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Control of squirrel-cage electric generators in a parallel intermediate DC circuit connection

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Abstract

The paper covers the theoretical background and tests of two asynchronous squirrel cage generators connected to voltage source inverters working in parallel. Inverters were connected in parallel by their intermediate direct current circuits by means of auctioneering diodes, and then to a DC power network. The real-time control algorithm of digital signal processor DSP and field-programmable gate array FPGA was used to achieve proper excitation of two different power machines, and to maintain high enough levels of direct current link voltage. Windings of both generators are fed by use of so-called machine side inverters. The asynchronous generator is a voltage source inverter controlled by a field-oriented control algorithm based on the current machine model. To prove robustness of the chosen algorithm, different types of load were applied while generators and inverters worked in parallel.

Introduction

Electrical grid DC systems have long been standard in the telecommunications industry (Roy, 2001), and with naval ships like DCZEDS system (Office of Naval Research, 2002). DC systems can also be used in small grids in home and residential applications (Salomonsson & Sannino, 2007) where power quality and reliability can be increased. This of course results in an improvement in electrical conversion efficiency. It is worth noting that direct current systems are inherently suitable for interconnecting such alternative energy sources as DC photovoltaic cells or DC current alternators, and that energy storage devices like accus, supercaps, and so on, can be used to improve the reliability of generation systems. A DC electrical grid has no AC disadvantages like synchronization problems and active/reactive power flows, problems which make a DC system by comparison useful when reliability and power quality are important. On board a vessel, the most important consideration is the reliability of the ship's electrical system. To improve redundancy, a DC system should consist of multiple electrical generators. The system shown in Figure 1 uses two independent generators of varying rotational speed.

Use of independent electrical generators provides multiple configuration options for supplying power to the ship's load: power can be supplied simultaneously, sequentially or from one bus exclusively (Balog & Krein, 2011). Power converters allow simultaneous operations from one or more generating sets, but they can be complicated to operate. Cycling through all available voltage sources but drawing power from only one at a time requires persistent switching and draws discontinuous current that can excite system resonances and cause voltage oscillations.

The current research of a group scientists and engineers at the Institute of Electrotechnics and Automation is focused on working with different types of generators connected in parallel through inverters. The "Green Energy", lab contains different types of generators connected in parallel and feeding the DC side of network. As the prime movers of electrical generators, squirrel cage motors

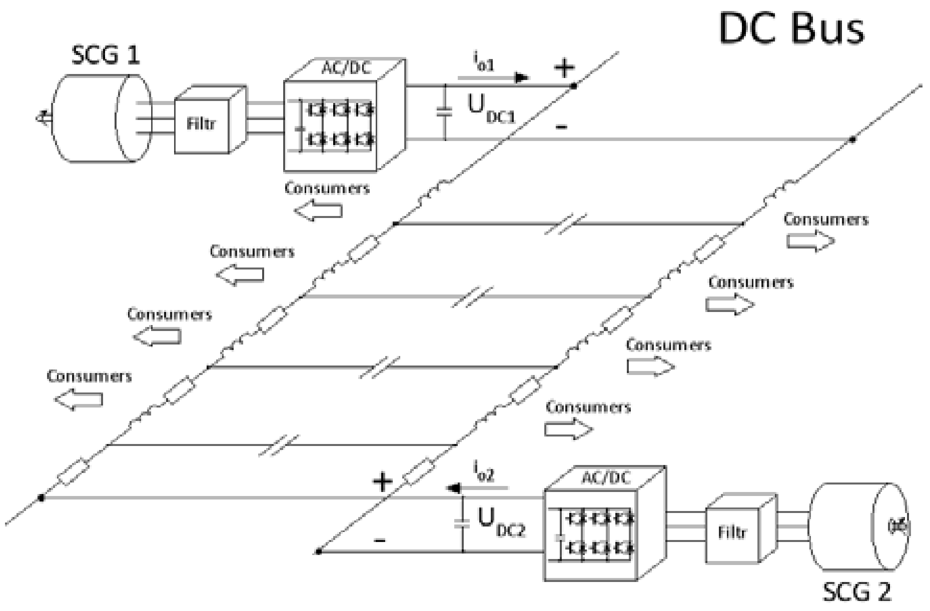

Figure 1. DC grid system based on two squirrel cage generators (SCG)

are used, controlled by vector sensorless commercial inverters. In classic ship designs the alternating current electrical grid is used, and MSB is the main point at which all electrical sources and loads are tied up together. The solution presented here is quite new and was introduced in a similar way back in 2013 in an offshore vessel called "Dina Star". From that time on, a few more ships with DC grids were built.

