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ANALYSIS OF ELECTRICAL NON-ISOLATED LOAD SHARING SYSTEMS OPERATION WITH USE OF THE AUCTIONEERING DIODES

The paper presents the background and results of numerical simulation and experimental research of a system using auctioneering diodes used to distribute the power of direct current between two power converters operating in parallel. Non-isolated power distribution systems using blocking diodes are used in the ship's electrical power systems, however, they create problems related to control and the possibility of ground faults. Another issue occurring during the operation of this type of systems is the increased heat dissipation. Selected problems related to the operation of the above systems have been identified by means of simulation studies and experiments carried out in a 11 kVA laboratory system and the theoretical basis along with results are provided in the article.

KEYWORDS: DC link, microgrids, FOC, asynchronous generator, synchronous generator, load sharing.

1. INTRODUCTION TO SHIPS DC NON-ISOLATED ELECTRICAL POWER DISTRIBUTION SYSTEMS

DC distributed power systems used onboard of specialized vessels are notable for good efficiency and high power density. They allow precise control of output voltage as needed by electrical and power electronics loads. Similar systems using direct current are proposed for aircrafts, smart grids, uninterruptible power systems and in telecommunications [1]. To increase reliability and obtain higher power level, two or more generators equipped with converters can be used simultaneously to supply the electrical consumers with means of DC distribution bus. There are examples given in the literature [2, 3, 4] of these converters-generators units working in the islanding (or stand-alone) mode but with such structures integrated with a common DC bus in parallel the potential issues which have not been discussed widely can occur. This paper focuses on parallel operation of two different types of alternating current generators connected by

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means of voltage sources inverters with the objective of control design and presenting interaction issues.

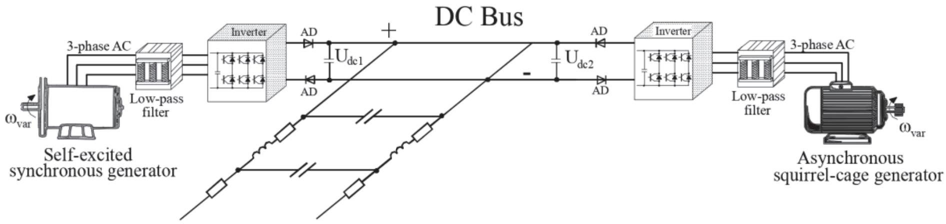

Fig. 1. An example of ship DC grid system based on a self-excited synchronous generator and an asynchronous squirrel-cage generator connected to the intermediate circuits of inverters in Master/Slave topology

The increasing output power capacity and system reliability of the uninterruptible inverter power system forced the use of parallel connected power converters. Because of wide use of such a systems there has been increasing interest in the parallel operation of converters for the reasons of fault tolerance (short circuit or ground fault of common bus) and the low-voltage with high currents demands for power supplies. Many of applicable topologies and proper control schemes have been presented in [5, 6, 7], however, there are only a few papers that are focused on parallel operation of non-isolated AC/DC converters and uneven power sharing.

In this paper, control techniques of asynchronous and self-excited synchronous generators connected with intermediate circuits are shown. Popular so-called master/slave control technique is used to ensure proper and tight electrical load sharing. Some modules interaction possibilities and thermal issues in the auctioneering diodes are presented in section 3. The simulation and experimental results are summarized in section 4.

2. PROPOSED SYSTEM CONSISTING OF INVERTER-GENERATOR SETS TIED WITH DC CIRCUIT

There are different methods leading to redundant connection of DC voltage sources. These methods incorporate isolation, high frequency transformers or semiconductor auctioneering diodes. The auctioneering diodes are widely used to separate power sources so that a single source failure will not bring down the entire system [7]. In the presented system diodes are necessary to avoid flow of circulating currents between machine windings and inverters. Systems incorporating auctioneering diodes are used to distribute power between renewables and their power converters. In such a system combination of parallel connected voltage sources acts as one large supply with controlled equal load on each of the units. There are several schemes designed to achieve load sharing between electrical voltage sources. The most common passive and active techniques are presented in [8]. The power-sharing techniques are suitable for the units supplying the systems in a reliable manner. The methods of implementation of power sharing are described in [9] but given the autonomous local control of the voltage sources, the focus was on droop methods.

