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APPLICATION OF SELF-EXCITED SYNCHRONOUS GENERATOR WITH INVERTER AS DC GRID VOLTAGE SOURCE

Self-excited generators are the most popular voltage sources installed onboard of modern ships. Because of fuel savings on some specialized vessels (PSV, cable layers etc.) varying revolutions drives are used and this trend seems to increase. Very interesting issue is use of such type of alternator working with inverter acting as rectifier in DC grid system. As the control method most suitable to use is modified field oriented control known from induction machines. This control method involves decoupling of currents and control voltages to flux and torque components and keeping them in optimal (orthogonal) condition. Theoretical background of inverter and synchronous generator adopted FOC control method along with experimental results obtained in laboratory of such system were presented.

KEYWORDS: Self-excited generator, FOC control, DC grid, controlled voltage source.

1. PROPERTIES OF SELF-EXCTITED SYNCHRONOUS GENERATOR WITH VOLTAGE REGULATOR

The 7 kVA self-excited synchronous generator (SESG) driven by squirrel cage motor was used for purpose of investigation. To obtain proper intermediate direct current voltage level electric generator has to be controlled in certain way. Because of self-excitation and use of the compound transformer feeding voltage regulator in synchronous generator there is no need to independent control of reactive current control so the field oriented control (FOC) algorithm was chosen. Compound transformer is very important part of investigated system because it assures proper excitation current that is composed of vector sum of resulting phase voltages and currents

In Fig. 1, the scheme of a brushless self-excited synchronous generator with compound excitation system and a voltage regulator is presented. The excitation winding of the synchronous generator receives power from the rotating rectifier, which is powered by a secondary coil of the compound current transformer. The compound transformer contains current coil ($coil_I$) and a voltage coil ($coil_U$). The

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summation of the both coils signals is done by the compound elements which are in this case the capacitors. Compound element converts $coil_U$ from a voltage source into a current source and shifts the phase (by about 90°) of the voltage signal.

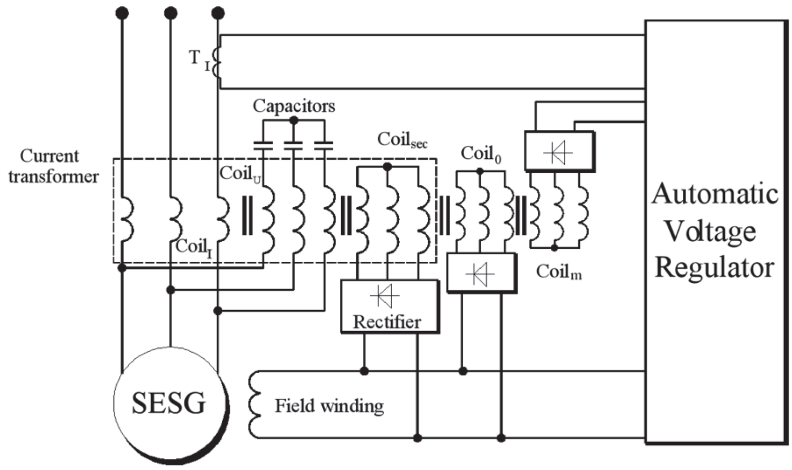

Fig. 1. Scheme of automatic voltage regulator with compound transformer [2]

To ensure a proper initial self-excitation of the synchronous generator, an additional coil, which powers the excitation coil (field winding) through a rectifier, is provided.

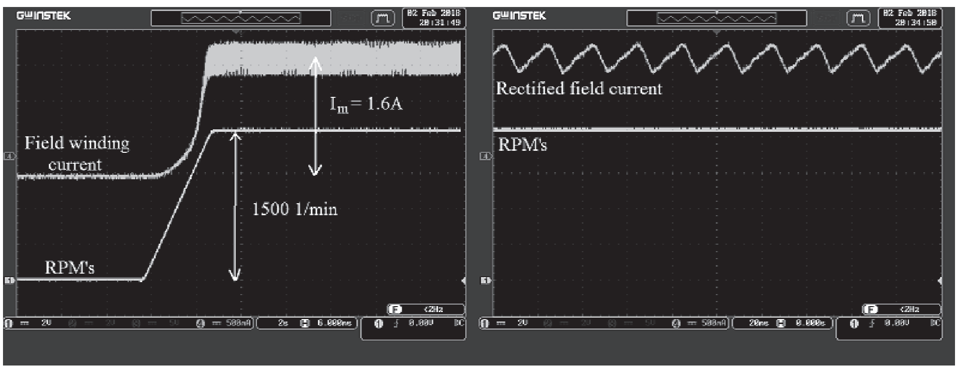

Fig. 2. Influence of rotational speed on field current and waveforms close-up of rectified field winding current

The compound transformer is designed to provide a higher voltage than the nominal one within the range from an idle to an initial load. The automatic voltage regulator selects the redundant power above the nominal voltage, so the regulation is done by decreasing current for most of the operation time. Simpler type of excitation unit is used in investigated system. It does not contain additional winding ($coil_0$) nor induction exciter with rotating rectifier.