Two generator-inverter sets in parallel: working concept

The proposed strategy for controlling the electrical generator is based on the assumption that every inverter unit assigned to its own generator can act as a power management system. While communication means the Modbus network is assured, the system can easily cooperate with Diesel control units to maintain an optimal point of combustion engine work to achieve best work parameters. Additional advantage of the proposed system is its possibility of operating it generators at variable speeds.

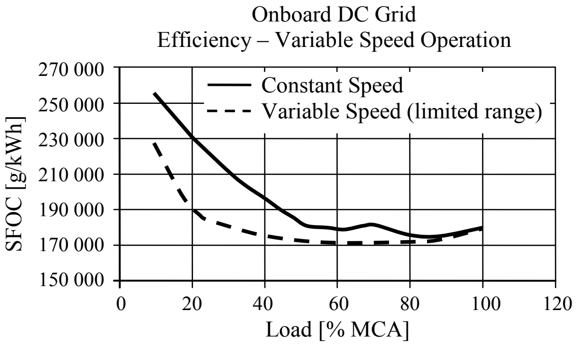

Figure 2. Comparison of variable speed operation efficiency against constant speed operation [ABB]

The presented solution has alternating voltage sources used as asynchronous squirrel cage generators marked as SCG. Both generators are driven by prime movers (PM) fed by drive inverters (DI). This kind of connection allows convenient driving of generator sets in wide range of RPM's, so testing of the whole system can be easily conducted. As it can be seen in Figure 3 that both inverters are connected back-to-back by their DC intermediate circuits, which can be extremely useful in case of power transfer. In the proposed solution, electrical energy is distributed by means of direct current, but most of consumers need inverters to work properly. Therefore, in Figure 3, there's line side converter (LSC).

Control of machine side inverters

The proposed system contains two real-time controlled inverters where a digital signal processor can be programed with VisualDSP++ 5.0, a high-level language. FPGA (field-programmable gate array) is programmed by Altera Quartus software. FPGA digital circuit controls the switching strategy of the IGBT (insulated gate bipolar transistor) transistors in the space vector pulse width modulation (SVPWM) and provides handling of analogy feed to digital sensors. DSP circuitry calls FPGA in software interruptions and reads values of measured current and voltages for control purposes. After the calculation loop is done, DSP sends voltage data in α–β coordinates to execute by FPGA, which enables switching of IGBT transistors. FPGA software inherently cares for power electronics dead time so

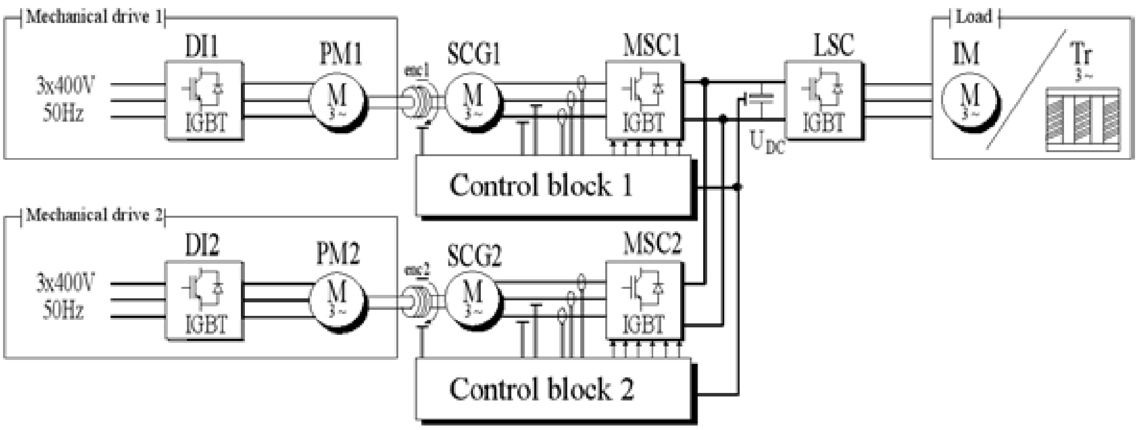

Figure 3. Block scheme of the tested system [authors' schema]

every change of state of a power device must be preceded by short (usually a few μs) delay.