2.1. Self-excited synchronous generator properties and the machine inverter FOC control method

The principle of the synchronous generators control with independent excitation winding involves the frequency and voltage control by adjustment of the active and reactive power. Such type of operation is considered as a scalar control procedure, which omits the coupling effect between the electrical axis found in the self-excited synchronous generator [10]. One of the suitable methods, is vector control based on the field orientation principle operation. Due to use of vector control, AC machine performance during operation becomes similar to that of DC machines. The mathematical background of the dynamic model and vector control of an AC machine is illustrated by the space-phasor theory [11], [12]. The rotor flux oriented synchronous machine model resembles a shunt excited direct current machine. It is suitable for the simulation of the synchronous generator operation however the control is implemented by means of a field oriented model, considering the stator flux. This model is analogical with a compensated DC machine, which allows the control of the two variables that produce the machine torque [11, 12, 13].

In a constant torque angle control maintain strategy, the current value in d-axis current is kept at zero. The vector of active current is aligned with the q axis. The torque equation for a self-excited generator, considering both i_{sd} and i_{sq} currents, can be depicted with equation:

$$T_e = \frac{3}{2}\boldsymbol{p}\left[\Psi_m i_{sq} + \left(L_d - L_q\right) i_{sq} i_{sd}\right] \tag{1}$$

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. Substituting the d-q currents in equation (1) and after applying some simplifications, the torque equation is given with:

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

By the linear dependency between machine torque and the active current the FOC control of the synchronous generator can be implemented. The i_{sq} control loop in the d-q coordinates provides a constant value for DC intermediate circuit voltage U_{dc}, while the reactive current i_{sd} is set to zero due to the creation of magnetic flux. In the presented system, to obtain the rotational speed and stator field angle value needed for the Clarke and Park transformations, a sensorless system was used however, in many commercial applications, the use of an encoder is preferred. The rotor position angle can be estimated by integration of the rotational speed [14].

A 5,5 kW self-excited synchronous generator driven by another electric motor was used as investigations object. In order to obtain a suitable DC voltage level, the electric generator was controlled in a certain way. Because of self excitation and feeding the voltage regulator by a embedded compound transformer independent control of the active and reactive currents was not needed.

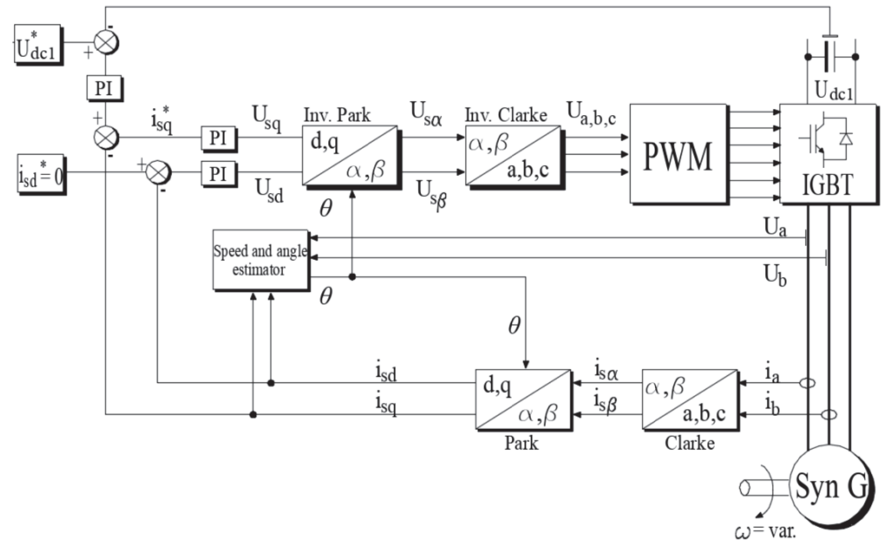

Fig. 2. The scheme of the field-oriented control structure of self excited synchronous generator

However, because of DC voltage regulator action, the process of excitation started from 250 V (rectified voltage on intermediate circuit) and voltage value was increased to 560 V only by i_{sq} current control.

