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A 100kW Three-Phase Power Inverter for Hybrid Energy Storage System Based on Batteries and Supercapacitors

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Abstract*: *The paper represents the design of a 100 kW three-phase network inverter for a hybrid energy storage system based on batteries and supercapacitors. The presented design is based on fast IGBT switches, provides their effective cooling and can be performed in a modular design. The inverter is designed for parallel operation with the network in bidirectional mode and island mode. The control algorithm allows for direct control of active and reactive power. The obtained simulation model and simulation results are used to calculate the inverter parameters and debug the control system. Simulation results show good performance and effectiveness of the invertor and the algorithm.

Index Terms*: *bidirectional DC/AC converter, hybrid energy storage system, IGBT, network inverter, PQ control, three-phase inverter.

I. INTRODUCTION

The specificity of many areas of technology requires the use of electric energy storage. They are widespread in the field of electric and hybrid transport and in the power supply systems of buildings, as well as areas that do not have a centralized power supply [1], [2]. Thanks to electric energy storage, the problems of ensuring long-term uninterrupted power supply in emergency modes, smoothening peak loads, regulating frequency and voltage, correcting the power factor are solved. The use of energy storage in power networks leads to increased reliability and efficiency of power supply reducing the risk of accidents in the power system [3]. Energy storage allows implementing the concept of Smart Grid and the introduction of renewable energy sources [4]. An additional effect of the use of energy storage is to reduce investment in the construction of long-range high-voltage lines with a technical connection of remote industrial and infrastructure facilities, as well as to reduce energy costs due to daily fluctuations in the cost of electricity [5].

Various types of electrochemical energy storage devices are used to implement these tasks, but the most optimal are lithium-polymer batteries, namely lithium-iron-phosphate. This technology is well developed and provides high specific energy capacity (up to 250 W·h/kg), no memory effect, low self-discharge (about 5% per month), wide temperature operating range (from -30ºC to +50ºC), long lifetime (up to 15 years), relatively high cyclic life (up to 5000), reliability and safety [6]. The main disadvantage of $LiFePO_4$ batteries is their relatively high cost.

Supercapacitors are a good technology that complements batteries. The specific power of supercapacitors can reach 15 kW/kg, which is several times more than that of lithium-polymer batteries, but the specific energy of supercapacitors is about ten times less than that of batteries and reaches a maximum of 0.3 W·h/kg. The useful feature of supercapacitors is a large cyclic lifetime exceeding 500 thousand cycles at a temperature of +25ºC [7].

Due to the complementary properties of these two energy storage technologies, the development and application of a hybrid energy storage device (HESS) is promising [8]. In such a system, it is possible to ensure optimal operation of lithium batteries and reduce unwanted loads by limiting the rate of change in the current of the batteries due to the low inertia of the supercapacitors. The combination of lithium batteries and supercapacitors in HESS allows extending the operational lifetime of the energy storage and reducing the cost of the system [9].

The basis of the network energy storage is a three-phase network inverter that connects the storage with the network and the load. The inverter must provide high-quality electricity, be able to work in parallel with the network and autonomously, to transmit energy both in the forward and reverse direction, and at the same time provide high efficiency and ease of operation [10]. Inverter control when working in parallel with the network should be implemented in the mode of separate control of active and reactive power to match the instantaneous power with the battery and supercapacitor units [11], [12].

This paper represents the results of the development of a three-phase inverter for a hybrid energy storage system rated 100 kW, as well as a simulation model of the inverter control system with simulation results.

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II. PROPOSED METHODOLOGY

a. Block diagram

Previously, a scheme of a hybrid energy storage system based on lithium-ion batteries and supercapacitors was proposed [13]. The scheme of the HESS is shown in Fig. 1. An active hybrid scheme was chosen for the implementation.

In this scheme, each of the energy storage devices, namely the battery module and the supercapacitor module, are connected through a separate DC/DC power converter to a three-phase inverter, through which the HESS is connected to the network and the three-phase load. In this scheme, the best utilization of energy in storage devices is achieved, as well as the flexibility of management due to the separation of power flows from batteries and supercapacitors [14].