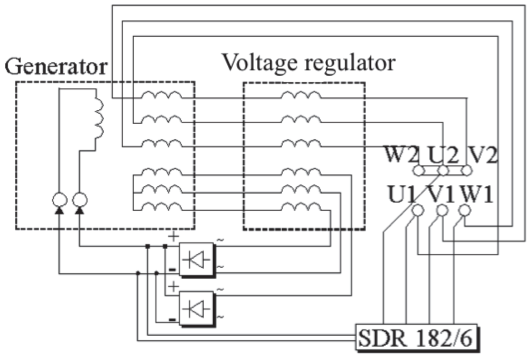

Fig. 3. Scheme of voltage regulator embedded in investigated system with compound capacitors denoted as SDR 182/6

All excitation direct current flows through two slip rings and brushes from voltage regulator into excitation windings. Still it is compound exciter which utilizes information of currents, voltages and phase shift to create proper, depending on load power factor rotor current. Most of synchronous generators with regulators are designed for continuous work with almost constant rotational speed, thus the speed change results in voltage changes. As it can be seen in the Fig. 3. while no-load startup process generator's voltage changes in nonlinear way.

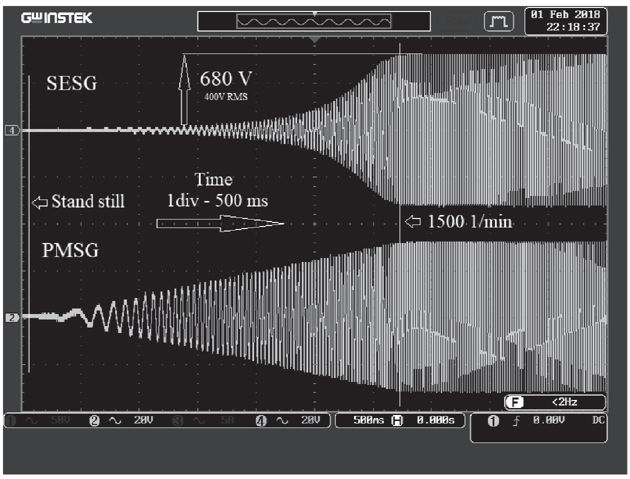

Fig. 4. Startup voltage of self-excited synchronous generator (SESG) compared to permanent magnet generator PMSG

In contrary permanent magnet synchronous generators have more linear dependence between rotational speed and generated voltages, so PMSG's slightly altered control techniques can be used for synchronous generators with compound voltage regulators. This property leads to conclusion that such type of generator can operate in limited range of rotational speed then PMSG.

1.1. Principle of synchronous generator operation

The classical control principle of the synchronous generators with independent exciting winding is well known, considering the frequency and voltage control by means of the active and reactive power adjustment. The active power is coming from the mechanical drive such as Diesel or gas combustion engines while the reactive power is commanded and controlled with the DC current excitation winding and voltage regulator. In most case the two control loops are operating separately each to others with use of RPM's governor and voltage regulator. This kind of operation may be considered as a scalar control procedure, which disregards some phenomena, i.e. the coupling effect between electrical axis the synchronous generator [1]. The vector control is based on the field-orientation principle. It can be used as an AC induction motor drives control, but also for squirrel cage generator running. Because of its performance during transient operation modes, it comes quite close to direct current machines. The mathematical background of the dynamic model and vector control of AC machine is given by the space-phasor theory [1], [5]. Thanks to field oriented control simplicity of DC machines control got into the AC motors and generators methods. The rotor flux oriented synchronous machine model is similar to a shunt excited direct current machine. It is suitable for the simulation of the synchronous generator operation, but the control will be realized with the field oriented model considering the resultant stator flux. This model leads to the analogy with the compensated DC machine, which allows the independent control of the two variables that produce the machine torque [1], [4], [5], [6]. In Fig. 5 there are shown the stator field oriented components of the stator current:

$$i_s = i_{sd\lambda} + \mathrm{j}\, i_{sq\lambda} \tag{1}$$

while the armature coil flux equals to:

$$\Psi_{ss} = \Psi_{ssd\lambda s} + \mathrm{j}\,\Psi_{ssq\lambda s} = L_{md} i_{sd\lambda} + \mathrm{j}\, L_{mq} i_{sq\lambda} \tag{2}$$

where λ_s is the angular position of the resultant stator flux Ψ_s.