2.2. Asynchronous generator properties and nonlinear multiscalar control

To control an asynchronous generator the special algorithm prepared for the inverter, supporting independent control of the magnetizing and active current was created. The control method chosen for this particular case was a multiscalar algorithm. The multiscalar control technique [16] utilizes variables like such as currents, voltages, and fluxes presented in the α-β plane and Park transformation is not needed. It can be assumed that every vector control scheme applied to a squirrel-cage alternator utilizes a numerical machine model (simulator or observer), because variables such as machine slip must be estimated.

The cross references in machine equations describing currents in the α-β planes can be eliminated via nonlinear control of the asynchronous generator. The coordinate change proposed in [16] for the rotor flux vector model transforms the induction motor model into a multiscalar model.

$$x_{11} = \omega_r \tag{3}$$

$$x_{12} = \Psi_{r\alpha} i_{s\beta} - \Psi_{r\beta} i_{s\alpha} \tag{4}$$

$$x_{21} = \Psi_r^2 \tag{5}$$

$$x_{22} = \Psi_{r\alpha} i_{s\alpha} + \Psi_{r\beta} i_{s\beta} \tag{6}$$

where x_{11} is the rotor speed, x_{12} is the variable proportional to electromagnetic torque, x_{21} depends on rotor flux value, and x_{22} represents the so so-called magnetized variable [16]. As it can be seen the asynchronous generator torque is independent of the rotor flux position and stator current in any reference plane so the generator torque depends on the mutual position of the vector flux and stator currents.

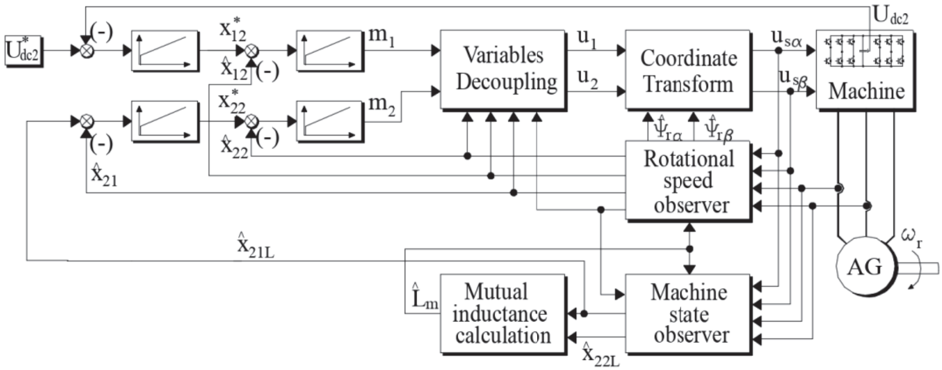

Fig. 3. The scheme of the nonlinear multiscalar control structure of asynchronous alternator

The speed of rotation is needed for further rotor angle calculation and precise DC voltage control. The value of the generator's rotational speed can be calculated by using the following formula, which includes the correcting coefficients ε_1 and ε_2 previously estimated in the speed observer:

$$\hat{\omega}_r = \frac{\varepsilon_1 \hat{\Psi}_{r\alpha} + \varepsilon_2 \hat{\Psi}_{r\beta}}{\hat{\Psi}_{r\alpha}^2 + \hat{\Psi}_{r\beta}^2} \tag{7}$$

Following an estimate of rotor speed and variables that control machine torque and magnetizing currents, regulator outputs are feed the decoupling equations for the system with variables designated m_1 and m_2. The outputs of the decoupling system generate signals for the modulator controlling the machine side inverter. The error signal creates the coefficients needed in the x_{12} regulator needed to produce required DC voltage value. The x_{22} variable depends on rotational speed and changes in the field weakening region (if needed) to obtain constant power.

