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POWER SHARING SYSTEM WITH USE OF DC-DC CONVERTER AND INTERMEDIATE CIRCUIT OF VSI INVERTER

The article describes issues related to power distribution between a power plant system consisting of a synchronous generator operating at variable shaft speed and a super capacitor which is a short-term source of electricity for sudden electrical load changes. In the presented system a generator and a battery of supercapacitors were connected with use of power electronic converters. The synchronous generator is connected to the DC network via an AC-DC converter and the super capacitor is connected with means of an isolated DC-DC converter. Both converters have been equipped with auctioneering diodes to prevent the flow of equalizing currents. The theoretical basis and results of experimental research obtained on a laboratory test-stand equipped with the aforementioned system are presented.

KEYWORDS: energy storage systems, synchronous generator, dual active bridge, DC grid, auctioneering diodes.

1. INTRODUCTOION TO THE DIRECT CURRENT GRIDS AND ENERGY STORAGE SYSTEMS ONBOARD OF SEAGOING SHIPS

The inexorable degradation of the natural environment and the related global energy challenges have forced the development of renewable energy sources based on efficient direct current network technologies, the so-called microgrids [1, 2]. The development of microgrids used in onshore domestic and industrial installations as well as electro mobile systems has been attracting increasing attention of scientists. DC networks can also be used in marine power systems which utilize, apart from converter generators, also electricity storage facilities consisting of accumulator batteries and ultracapacitors, reducing fuel consumption and pollutant emissions. Such a solution is a relatively small-scale stand-alone system, consisting of several active and passive electricity sources for most of the ships from non-renewable resources, energy storage systems (ESS) and power electronics converters. It can work as a fully autonomous system while the ship under way but can be connected to the onshore power grid when at berth [3-6]. The main advantage of this solution is the possibility to control the load of individual

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sources by using an appropriate power distribution algorithm. The paper presents theoretical assumptions and results of experimental research of a system consisting of variable-speed rotating generators, a super capacitor (SC) with a bi-directional DC-DC converter supervised by an original power distribution system on the DC side.

In contrast to microsystems connected to the power grid, which have virtually unlimited support from high inertia generators, seagoing vessels power grids should use passive ESS energy storage to balance the mismatch between the energy they produce, and the energy consumed. Batteries and ESS supercapacitors act as a buffer to store excess energy and deliver it back to the system when needed. ESS in soft networks also play an important role in regulating momentary power fluctuations and maintaining energy quality [7]. The article [8] summarizes the individual elements of ESS systems and indicates their key features. In a ship's network, the power incoming and outgoing from active (generators) and passive (energy stores) sources varies considerably depending on the momentary changes of power and load state. Due to the dynamics of power exchange processes, high-frequency components such as sudden power demand peaks when switching on large consumers or intermittent generation of electricity by a shaft generator in case of propeller emergence out of the water can be indicated. The occurrence of low-frequency components can be observed, such as the average daily energy consumption pattern. High-frequency and rapid changes in power consumption usually require fast response time components (supercapacitors), while low-frequency components require ESS components with high energy density (electrochemical batteries).

This paper presents the chosen results of tests involving long-term parallel operation of a synchronous generator equipped with a bidirectional AC-DC converter with a supercapacitor connected to a grid thorough an isolated DC-DC converter providing fast response to sudden load changes. Both converters were connected by direct current intermediate circuits in a way allowing controlled load sharing of both sources in order to obtain favorable mechanical characteristics of the driving combustion engine.

1.1. The variable speed synchronous self-excited generator (SESG)

The synchronous generators control with independent excitation winding is very well known and widely used in power plants. The control method involves the frequency and voltage regulation by means of the active and reactive power adjustment. The active power is provided by the mechanical drives such as combustion engines or rotating turbines while the amount of reactive power is controlled by means of current excitation winding and electronic voltage regulator. The two independent control loops operate with the use data incoming from rotational speed governor and automatic voltage regulator. This kind of operation is a simple, straightforward scalar control procedure, which omits some phenomena such as the coupling effect between the electrical axis in the synchronous generator [9]. One of the many suitable for this purpose methods, is based on the field orientation principle of vector control. Due to the principles of vector control, AC machine performance during transient operation modes comes quite close to that of direct current machines. The mathematical background of the dynamic model and vector control of an AC machine is illustrated by the space-phasor theory [10, 11]. The rotor flux oriented synchronous machine model is suitable for the simulation of the generator operation, but the control is implemented by means of a field oriented model. This idea seems very similar to a DC machine with independent control of the two variables producing electromechanical torque. In the synchronous generator the stator current is given by:

$$i_s = i_{sd\lambda} + ji_{sq\lambda} \tag{1}$$

and the winding flux can be expressed as:

$$\Psi_{ss} = \Psi_{ssdds} + j\Psi_{ssq/s} = L_{md}i_{sd\lambda} + jL_{mq}i_{sq\lambda} \tag{2}$$

where: λ_s is the position of the stator flux Ψ_s.