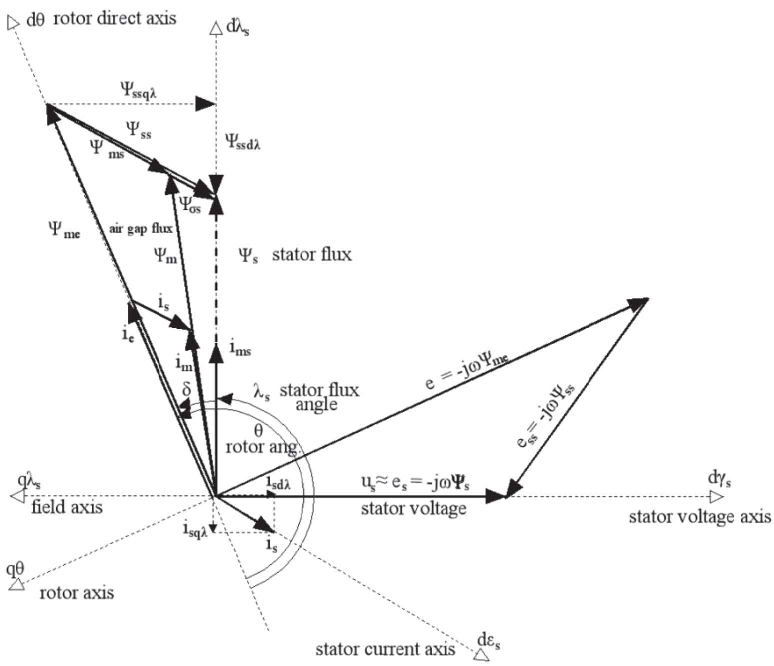

Fig. 5. Diagram of the synchronous generator with leading stator current, and the stator-field oriented space phasors of the stator current [1]

In generating mode, the quadrature component of the armature flux $\Psi_{ssd\lambda}$, which determines the active power and dc intermediate circuit voltage will be negative due to the reversed active energy flow. Flux denoted as $\Psi_{ssq\lambda}$ is also negative, due to its demagnetizing character. This flux corresponds to the reactive power. The exciting current has influence on an active component, which produces the torque in the air-gap. Because of decoupled control the longitudinal component of the field oriented exciting current contributes to the magnetizing phenomena in the synchronous machine. Neglecting the stator resistance, the triangle of the machine powers become also similar to that of the stator currents [1]. In such a case, active and reactive power can be controlled independently by means active and reactive stator current components. To control the power flow, the stator current has to be oriented according to the magnetizing direction of the resultant stator flux $\Psi_{ssq\lambda}$, realized by a Clarke and Park (α-β and d-q) transformations (see Fig. 7).

1.2. Synchronous generator FOC control properties

In order to have a simpler control for SESG some simplification have to be taken into consideration regarding the produced torque. The load torque can be controlled by controlling the torque angle. In the constant torque angle control strategy, the d axis current is kept zero for all of the operation time, while the vector current is aligned with the q axis in order to maintain the torque angle equal to 90°. This is one of the most used control strategy because of its simplicity. The torque equation for a SESG, taking into account both i_{sd} and i_{sq} currents is the one derived in:

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

where: p is a number of pole pairs and ψ_m is field winding flux.

After substituting the *d-q* currents in equation (3) as presented in Fig. 6 and after a few simplifications the torque value is the one presented in equation (4).

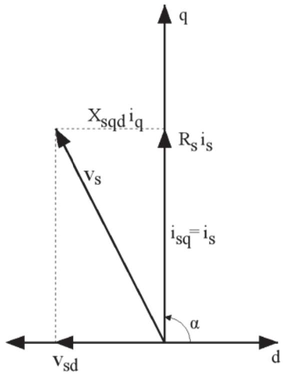

Fig. 6. Vector diagram for constant torque control of SESG in steady state operation [6]

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

From above equation it can be easily observed that the control property is very simple to implement, just by representing the linearization between the torque and machine current.