Proper operation of individual load inverters is ensured while direct current link voltage is maintained at desirable level. In the tested system, DC voltage was set at 700 V and was kept almost constant by machine side inverters.

Asynchronous generator control strategy

The case of asynchronous squirrel cage generators (SCG), which are regular squirrel cage motors tasked with excitation and stable work, is more complicated than in other self-excited generators. First of all, DC link capacitors must be charged from some external source. The contactor must be closed while DC voltage is high enough. With stored energy in capacitors of intermediate circuit, the generator is put into operation, initially taking energy from capacitors or supercapacitors for magnetization purposes. Small amounts of electrical charge are needed also to cover mechanical losses. Decoupled control of magnetizing and active current is provided by means of properly programmed machine side inverters. After initial voltage build-up, the contactor opens its contacts and the voltage of the DC bus is maintained by a control algorithm.

As control method algorithm the field oriented control (FOC) was chosen for this purpose. There is a way in which this method there can be used to independently control active and reactive currents. The active current, i_{sq}, control loop in *d–q* coordinates provides constant DC link voltage, U_{DC} in value, while reactive current, i_{sd}, is set to a value nearly equal to t_i, the value of the idling motor.

The core of FOC is use of transformations calculated in real-time. Using the space vector properties allows the possibility of projecting sinusoidal balanced three phase quantities to control constant values of currents, voltages and fluxes easily. For example, the space vector $\bar{x}_S$, representing aforementioned quantities, can be expressed by two-phase

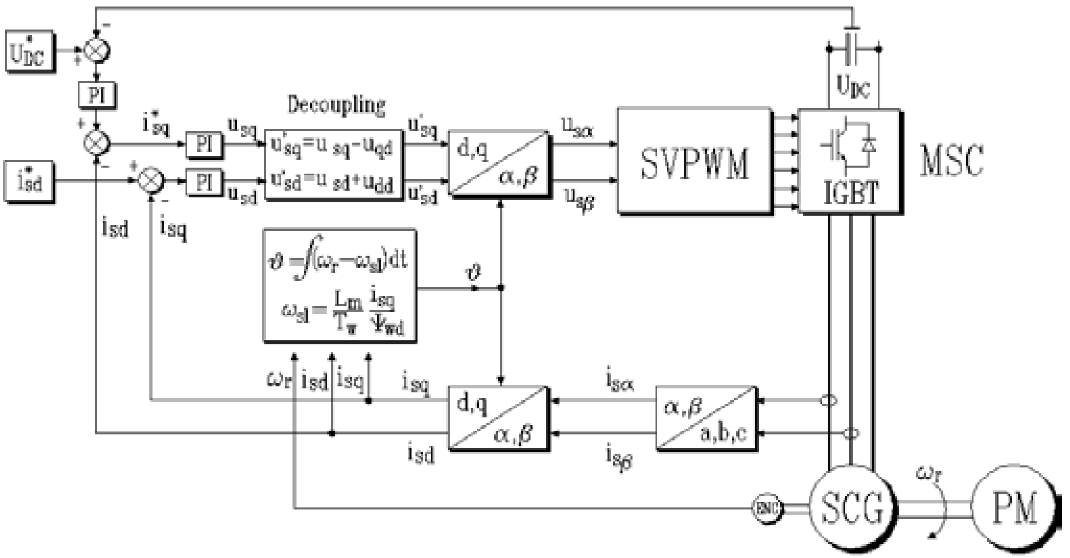

Figure 4. Scheme of squirrel cage asynchronous generator FOC control

magnitudes called x_α and x_β in the real-imaginary complex plane. Mathematically this relationship can be written as:

$$\bar{x}_S = x_\alpha + jx_\beta = \frac{2}{3}\left(x_a + ax_b + a^2x_c\right) \tag{1}$$