In generating mode operation, the quadrature component of the flux controls and determines active power and intermediate circuit voltage and is negative due to the reversed energy flow. Flux component due to its demagnetizing character, has also a negative value and corresponds to the generated reactive power. The exciting current influences on an active current component, which creates the torque. Because of decoupled control, the longitudinal component of the field oriented exciting current contributes to the magnetizing properties of the machine.

In order to control the power flow, the stator current must be oriented according to the magnetizing direction of the resultant stator flux. It is implemented in control algorithm with use of a Clarke and Park (α-β and d-q) transformations. In a constant torque angle control strategy, the d axis current is maintained at zero all the time, while the vector current has to be aligned with the q axis. The torque equation for an SESG, considering both i_{sd} and i_{sq} currents, is the one as follows in:

$$T_e = \frac{3}{2}\boldsymbol{p}\left[\Psi_m i_{sq} + \left(L_d - L_q\right)i_{sq}i_{sd}\right] \tag{3}$$

where: p is the number of pole pairs, Ψ_m is field winding flux, and L_d and L_q are values of the stator self inductances in the d-q plane. After applying some simplifications, the torque equation becomes as follows:

$$T_e = \frac{3}{2}\boldsymbol{p}\Psi_m i_{sq} \tag{4}$$

From equation (4) it can be observed that the field control of the generator can be achieved because of the linear dependency between machine torque and active current. The i_{sq} control loop in the d-q coordinates ensures a constant value for DC intermediate circuit voltage U_{dc}, when the reactive current i_{sd} is set to zero. To obtain the rotational speed and stator field angle value, which is needed for the Clarke and Park transformations, a sensorless system was applied.

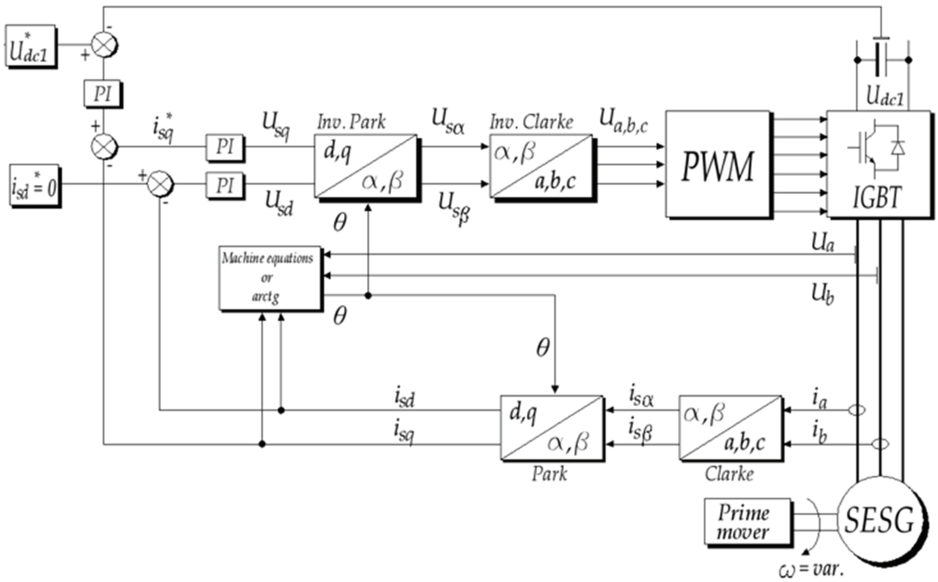

Fig. 1. Scheme of the self excited synchronous generator FOC control structure [12]

The applied field oriented control method allows for long-term maintenance of DC voltage value, but also thanks to current limitation controlled power distribution between other DC sources is possible.

1.2. The energy storage systems with use of DC-DC converters

In recent years, bidirectional DC-DC converters have received much attention as they are widely used in various applications such as renewable energy systems, electric and hybrid vehicles including ships.

In these systems, the possibility of bidirectional power flow between the load and energy storage systems is desirable, allowing the process of charging and discharging the storage system [13–14]. In ship applications where the power source is switched off or operates with power limitation, the battery or supercapacitor acts as the power source. Different topologies of two-way converters can be distinguished, and among them those that use galvanic isolation are particularly interesting.