2. INVESTIGATED SYSTEM WITH GENERATOR CONNECTED TO THE INVERTER

Control technique is based on FOC method known from induction motors drive applications. Main advantage of proposed method is possibility of intermediate voltage control with means of control active current loop.

In a manner of field oriented control there can be independently controlled active and reactive currents. Active current i_{sq} control loop in *d-q* coordinates provides constant DC link voltage U_{dc} value, while reactive current i_{sd} is set to zero because of rotor current creating magnetic flux. In addition, there is calculating block (Machine equations – see Fig. 7) which can be useful in case of sensorless control of generator. In the investigated system incremental encoder was utilized to obtain rotational speed and stator field angle needed in Park and Clark transformations.

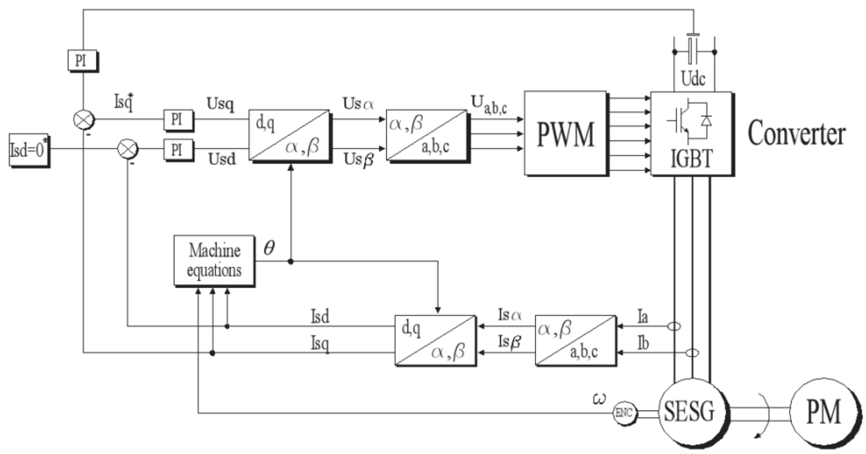

Fig. 7. Vector control structure of the self-excited synchronous generator with stator-field orientation

The core of FOC is use of transformations calculated in real-time. Using of space vector properties there's possibility of projection sinusoidal balanced three phase quantities as easy to control constant values of currents, voltages and fluxes. For example, space vector x_s representing aforementioned quantities can be expressed by two-phase magnitudes called x_α and x_β in the real-imaginary complex plane. Mathematically this relationship can be written as:

$$\overline{x_s} = x_\alpha + jx_\beta = \frac{2}{3}\left(x_a + ax_b + a^2 x_c\right) \tag{5}$$

The *α-β* components of the space vector can be calculated from the *abc* magnitudes according to:

$$x_\alpha = \mathrm{Re}\left\{\overline{x_s}\right\} = \frac{2}{3}\left(x_a - \frac{1}{2}x_b - \frac{1}{2}x_c\right) \tag{6}$$

$$x_\beta = \mathrm{Im}\left\{\overline{x_s}\right\} = \frac{2}{3}\left(\frac{\sqrt{3}}{2}x_a - \frac{\sqrt{3}}{2}x_b\right) \tag{7}$$

Another very useful set of equations transforms stator phase quantities from the stationary *abc* reference frame to the *d-q* reference frame which rotates with the rotor is called Park transform.

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{8}$$

Equations given in 4-8 are hard coded into VDSP++ and executed in real time just to obtain values of currents and voltages needed for easy control machine inverter and DC link voltage. To proper operation of algorithm there is need for rotating frame angle θ calculation. To obtain rotor angle it crucial to know value of rotational speed of the shaft. In this particular system of synchronous generator in the steady state angle is calculated with utilizing trigonometric functions and α-β plane voltages and currents. In the literature there are shown indirect methods of calculating rotor position angle by integration of the speed or using machine state simulators and observers [3].

2.1. Stand-alone work of the generator in dc intermediate circuit voltage control loop

While in so called island operation synchronous generator works in the principle of maintaining constant DC voltage on inverter's intermediate circuit capacitors. Because of nonlinear flux current dependency on rotational speed there is minimal value of generator RPM's which ensure proper excitation and operation.