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

$$x_\alpha = \mathrm{Re}\{\bar{x}_s\} = \frac{2}{3}\left(x_a - \frac{1}{2}x_b - \frac{1}{2}x_c\right) \tag{2}$$

$$x_\alpha = \mathrm{Im}\{\bar{x}_s\} = \frac{2}{3}\left(\frac{\sqrt{3}}{2}x_b - \frac{\sqrt{3}}{2}x_c\right) \tag{3}$$

These two relations can be represented in matrix form as follows:

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{4}$$

For practical use it is convenient to define matrix given in (4) as follows:

$$T = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{5}$$

Another very useful set of equations transforms stator phase quantities from the stationary *abc* reference frame to the dq0 reference frame which rotates with the rotor is called Park transform.

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \\ = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{6}$$

Equations given in (4)–(6) are hard coded into VDSP++, and are executed in real time just to obtain values of currents, voltages and fluxes needed for easy control machine side inverter and DC link voltages. To proper operation of algorithm is needed to maintain the rotating frame angle *θ* calculation. To obtain the *θ* angle, it crucial to know the slip value and rotational speed of the shaft. Revolutions of the shaft can be taken from incremental encoder, but calculation of slip is more complicated. Since slip of an asynchronous induction machine changes with load, and if we want to independently control active and reactive currents, some assumptions must be made.

The set of machine equations needed for use of FOC is as follows:

$$\frac{\mathrm{d}i_{s\alpha}}{\mathrm{d}t} = \frac{L_m}{\sigma L_r L_s}\omega_r \Psi_{r\beta} + \frac{R_r}{L_r}\frac{L_m}{\sigma L_r L_s}\Psi_{r\alpha} + \\ -\left(\frac{R_s}{\sigma L_s} + \frac{R_r(1-\sigma)}{L_r\sigma}\right)i_{s\alpha} + \frac{1}{\sigma L_s}u_{s\alpha} \tag{7}$$

$$\frac{\mathrm{d}i_{s\beta}}{\mathrm{d}t} = \frac{L_m}{\sigma L_r L_s}\omega_r \Psi_{r\alpha} + \frac{R_r}{L_r}\frac{L_m}{\sigma L_r L_s}\Psi_{r\beta} + \\ -\left(\frac{R_s}{\sigma L_s} + \frac{R_r(1-\sigma)}{L_r\sigma}\right)i_{s\beta} + \frac{1}{\sigma L_s}u_{s\beta} \tag{8}$$

$$\frac{\mathrm{d}\Psi_{s\alpha}}{\mathrm{d}t} = -\omega_r\Psi_{r\beta} - \frac{R_r}{L_r}\Psi_{r\alpha} + \frac{R_r}{L_r}L_m i_{s\alpha} \tag{9}$$

$$\frac{\mathrm{d}\Psi_{s\beta}}{\mathrm{d}t} = \omega_r\Psi_{r\alpha} - \frac{R_r}{L_r}\Psi_{r\beta} + \frac{R_r}{L_r}L_m i_{s\beta} \tag{10}$$

The idea of field oriented control is based on assumption that the *d*-axis of the coordinate is aligned with rotor flux vector; hence the *d*-component of current is in phase with the rotor flux vector, and it is called "flux component" or "magnetizing current," while the *q*-component of current is perpendicular to rotor flux and is responsible for producing motor torque.

$$\Psi_{rq} = 0 \tag{11}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\Psi_{rq} = 0 \tag{12}$$

After transformation of equations (7)–(10) to *d–q* rotating frame, and after taking into account (11)–(12), we obtain simplified equations of FOC control.

In control of electrical machines, an extremely convenient way is to use machine state equations in matrix form, so machine equations are like this (13).