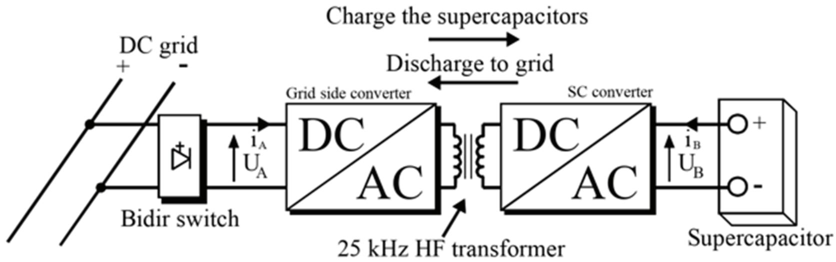

Fig. 2. The internally isolated DC-DC converter

Internally insulated dual active bridge DC-DC converter consists of two transistor converters (inverter and active rectifier) connected via a high frequency transformer to rectifier. The use of galvanic separation makes such a circuit suitable for connecting low-voltage input circuits in DC voltage sources and provides a wide range of voltage outputs. In addition, this system increases operation safety by separating the capacity of supply lines, reduces noise and ensures the correct operation of protective systems [15]. System technologies using supercapacitors and ultra-capacitors have the ability to store and discharge electricity quickly and efficiently. Super-capacitors are now widely used in many applications and will be developed more and more rapidly in the future as a result of the drive to create and use carbon-free sources. Compared to electrochemical batteries, supercapacitors have such advantages as possibility of quick charging and discharging, high power density, relatively low weight, and long lifetime. However, the supercapacitors voltage drops quickly during the discharge while in contrary the voltage of electrochemical batteries remains almost constant.

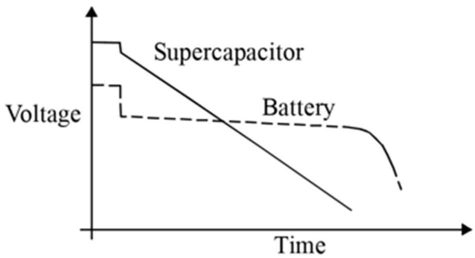

Fig. 3. Discharge voltage curve of a supercapacitor and a battery

Therefore, in order to take full advantage of the supercapacitors capabilities, connected power electronics system should provide stable output voltage over a long time [16]. The capacitors store energy in electrostatic form, and the voltage drop as current flows is essentially linear. Thus, they can be recognized as a current-based power source. They attain an efficiency of around 98% and operate without damage within a wide temperature range. Thanks to an ESR (equivalent series resistance) in the milliohm range, current peaks of several hundred to a thousand amperes are possible. The energy content of supercapacitors is calculated by the equation:

$$W = \frac{C\Delta U^2}{2} \tag{5}$$

where: W means maximum stored energy content, C denotes supercapacitor energy capacity and ΔU is the voltage swing from U_{min} to U_{max}.

The operating modes of a two-way converter can be divided into two modes: storage system charging mode and supercapacitor discharging mode. In the discharge mode, the converter works as an auxiliary system, i.e. relieving other sources such as generators driven by combustion engines and is controlled by switches of the inverter connected to the supercapacitor. In the charging mode, the converter is controlled by the charger switches on the side of the operated system [17].

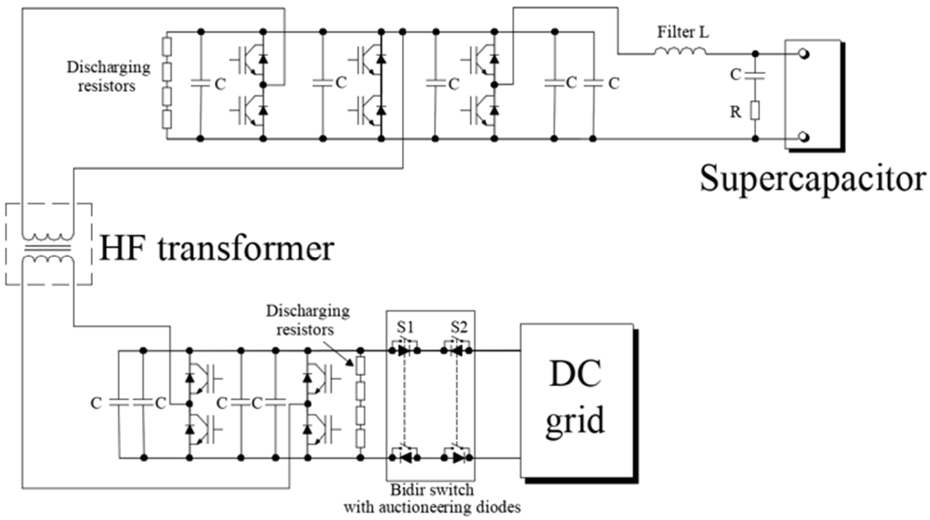

Fig. 4. Circuit of bidirectional DC-DC converter with high frequency transformer and auctioneering switch module