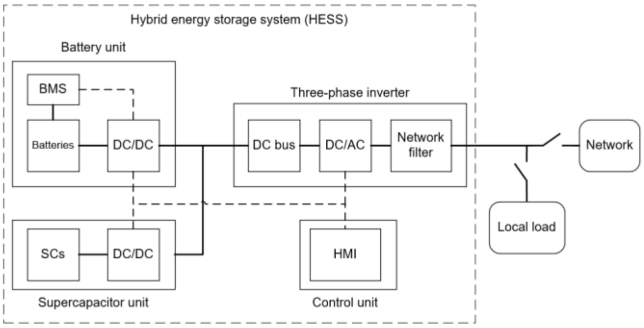

Fig. 1. Hybrid energy storage system diagram,

where BMS is a battery management system, DC/DC is a DC/DC power converter, SCs are supercapacitors, DC/AC is a three-phase inverter, HMI stays for a human-machine interface To ensure the required characteristics of the inverter, the power IGBT modules of the SEMIKRON SKiiP series were selected, including a three-phase assembly of IGBT switches with reverse diodes placed on a heat sink, a switch driver and a protection device. The electrical circuit of the inverter is shown in Fig. 2. The purpose of the capacitors C10, C11 and C12 is to compensate for the distributed inductance of the DC bus to protect transistors from overvoltage. Capacitors C1 – C6 are designed to stabilize the DC bus voltage. Resistors installed in parallel with each of the DC bus capacitors are used to provide a gradual discharge of capacitors in a disconnected installation for safe maintenance. The three-phase power choke L1 is necessary to protect the network from higher current harmonics, as well as to protect the inverter from impulse voltage surges in the network. EMI filter is used to reduce electromagnetic interference emitted into the network when working in parallel with the network. The main contactor KM40 performs commutation of the inverter to the network. The pre-charge of the DC bus is carried out through the current limiting resistors R31, R32 and R33 by closing the contactors KM31, KM32 and KM33. The contactor SF1 provides protection of the inverter against short circuits and overload. S1 switch is used for safe connection of the setup to the network.

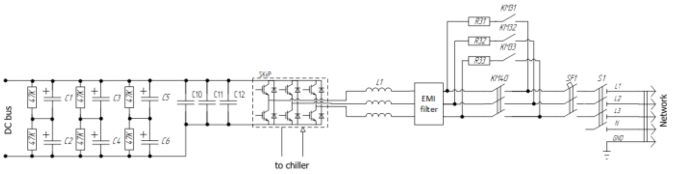

Fig. 2. Electrical scheme of the three-phase

During operation, the IGBT switches are operated with a specified pulse width modulation (PWM) duty cycle with a 120º phase shift. The higher the PWM frequency, the better the harmonic composition of alternating currents and the lower the required inductance of the choke. However, with an increase in the switching frequency, the losses in the swithes increase significantly. Instantaneous values of currents and voltages, the state and temperature of the switches are transmitted from the switch driver to the inverter control unit, which performs calculations and generates control signals for the implementation of the specified set points. The control unit monitors the status of the inverter and the network and controls the pre-charge circuit contactors and the main contactor. The inverter operating setpoint is supplied to the control unit via the CAN data bus from the operator or the higher-level control system. In this scheme, the three-phase inverter can be used in a bidirectional mode as a part of the HESS operating in parallel with the network and provide high power quality and control.

b. Design of the converter

The design of the three-phase inverter consists of several elements fixed on a flat plate. The purpose of the design was a compact device that provides a minimum length of connection lines between the components. Electromagnetic compatibility was also taken into account. The developed design is shown in Fig. 3.

The capacitors of the DC bus are fixed to the heat-dissipating platform and connected to the corresponding terminals to the plus and minus buses, and also have a connection at the middle point. Copper busbars are separated by layers of insulating material and are connected to a semiconductor module. The semiconductor module has terminals for connection of liquid cooling circuit. Directly on the positive and negative contacts of the semiconductor module snubber capacitors are fixed. The u, v and w terminals are located on the opposite side of the semiconductor module and are connected to the three-phase choke terminals by copper buses. Connection of switching equipment to the installation is done at the choke terminals. The control circuit board is placed above the semiconductor module on a metal plate.

