized using Zero order hold, 1/z elements and Quantization block. The calculation of control actions is carried out in per unit values. The voltage of the DC bus 650 V is taken as the base voltage, and the rated power of the converter 100 kW is taken as the base power. To switch between boost and buck mode, a comparison of the voltages on the low and high side of the converter is made.

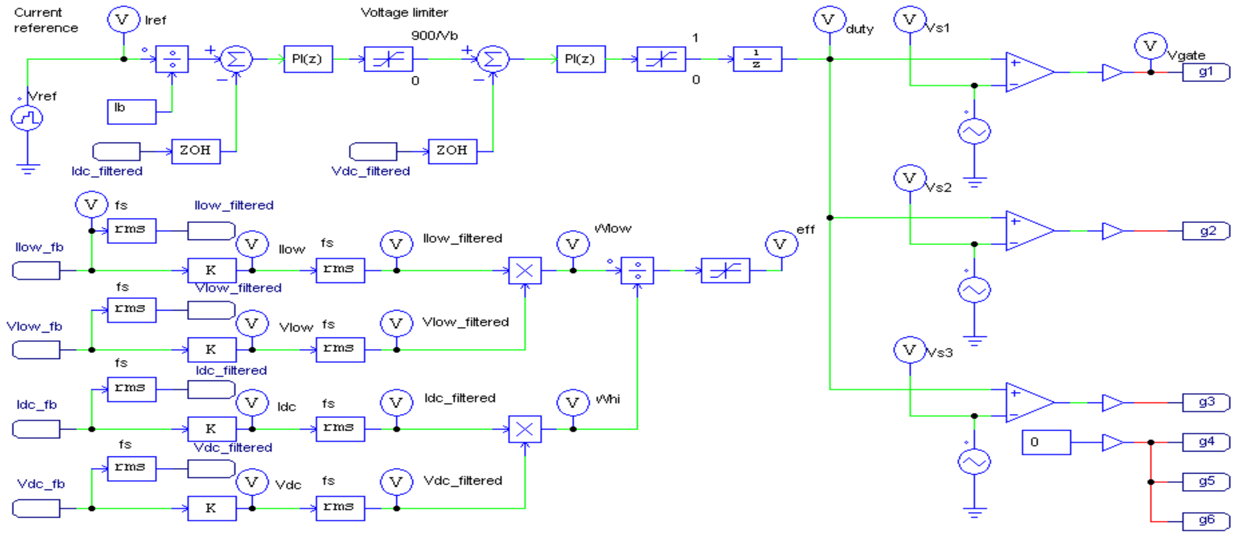

Fig. 6. The control scheme of the three-phase DC/DC power converter.

The developed model is used to configure and setup control system regulators and can be easily scaled to simulate the operation of an n-phase converter.

F. Simulation Results

Fig. 7 represents the example of the simulation results of the three-phase DC/DC converter in boost mode. The plots show current curves on the low and high side. The DC bus current curve (red line) follows the setpoint curve (green line). In this case, the current ripple in the source (blue line) does not exceed 5%. The input current ripple in the multi-phase converter depends on the PWM duty cycle value and has a maximum value with a duty cycle of 0.17, 0.5 and 0.83, while the minimum ripple is achieved with a duty cycle of 0.33 and 0.66. At load increasing, a smooth increasing of the PWM duty cycle and voltage on the DC bus, as well as the output power, occurs. When the maximum allowed voltage on the DC bus is reached at 1.5 seconds, the current is limited to maximum allowed value.