Figure 4 shows a proposed bidirectional DC-DC converter, which consists of two transistor H-bridges (dual active bridge – DAB in short), buck-boost converter an isolation transformer and set of auctioneering diodes. The H-bridges are acting as a 1-phase inverters which change the DC voltage into the high frequency AC waveforms needed for HF transformer. The power flow is controlled and regulated by voltage source inverters which change phase shift between primary and secondary windings. When power is needed for the DC network, the secondary side inverter changes to a phase voltage that leads phase of the primary winding. The bidirectional buck-boost converter controls the input voltage of active bridge and keeps it value on programmed level. This allows bridges to work in operating point and with a maximum efficiency. By using a double active bridge, the DAB converter allows power control by phase shifting of quasi-sinusoidal (or rectangular) voltage waves on both windings of the HF transformer. With such control, the leakage inductance of the transformer windings creates the dominant reactance, which limits the resulting current. By current limiting obtained power can be controlled and regulated by the phase shift angle φ. Due to the highly inductive character of the transformer windings, it is unavoidable that in the alternating current link, i.e. the transformer and both inverter bridges, some amount of reactive power is generated in addition to the active power. This property causes that the apparent power value of the power electronics link may be much higher than the rated active power. The apparent power value S increases especially when the voltage of both sources is significantly different.

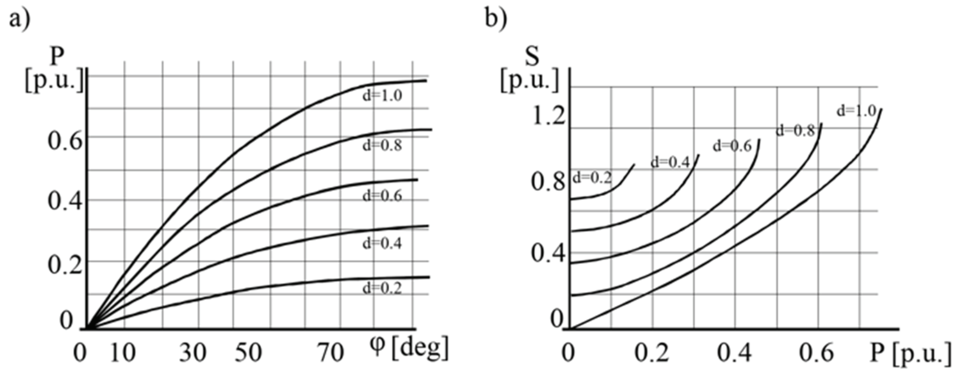

Fig. 5. Circuit of bidirectional DC-DC converter with high frequency transformer and auctioneering switch module [18]

From (5) the energy W stored in supercapacitor C depends also on squared voltage U and the capacitor voltage change is given by the following relationship:

$$\Delta U = \sqrt{\frac{2W}{C}} \tag{2}$$

It is obvious that the processes of current charging and discharging the supercapacitor will always result in huge voltage changes, which of course creates the risk of exceeding the maximum SC voltage and damaging it. Setting the lower limit of the operating voltage to half of the nominal voltage and taking into account the fact that the electrical power delivered to the DC grid must be independent of the capacitor voltage is the most important factor to take into account when programming the SC interface converter. Therefore, an additional buck-boost system is necessary to shape the DC voltage characteristics on the supercapacitor terminals in order to keep the output voltage constant. The control of this circuit is independent from other converters but can be modified according to the SC protection needs and appropriate system is presented in fig. 4. Such a connection enables current control in such a way that the current pulse phase of the DC side can be shifted by 0-180 degrees in relation to the output AC voltage and the power flow is controlled by change of the DC current flowing through the filter coil L and charging (or discharging) the supercapacitor. This control method must take into account the actual value of the SC terminal voltage.

For reasons of current control on the supercapacitor side, the analysis of system operation must be carried out using an equivalent system based on a pulse type current source. The electrical diagram of the equivalent circuit is useful for mathematical description of processes taking place in such a converter.