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_{sd} \\ i_{sq} \\ \Psi_{rd} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{\sigma L_s} - \frac{R_r(1-\sigma)}{L_r\sigma} & \omega_s & \frac{L_m R_r}{\sigma L_s L_r^2} \\ -\omega_s & -\frac{R_s}{\sigma L_s} - \frac{R_r(1-\sigma)}{L_r\sigma} & -\frac{\omega_r L_m}{\sigma L_r L_s} \\ \frac{L_m R_r}{L_r} & 0 & -\frac{R_r}{L_r} \end{bmatrix} \cdot \begin{bmatrix} i_{sd} \\ i_{sq} \\ \Psi_{rd} \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \end{bmatrix}\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} \tag{13}$$

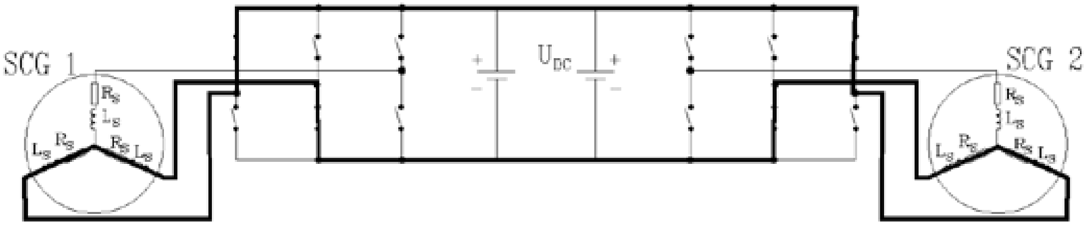

Figure 5. Flow of circulating currents in absence of auctioneering diodes

Third line of machine equations gives:

$$\frac{\mathrm{d}}{\mathrm{d}t}\Psi_{rd} + \frac{R_r}{L_r}\Psi_{rd} = \frac{L_m R_r}{L_r} i_{sd} \qquad (14)$$

$$\omega_s = \omega_r + \frac{L_m R_r}{L_r \Psi_{rd}} i_{sq} \qquad (15)$$

Equation (14) is the core of the FOC, and after some transformation gives value of machine slip (15).

Use of auctioneering diodes

To prevent circulating currents from flowing thru conducting transistors the auctioneering diodes must be implemented.

As can be seen in Figure 5, placing only one diode on positive output would be fair enough in although the presented system used another approach. Auctioneering diodes were 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.

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 (Balog & Krein, 2011).

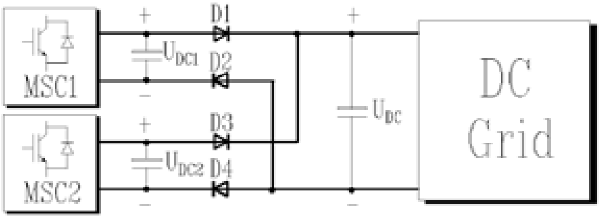

Figure 6. Scheme of proposed system with use of auctioneering diodes

C++ simulations results

To verify the assumptions made some simulations of proposed system were run. All simulations including discretized asynchronous generators models were prepared in Watcom C++ language. Control algorithms and procedures were coded in a manner that gave possibility to move straight the source code into VisualDSP++ language, which is native for Analog Devices DSP processor. Some