2.3. Specific connection of non-isolated DC intermediate circuits and power sharing method

In the investigated system, auctioneering diodes are placed in series with the positive and negative inverters outputs. This prevents circulating currents from flowing through inverters and machines windings and allows power sharing between parallel connected converters.

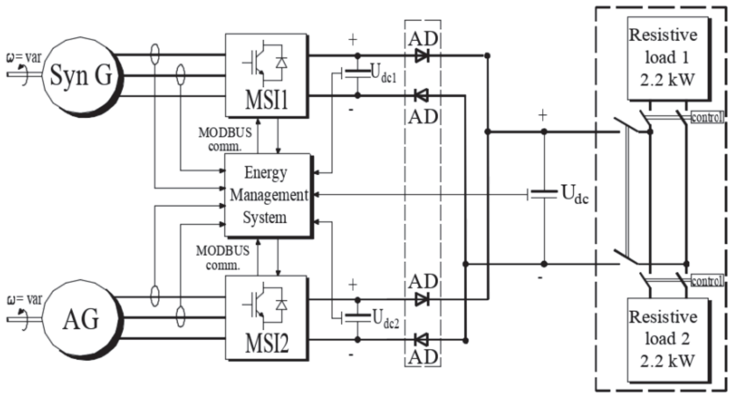

Fig. 4. DC distribution grid equipped with energy management system (EMS) connected through auctioneering diodes (AD) to the intermediate circuits of parallel operating machine side inverters MSI1 and MSI2

When one of the generators is set as the master, its voltage U_{dc1} is maintained for the common bus and consumers while the current limitation not exceeds the nominal value of the machine side inverter. To get the other generator into parallel operation its voltage U_{dc2} must be kept below bus voltage U_{dc}. Because of this in the idle operation second (slave) generator does not deliver power to the common DC bus. Due of auctioneering diodes action, the intermediate circuit of second inverter is not charging. When the signal commanding power sharing operation shows up, the DC voltage regulator of the slave inverter increases U_{dc2} and its voltage extends the bus voltage U_{dc}. From this moment on the paralleled unit takes over part of the load. It is clear that with higher generated voltage, the greater load is taken by the inverter and generator. Because of the impulse-like charging currents there is some disturbances in resulting DC voltage, the auctioneering diodes are switching on and off continually which is the main reason for increased heat dissipation. Moreover, the silicone-based diodes are characterized by a negative temperature coefficient therefore so without a current limiting a load increase would occur.

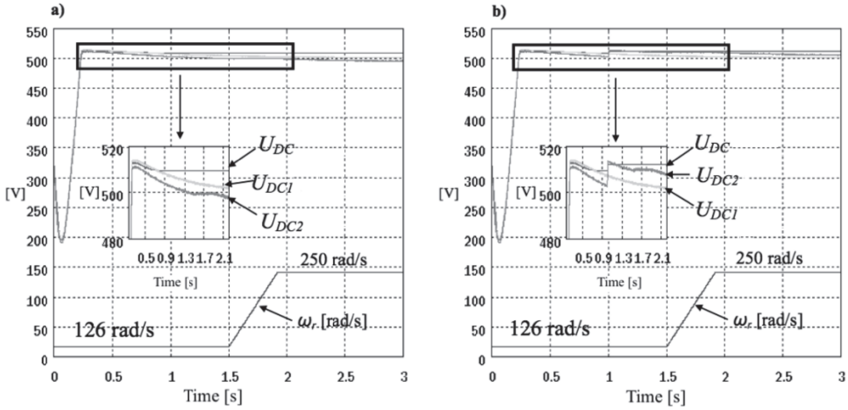

Fig. 5. Simulation results of small DC voltages commanded to inverters during power sharing operation [17]

Differences in the voltage values commanded to inverters during power distribution are small, therefore, to achieve precise management of load sharing, the control system was the basic system has been enriched with an additional PI regulator. In the main algorithm the DC voltage is kept at a constant, fixed value.