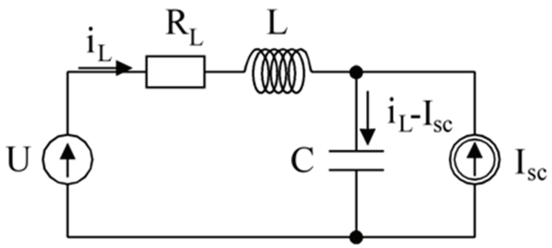

Fig. 6. Scheme of DC-DC converter equivalent circuit

From the Kirchhoff's 2-nd law regarding above equivalent scheme voltage equation becomes as follows:

$$U - R_L i_L - 2\pi f L \frac{di_L}{d\zeta} - \frac{1}{Y_{SC}} \int (i_L - I_{SC}) d\zeta = 0 \tag{3}$$

where: $Y_{SC} = \left((2\pi f)^2 L_\sigma C_{SC} + 1 \right) / 2\pi f L_\sigma, \zeta = 2\pi f t$.

On the basis of (3), a numerical model was created, which confirmed the validity of the assumptions and proved the correct operation of the DC-DC system.

The control of the converter is realized by change of current I_{SC} along with duty ratio of the current pulses produced by boost-buck converter. In order to improve overall efficiency of the system in [18] the authors proposed synchronization of the current pulses delivered by the DC-DC converter into the 1-phase inverter. Presented system seems to be most widely used solution because the dual active bridge works in one operating point thus with a maximum efficiency. The high frequency transformer provides additional boost and isolation. The main drawback are the relatively high losses due to number of used elements and components.

1.3. Operation of presented system and importance of the auctioneering diodes

The way the system operates in the supercapacitor discharge and charging mode of the proposed converter is as follows. Action of energy management system (EMS) causes that bidirectional switch S1 (see fig. 8) is closed, which makes the current flow possible in one direction through the bidirectional auctioneering diodes. In the absence of auctioneering diodes, equalizing currents would flow through closed DC-DC converter switches and other converters connected to DC busbars, making distribute the electrical load between parallel operating sources impossible.

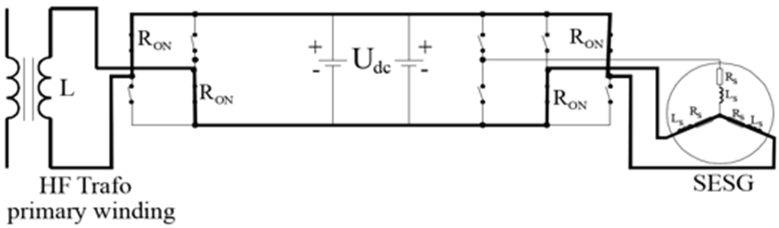

Fig. 7. Circulating currents path in absence of auctioneering diodes

The DC chopper connected to SC works in charging mode by slightly increasing the voltage on supercapacitor terminals and the same time, line side inverter shifts phase to make the power flow from DC grid across auctioneering diodes.

When energy management system needs to draw energy from supercapacitor then switch S1 closes and S2 opens. Again, the DC converter works as boost converter and by line side inverter phase change, system delivers energy to the DC grid thus takes some part of electrical load. The amount of delivered energy is controlled by synchronous generator intermediate circuit inverter which changes the DC grid voltage. There is possibility to attach another generator by intermediate DC circuit and such system operation was described in [19]. As it was mentioned the important part of the system are the auctioneering diodes. In the time when diode stops conducting snubbers may be needed. The snubbers are crucial in the case when the diode has to turn off currents with a high rate of fall of a current.

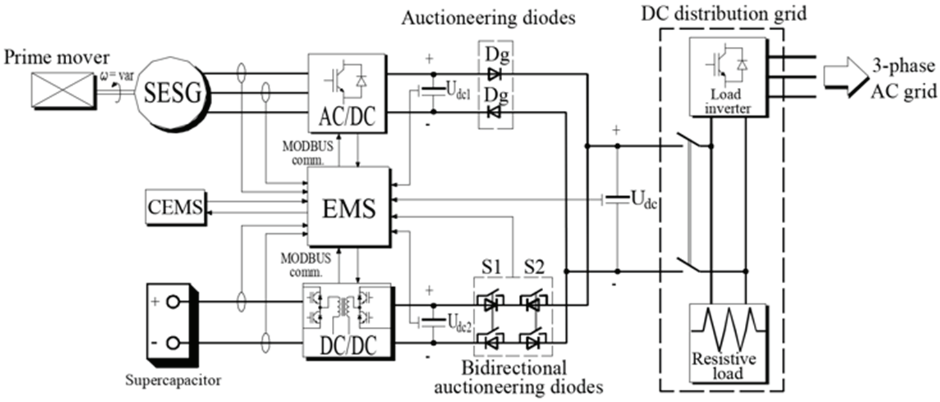

Fig. 8. DC grid connected through auctioneering diodes to the intermediate circuits of parallel- operating machine-inverter and DC-DC converter

For a short period of time a reverse recovery current flows before a diode turns off completely.