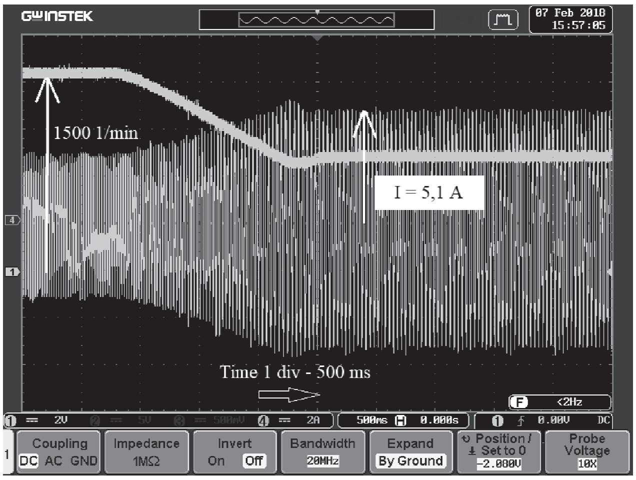

Fig. 8. Change of generator phase current due to speed decrease (1500 min^{-1} down to 900 min^{-1}) under resistive load of 2,1 kW.

In presented system minimal speed of operation was set to 800 RPM's. Unlike in the generator working with constant speed the resulting electrical power depends on temporary rotational speed and this relationship is included in the machine inverters control algorithm. The control method is based on real time rotor angle calculation and instant inverter frequency changes. With increasing load, the voltage frequency changes to the stable point of operation. While stand-alone operation intermediate circuit voltage U_{dc} changes with load applying for short time needed by PI regulators to set error value to zero. The electrical load applied to DC bus can vary in wide range so the values of proportional term should also change.

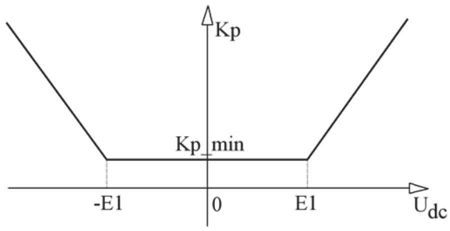

Fig. 9. Dependence between proportional gain term and DC bus voltage error

With significant error value in actual DC voltage while transient processes values of proportional gain i_{sq} changes in the manner shown in Fig. 9. When DC voltage error increases above minimal allowable level proportional term is getting more significant so the set voltage value can be obtained in shorter time. When DC voltage signal error decreases proportional gain term also decreases so the voltage overshoot is relatively small and the oscillations are getting negligible.

3. USE OF AUCTIONEERING DIODES

To prevent circulating currents flow through conducting transistors of the SESG inverter and another converter connected in parallel the auctioneering diodes must be implemented into the power circuit [5]. This is especially important while paralleling generator in DC power grid. Such systems are widely used in power electronics circuits with controlled rectifiers and power diodes.

As it can be seen in Fig. 10 placing only one diode on positive output would be fair enough but in presented system was used another approach. Auctioneering diodes are placed in series with both the positive and negative output feeds. Although the negative leg diode adds losses to the system this approach has some advantages especially while ground fault operation.

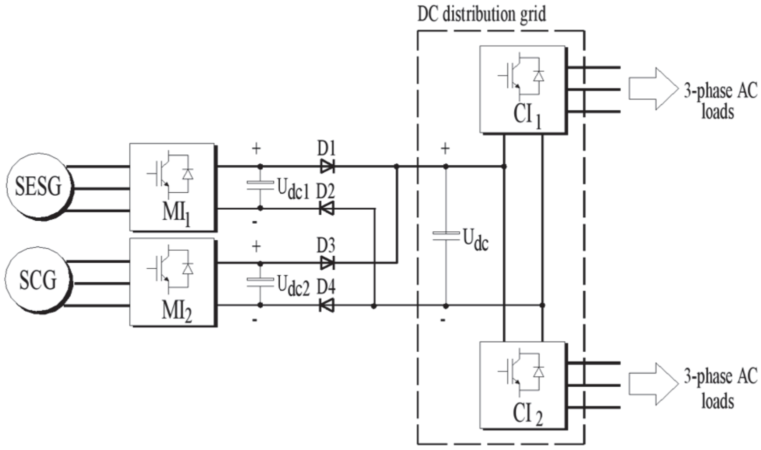

Fig. 10. Scheme of proposed system with use of auctioneering diodes

Since symmetry is desirable in systems that involve switching power conversion, common mode and differential mode behavior is important. The consideration of the dual ground fault scenario leads to following conclusions. Auctioneering diodes in the positive feed only will mitigate voltage doubling stresses on downstream loads during a dual ground fault of opposite polarity on opposite buses and the asymmetry of auctioneering diodes in the positive feed only will lead to high common mode circulating currents between DC/DC converters that needs to be managed by converter controls and protections [6].