2.4. Experimental results of uneven load sharing

To verify the developed power sharing method, the proposed system was subjected to laboratory tests. The tests were performed to check the asynchronous generator in an island operation. The switching on of the asynchronous inverter was preceded by charging of the initial capacitors from rectified 3-phase AC voltage to 600 volts.

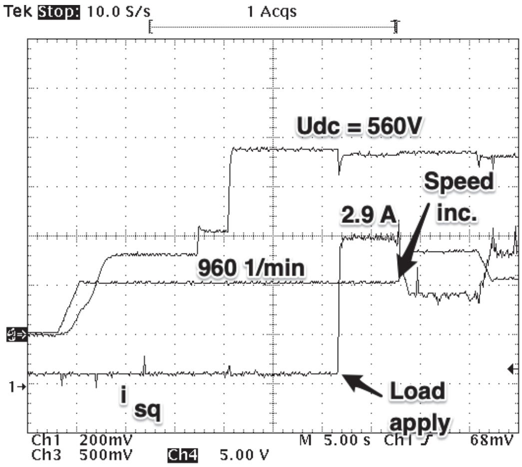

Fig. 6. Waveforms of DC voltage, active current, with load apply application and load shedding during rotational speed changes

The following tests were performed to check the asynchronous generator in a stand-alone. The switching on the DC bus of the inverter was preceded by initial charging of the capacitors to 600 volts. Next after the excitation process, the contactor was set to open position and all electrical energy was drawn out of capacitors.

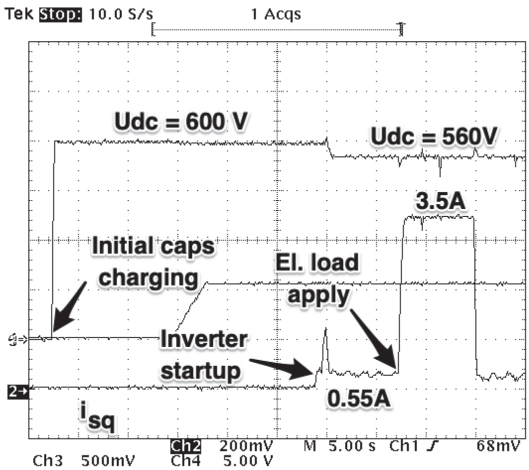

Fig. 7. Effects of 1.5 kW resistive load apply and load shedding of the asynchronous generator during island operation

To prove the robustness of sharing current-sharing algorithm with an additional PI voltage controller, two types of alternators were connected through auctioneering diodes to a common bus. The voltages on inverters intermediate circuits were maintained at 560V. The resistive load was applied to the asynchronous alternator which was acted as a “master”. Next the generator was connected to the common bus and set into power sharing mode. The DC voltages has increased, and the extra PI regulator embedded in the control unit pulled the voltage up to value limited by the active current.

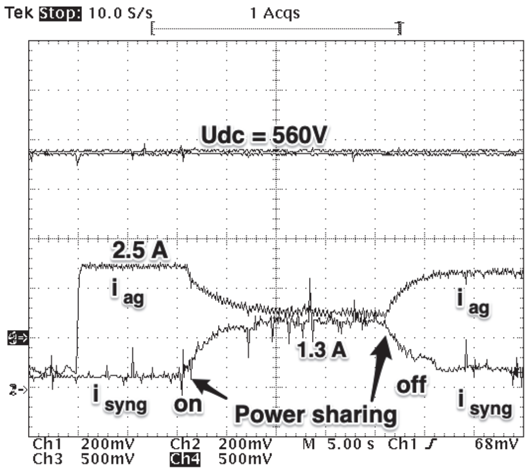

Fig. 8. Waveforms of DC quantities and load sharing between two generators in constant RPM operation

The active current limit was set that all the power was taken by the slave generator. The slave alternator was commanded to drop notable part of the load so the increase in the load share of the master generator was observed.