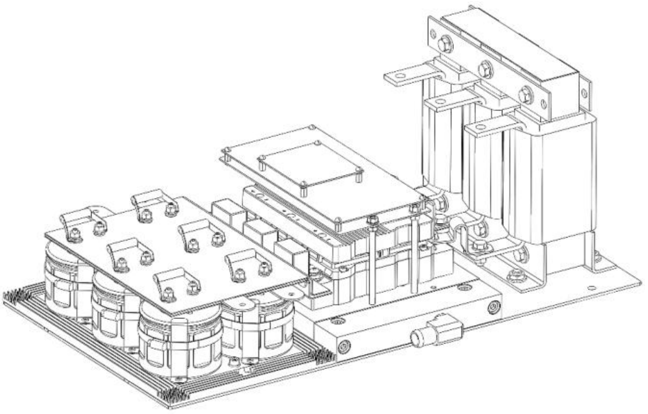

Fig. 3. Design of the three-phase network inverter

The design took into account the problems of cooling the components because of large currents, as well as electromagnetic compatibility.

Reducing the length of connection lines is necessary to reduce the value of distributed inductances to reduce transient overvoltages and the level of electromagnetic emission.

The device is designed to be placed inside the electrical cabinet and is modular for easier scaling of the output power of the drive.

c. Simulations

The search for the optimal parameters of the three-phase inverter and its components was carried out in specially designed computer simulation models. The general view of the power part of the model is depicted in Fig. 4. It includes the IGBT switches with reverse diodes. The capacitors of the DC bus and snubber capacitors are taken as equivalent elements with a total effective capacity. The DC bus voltage is determined by the voltage of the voltage source. The three-phase choke is modeled as a series of inductance and active resistance, simulating the resistance of the windings in each phase. Measurement of currents and voltages in each of the phases between the inverter and the network is carried out using sensors with a transfer ratio of 1:1. The network is modeled as a three-phase EMF source with low internal resistance.

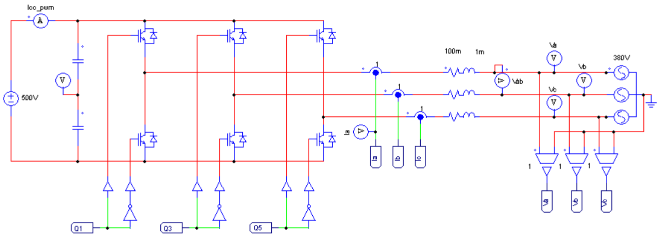

Fig. 4. Simulation model of the three-phase inverter

Control of the three-phase inverter in parallel with the network is carried out by the control circuit shown in Fig. 5. The inverter is controlled separately with the active P_{ref} and reactive Q_{ref} power. A positive value of the setpoint means the power flow from the inverter to the network and vice versa. The conversion of three-phase values of the measured currents and voltages i_a, i_b, i_c, u_a, u_b and u_c is performed using the transformation of coordinates according to the Clark equations in a two-phase system i_d, i_q, u_d and u_q. Next is the conversion of current set points and compensation of deviations of the measured currents from the set points using a proportional-integral controller (PI). The PI controller converts the received signals to the output voltage components v_d and v_q, which are then converted to a three-phase coordinate system. By means of the PWM generator, the received signals are transmitted to the corresponding power semiconductor switches with a 120° phase shift. Operation of the upper and lower switches is carried out in the reverse phase. The calculation of control actions is carried out in unitless variables. The voltage on the DC bus is taken as the base voltage, and the nominal power of the inverter is taken as the base power.