3.1. Parallel work of the self excited synchronous generator in dc grid

Auctioneering diodes allow parallel operation of SESG along with other direct voltage sources like DC-DC converters or other types of generators and controlled rectifiers in DC grid. In the investigated system as other DC source asynchronous squirrel cage generator (SCG) with its machine inverter was chosen as it is shown in Fig. 10. In such a grid all of the AC consumers must be equipped with dedicated inverters but lack of transformers and other accompanying devices reduces weight and size of ships electrical system of about 30%. Another great benefit of using DC system working in parallel is possible use of batteries and work with varying rotational speed. Such system doe not require synchronizers because connecting other DC sources is based on slight changes of voltages to the level of common bus voltage. Another great thing about presented system is robust power distribution algorithm. Generator denoted as SCG in Fig. 10 while parallel grid operation works as a so called “master” and controls level of DC bus voltage. Because of its power (this is weak grid) level of maintained voltage changes slightly according to electrical load. Synchronous generator in parallel mode works in power sharing mode. There is limit set on active current i_{sq} and in case of exceeding this value voltage drops so load of generator and inverter decreases too. This method allows connection theoretically unlimited number of converters and generators equipped with current control algorithm.

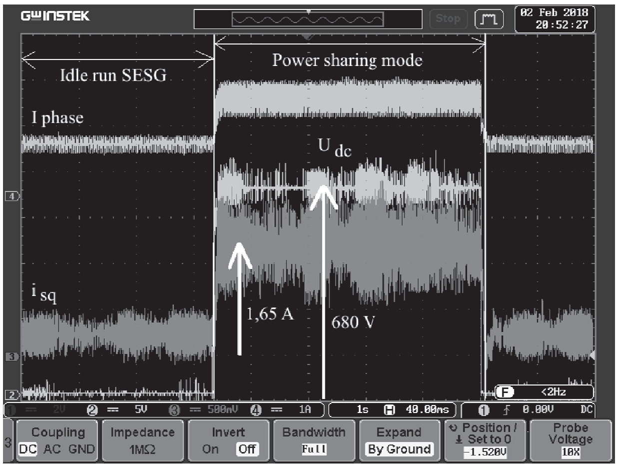

Fig. 11 Process of parallel connected SESG load sharing

In parallel operation control algorithm can be set to distribute power between SESG and another source in order to synchronous generator rotational speed change and such type of control is shown in Fig. 12.

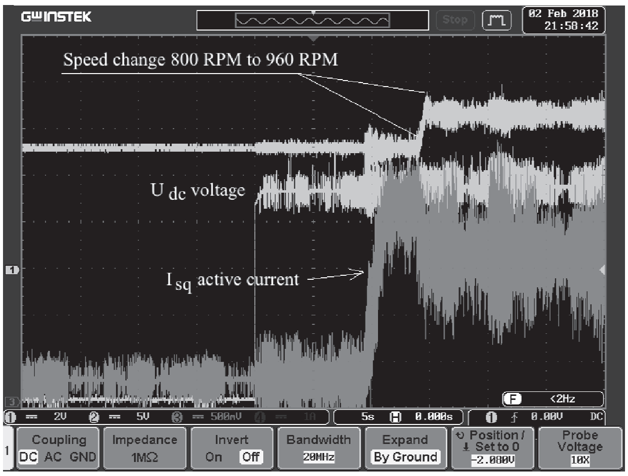

Fig. 12 Process of parallel operation SESG in power sharing mode while rotational speed change

As it can be observed that with rotational speed increase active current value drops because the amount of generated power is still the same. What is important all characteristics can be customized for flawless work with digital energy management system and digital governors to obtain optimal fuel consumption by prime movers [5].

4. CONCLUSIONS AND FURTHER WORK

Proposed system including variable speed generators in altered versions is now tested onboard of few seagoing specialized vessels. Estimated fuel savings values are in range between 22% and 30% depending on the ships work conditions. As it was proven in laboratory test bench system is very stable and DC voltage variations does not exceed 5% in steady state and 10% in transient operation. Further work will focus on integrating ultracapacitors with controlled DC-DC converter to presented system. Thanks to its properties, the system will be further developed towards further optimization and easy integration with existing solutions.

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