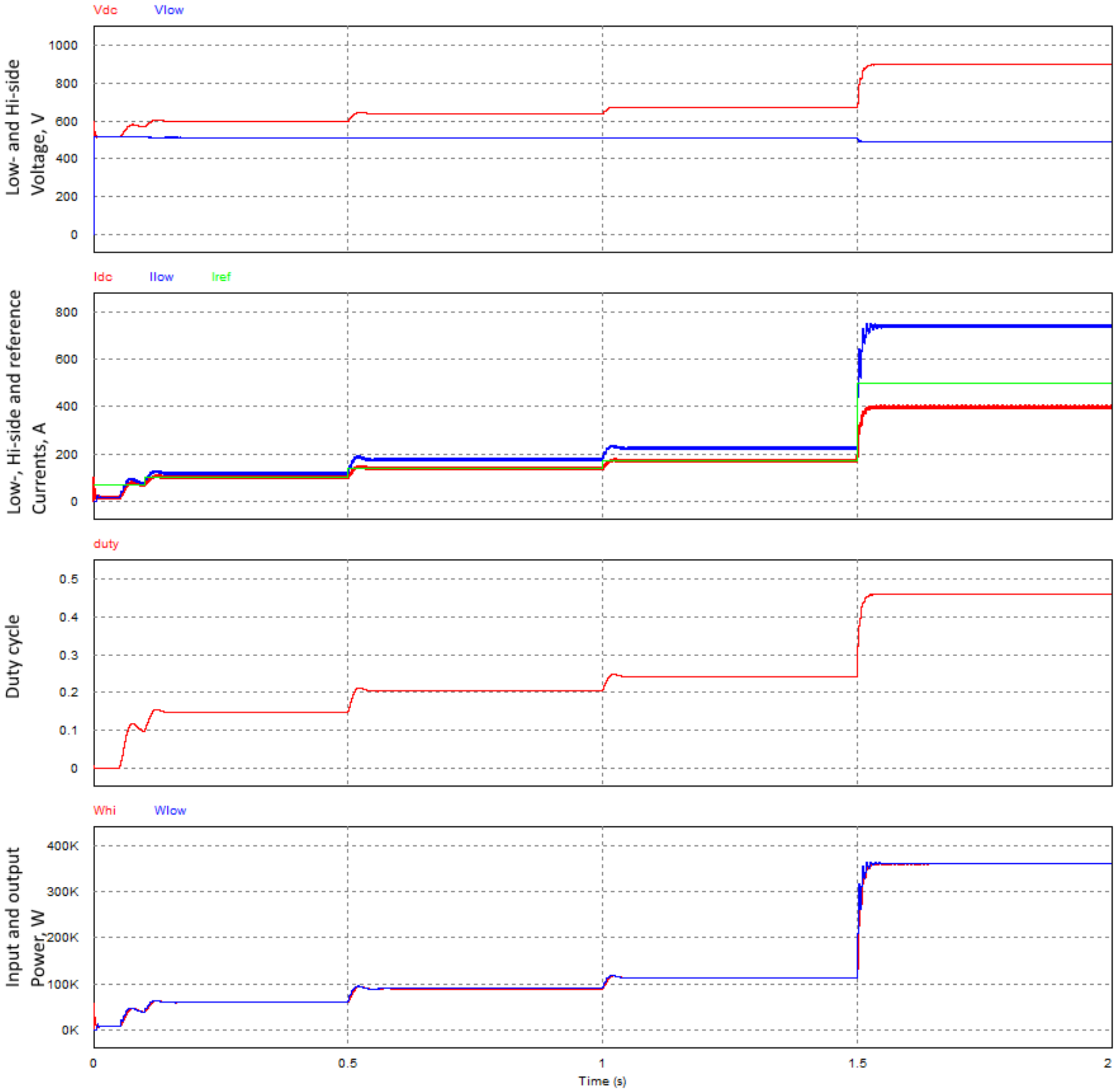

Fig. 7. Simulation results of the three-phase DC/DC power converter in boost mode.

Thus, it can be concluded that the model of a three-phase 100 kW DC/DC converter for a hybrid energy storage device based on batteries and supercapacitors is adequate and allows for simulation, modeling and adjustment of converter controllers.

IV. CONCLUSION

In this work, a 100-kW three-phase DC/DC power converter for HESS based on lithium-ion batteries and supercapacitors was developed. The development was carried out, taking into account the requirements for the design and electrical parameters for network power converters. The developed design has the minimum lengths of communication lines between the elements and an effective cooling system and provides the necessary modularity.

A converter control circuit was developed in boost and buck mode. The external control loop is configured to control the DC bus current. When this occurs, the DC bus voltage is limited to no more than a specified value. The three-phase circuit allows reducing input current ripple and obtaining the required power of 100 kW.

Simulations of the converter showed the effectiveness of the control system and the proper functioning of the developed converter. The resulting solutions and developments can be successfully applied for the further development of modular energy converters.

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