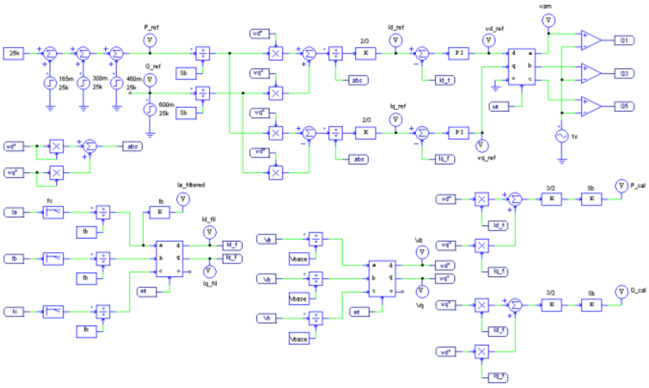

Fig. 5. Control system of the three-phase inverter

The developed model is used to determine the parameters of the three-phase inverter, adjust and debug the controllers of the control system to obtain the required quality of regulation.

III. RESULT ANALYSIS

The simulation results of the three-phase inverter in parallel mode with the network are shown in figure 6. The first plot shows the line-to-line voltage V_{ab}. The second plot shows the current in one of the phases of the inverter I_a. The third plot shows the calculated values of the current set points in the synchronous coordinates I_{dref} and I_{qref}, as well as the values obtained by recalculating the measured values of the three-phase currents I_{dfil} and I_{qfil}. The last plot shows the active and reactive power setpoints P_{ref} and Q_{ref} and their actual values P_{cal} and Q_{cal}.

The P_{ref} setpoint changes every 0.15 s and takes values: 25, 100, -100, 50 kW. The Q_{ref} setpoint changes from 0 to 50 kW at 0.6 s. The controller monitors the difference between the setpoints and the actual values and adjusts the output signals to match the set point. Overshoot in the process of a sudden change in the load can be reduced by fine-tuning the coefficients of the PI controller. THD output current of the inverter in a steady state does not exceed 1%.

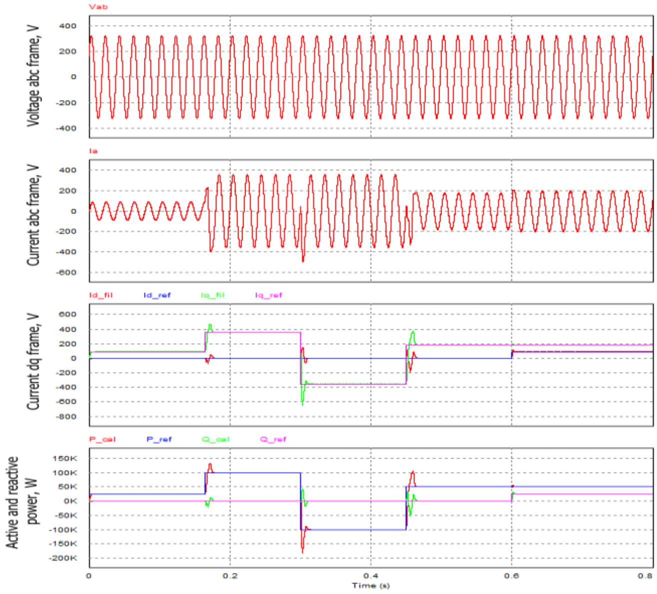

Fig. 6. Simulation results for the three-phase inverter

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Thus, the control of the three-phase inverter by the applied control technique can be carried out separately for active and reactive power in a bidirectional mode. It can be concluded that the model of a 100 kW three-phase inverter for a hybrid energy storage device based on batteries and supercapacitors is adequate and allows simulation and adjustment of the converter regulators.

IV. CONCLUSION

In this work, a 100 kW three-phase inverter for a hybrid energy storage device based on lithium-ion batteries and supercapacitors was developed. The developed design is compact and has a minimum length of connection lines between the elements, an effective cooling system, and provides the possibility of modular design.

The inverter control scheme for parallel operation with the network was developed. Inverter control is carried out separately by active and reactive power. At the same time, the high quality of regulation and quality of the electric power are provided. Simulation of the inverter showed the efficiency of the design and control system. The obtained solutions and results can be successfully used for further development of the technology of modular energy converters.

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