3. THERMAL CONSIDERATIONS OF AUCTIONEERING DIODES

A space charge enclosed within a semiconductor junction has to be prepared before the forward current flow. The aforementioned space charge can be established in short time because an applied biasing voltage can route electrons externally. Because of this negative charges diffuse from the n-type side into the outer layer of the p-type junction side when the so-called holes in the p-type material diffuse into the edge of the n-type side, and at the metal interfaces, the electrons are injected into the n-type end while the holes are generated at the p-type material to produce negative charges (majority carriers - electrons) that can flow in the external circuit. Flow of this charges can be considered as majority carriers flow in regarding materials, so diffusion occurs in very short time. A space charge is created because majority carriers are flowing to turn the diode on specifically electrons in the n-type end, and holes in the p-type side of crystal structure of semiconductor material. The charges flow in the reverse recovery time is referred as "reverse recovery charge" and the diode has to shut it off (so it's the "recovery" from reverse to neutral state of junction) before it can be turned on. The process of reverse recovery depends mainly on silicon doping and junction geometry and is considered as a parasitic effect in diodes, because energy involved in such a process is lost and some of it is dissipated in the form of the heat.

In order to check the influence of this phenomenon on the operation of the proposed system, the surface temperature of the operating auctioneering diode casing was measured with the thermal camera. The first measurement was performed on the diode operating in stand-alone mode. The diode was conducting all the current drawn by electrical load with no additional, parallel voltage source connected. Next experiment was conducted in a way that both generators were connected in parallel but the current drawn by investigated diode was the same as in previous test. All the lasting current was covered by the second inverter.

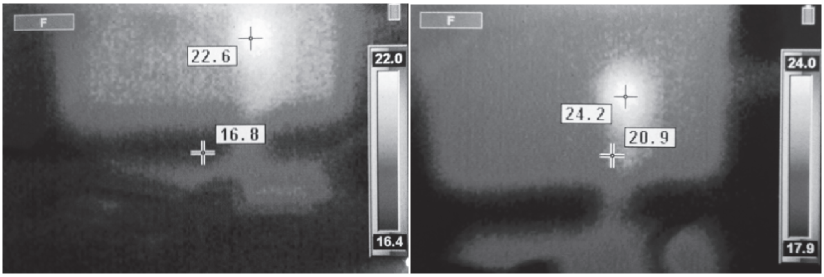

Fig. 9. Thermal images of auctioneering diode working in stand-alone mode (left) and in parallel (right) when conducting the current of the same value. (Ambient temp. 20.2°C)

The examined diode was mounted on passive radiator selected to match loses and dissipate it efficiently. As it can be seen in figure 9 the temperature of parallel operating semiconductor diode is notably higher in comparison to islanding mode (24.2° C vs. 22.6 °C) so the means needed to dissipate extensive heat must be always provided. There were 12 subsequent tests conducted providing exactly the same results.

4. CONCLUSIONS AND FURTHER WORK

On the basis of the results of the experimental studies it is clear that system consisting of two alternators can operate in parallel connection of their intermediate circuits for a long period of time. An appropriate control technique allows use of wide-range variable speed generators.

The amount of power dissipated in auctioneering diodes is higher in parallel operation in comparison to island mode therefore this type of system definitely requires more efficient cooling. The introduced PI regulator enables the fine regulation of a DC bus voltage, and precise active current limitation.

Despite some obvious disadvantages further work will be carried out in order to identify thermal problems. Tests will be performed with the use of permanent magnet generator and a bi-directional isolated DC-DC converter with a battery of accumulators and ultracapacitors.

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