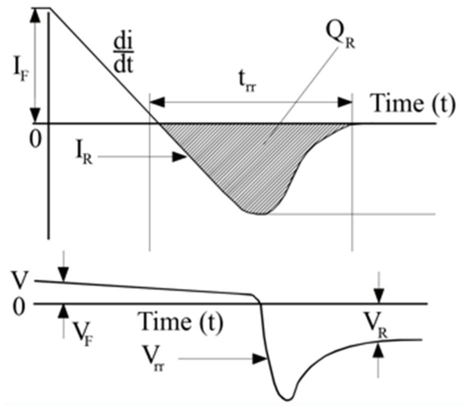

Fig. 9. Diode reverse recovery characteristic

When the fault occurs on the voltage source side, the diode current value will decrease with a rate dependent on the load side voltage and the circuitry parameters. In the case of solid short circuit on source side the value of inductance is low so the current increases very rapidly, what can damage the semiconductor structure of diode. Therefore, it is important to determine if the auctioneering diode can manage the resulting current increase ratio without a snubber [18]. Snubbers for auctioneering diodes consist of a series combination of a resistance and capacitance so they act as some kind of low frequency filters. The use of a snubbers can result in a relatively low impedance value for high-frequency current flow between two sources when the diode is switched off. The interaction of snubbers with the source the load filters and a power electronic converter should be checked each time by prior digital simulation in order to select the parameters that ensure correct operation.

2. THE SIMULATION RESULTS AND EXPERIMENTAL RESEARCHES

Due to the high level of complexity of the proposed system and the discontinuous nature of its control, it was decided to perform model tests determining the parameters necessary to program the real system. Based on the layout shown in fig. 8, a simulation system was prepared using the Matlab/Simulink environment. The model shown does not fully reflect the complexity of the real system consisting of a signal processor DSP and FPGA operating in its program interruptions. The situation is similar for communication with the energy management system, i.e. the simulation does not consider the time lags arising from communication between the control modules of the generator and the energy storage system. The parameters of the elements of the system were set the same as those used later in the laboratory experiments.

2.1. Simulation model and numerical tests of proposed system

The digital model was prepared using pre-programmed models containing machine converters and ready-made systems cooperating with super capacitors. The most interesting part of simulation model was unit modeled as a buck/boost converter connected to the model of supercapacitor.

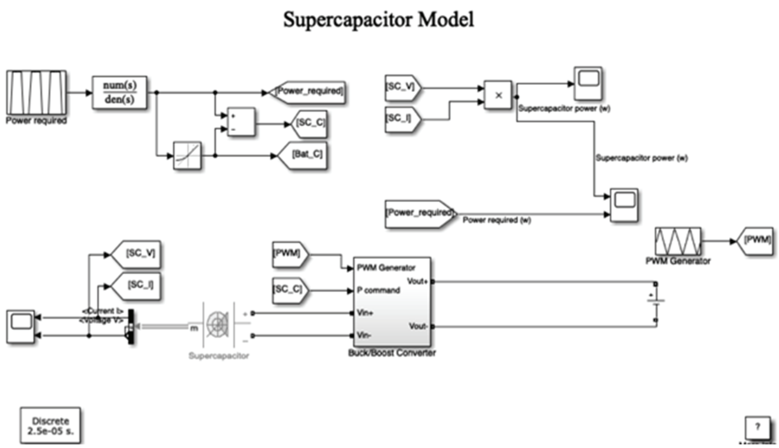

Fig. 10. The Simulink model of DC-DC converter with connected supercapacitor

The results of the simulation tests served as a source of information on the values of charging and discharging currents of the supercapacitor and also indicated the limitations of the system. The process of fast charging of the supercapacitor is non-linear and therefore the results of the simulation allowed to select the settings of the capacitor current controllers so that these values do not exceed the permissible currents generated by the machine inverter and the stability of operation would be maintained.