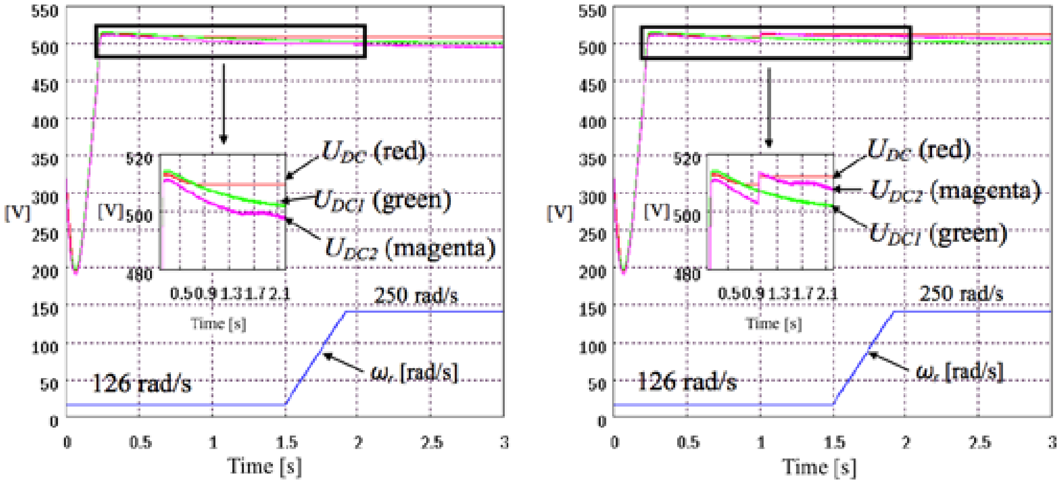

Figure 7. Simulation results of start-up and parallel operation of two squirrel cage generators: a) without power sharing algorithm enabled b) with automatic power sharing enabled

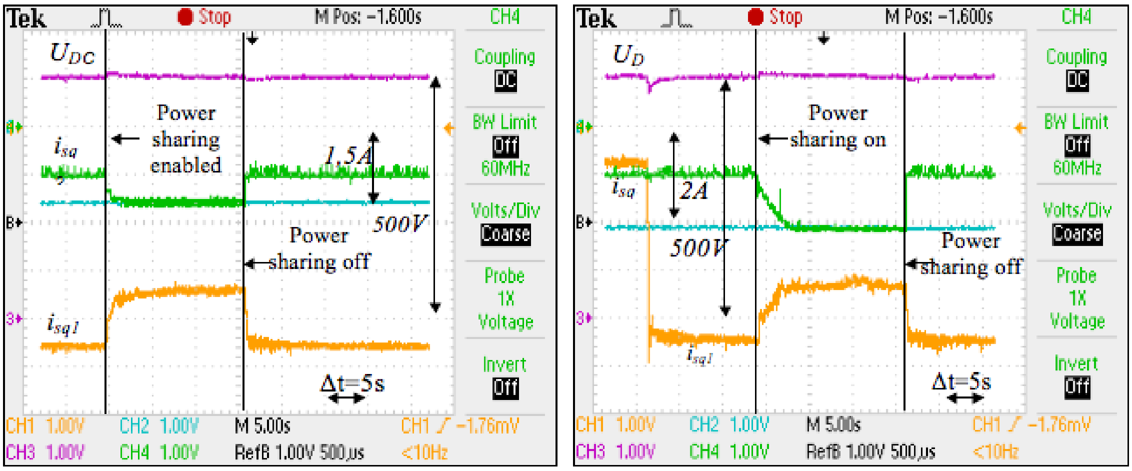

Figure 8. Experimental results of power sharing in parallel connection of two asynchronous generators: a) current limit set to 1.5 A, b) current limit set to 2 A

parameters tuning was applied and simulated results were obtained.

As it can be seen in Figure 7, stable parallel operation of asynchronous generators was achieved and an algorithm of power sharing based on independent DC voltage regulators worked seamlessly.

Experimental test bench and results

For purpose of further researches a laboratory test bench was created. The system consisted of two generators with power outputs of 1 kW and 4 kW, respectively. Both of them were tied up to IGBT inverters controlled by one FPGA/DSP unit. LEM current and voltage transducers performed measurements. Field programming array FPGA works with DSP interrupts. In an interrupt call DSP is sending voltage waveforms of 16-bit length to FPGA. At the same time DSP reads values from analog-digital converters that are fed with data by LEM transducers. In FPGA space, the vector modulation program is executed in an endless loop. Auctioneering diodes are soldered on separate PCB boards along with an electrolytic capacitor bank. All software needed by DSP and FPGA was initially compiled on PC and later sent to units. As a load, power resistors and plain bulbs were used. Additionally, the commercial inverter was attached to DC link as a load. The unit was tested up to nominal value of load and changing rotational speed condition. To maintain proper power sharing, voltage of one generator was slightly raised and resulting generator current was then limited. The next generator in parallel provides power for the remaining load. This kind of system gives possibility to connect another generator while easily controlling power distribution and current flow.

Conclusions

The presented system allows easy distribution of electrical power and long-term cooperation of different electrical sources such as electric generators of different types working in parallel with changing in a wide range of angular speeds. The system is still under development with the addition of new generators (e.g., a reluctance machine), and by applying and testing new control algorithm.

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