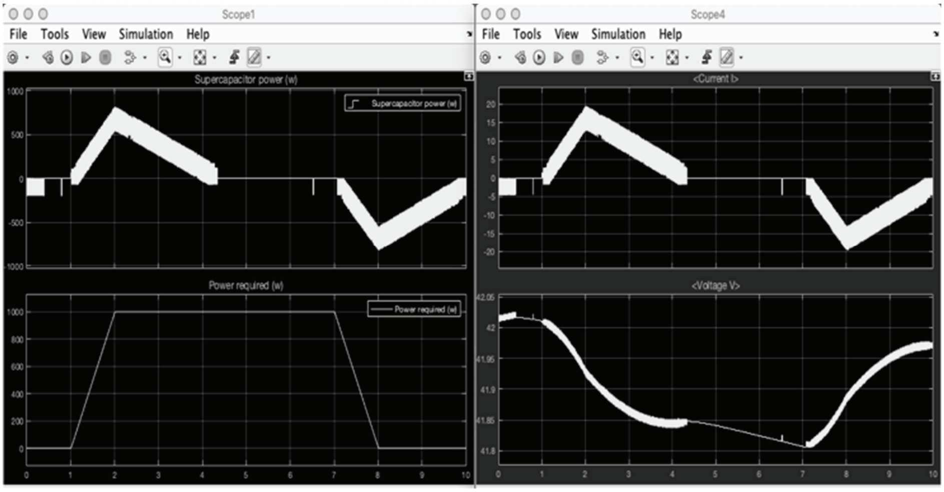

Fig. 11. Chosen simulation results of supercapacitor with DC-DC converter taking over an electrical load of 1kW

2.2. Laboratory setup and chosen experimental results of proposed system

The laboratory test bed consists an AC/DC converter of 7 kVA and a 7 kVA DC-DC internally isolated converter. The inverter use MMG50SR120B, 1200 V, and 50A IGBT module which drives the 5,5 kW machine. Capacitors of the intermediate circuit were designed to withstand a maximal voltage of 1200 V and in parallel, the total capacitance equals to 200 uF. Because of relatively small power the switching frequency was set at 20 kHz. The DC-DC converter is made of CAS120M12 SiC transistor half bridges. The bridges operation frequency was set to 25 kHz while the boost-back converter works at 20 kHz. The supercapacitor used was Maxwell BMOD0165 P048 with 165 farads at 48 volts. Chosen SC has maximum current of 1900 A and its typical applications hybrid vehicles and heavy industrial equipment are mentioned.

For voltages measurements, an LEM CV 3-1000 transducers were used. All of the auctioneering diodes were of the 16FR120M type, and they were capable to withstand 1200 volts with 16 amperes of continuous current when installed on heat sinks. The electrical loads were connected by direct current two two-poles contactors controlled by PLC. The DC-DC converter and machine inverter were equipped with digital control unit. Both of control units consisted of a SH363 processor board with an ADSP21363 digital signal processor with a FPGA board. The control programs were executed in an infinite loop in DSP, whereas an Altera FPGA board was called in processor subroutines. The ADC’s were embedded into the FPGA board and input signals coming from isolated transducers in the interrupts were directed to DSP. The FPGA digital outputs controlled the gating of the transistors through the dedicated drivers. The energy management board was based on the SH363 type processor and consisted of two boards. The FPGA board had input/output port which was electrically compatible with an industrial Modbus RS485 two-wires port. To reduce the impact of electromagnetical noise optoisolation gates were introduced into Modbus communication lines which has resulted in a significant improvement in the quality of the frames transmitted.

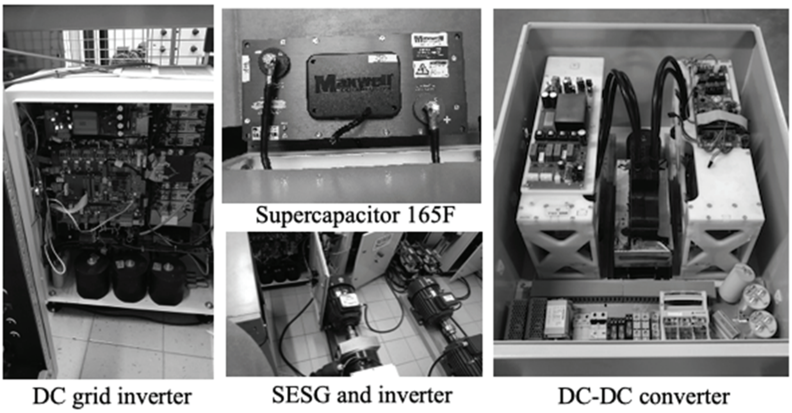

Fig. 12. Overview of investigated laboratory setup

The power sharing feature of presented system was tested in supercapacitor discharge mode. Initially the supercapacitor was charged up to 43 volts leaving safety limit in the case of possible overvoltages. Then line side inverter was turned on into operation and thanks to phase shift introduced by storage system inverter the power could be delivered to DC grid through auctioneering diodes and closed switch S2. The auctioneering diodes made impossible to reverse power flow from grid into the high frequency transformer primary winding. The filtered constant voltage on the output of the line side inverter was set at 570 volts and maintained by DC-DC converter control system. In addition, there was direct current limit as not to exceed its nominal value. Energy management system has been set up to control the amount of power generated by synchronous generator on the DC bus by changing the voltage of the inverter's intermediate circuit and applying proper current limit. First on the DC busbar was applied DC-DC convertor voltage and next some electrical load. After that the generator's inverter was put into a parallel operation taking some part of the load. The control of power sharing was possible because of slight voltage changes by power electronics control system. In the presented system it is possible to alter the DC-DC converter output voltage in order to improve the power sharing operation and voltage quality but for the sake of simplicity only the machine inverter side voltage was used to power distribution.

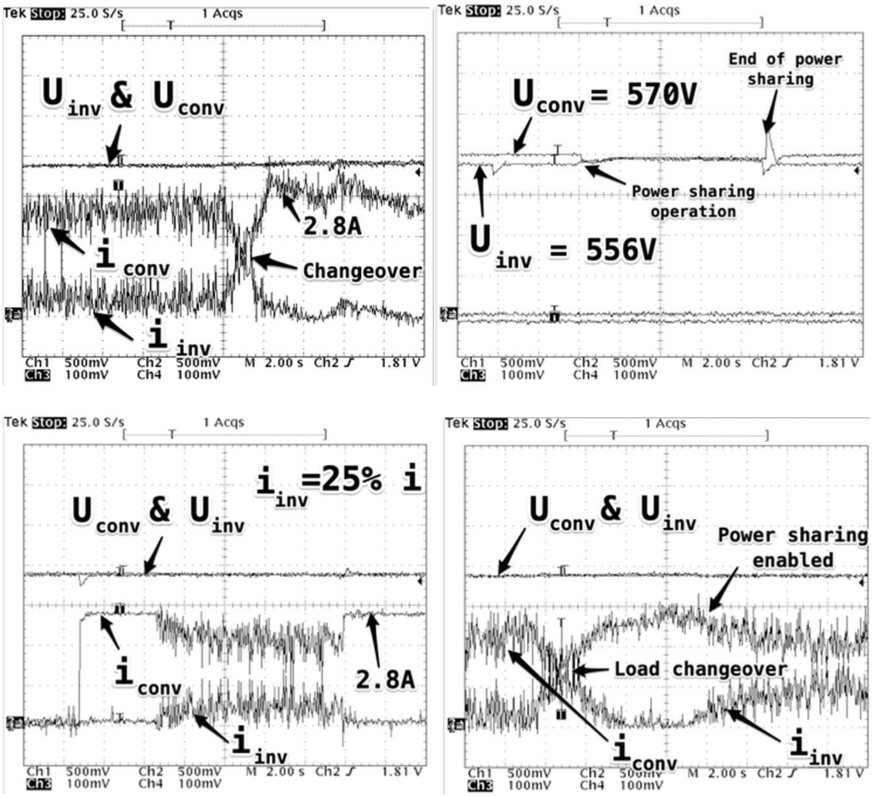

Fig. 13. Waveforms of currents and voltages while power sharing operation

As it can be observed the power distribution between supercapacitor and machine inverter thanks to use of auctioneering diodes is possible and was fully achieved what has been proved in tests. After analysis of results it turned out that there are a few important factors which should be considered when it comes to power distribution in DC grid. One of it is the importance of snubbers that should be used along with diodes. High ratio of current raise di/dt while switching between diodes causes a lot of stresses on semiconductors so to avoid them the filtering system should be carefully considered. Another unavoidable thing is heating the inner structures of diodes. Without control of switching frequency the amount of heat is quite large and in high power applications the control algorithm must take this phenomenon into account. The power distribution process itself works properly and is fully controlled.

3. CONCLUSIONS AND FURTHER WORK

The article presents selected test results of a system using a supercapacitor converter in discharge mode. The system is stable, and the proposed power distribution algorithm works properly. The obtained results encourage to further work, which will include the fast switching mode including charging processes. The proposed system will be enriched with snubbers which will improve the quality of generated energy, especially during parallel operation. As the last improvement the li-ion battery pack will be connected, and a switching system embedded.

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