POZNAN UNIVERSITY OF TECHNOLOGY ACADEMIC JOURNALS
No 90 Electrical Engineering 2017

DOI 10.21008/j.1897-0737.2017.90.0032

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EXPERIMENTAL RESULTS OF PARALLEL CONNECTED INVERTERS FEEDING MEDIUM VOLTAGE TRANSFORMER

Development of medium voltage, high power ship electrical installations on board of special purpose vessels, has led to use of grid side inverters along with step-up grid transformers. In this paper there is presented theoretical background and experimental results of two inverters in parallel connection feeding one 0,4/15 kV transformer.

KEYWORDS: electrical transformer, line side inverter, inrush currents, inverter parallel operation

1. USE OF MEDIUM VOLTAGE ONBOARD OF MERCHANT SHIPS

1.1. Introduction

Because of growing electrical power demand onboard of seagoing vessels as the reasonable solution medium voltage (MV) electrical installations were introduced many years ago. Permissible levels of alternating voltages used onboard of ships are 3,3, 6,6, 11,0 and 15,0 kV with 50 or 60 Hz [1]. The distribution system is designed to keep cable costs at the very minimum rate by providing power to panels closely located to user services.

In aforementioned systems in most cases main busbar and generators are working on medium voltage level while minor consumers are feed with means of low voltage which is generated by step–down transformers. Huge electrical consumers (e.g. bow and aft thrusters, air compressors etc.) are powered directly from busbar with medium voltage. In spite of overall low power demand on some vessels there is no need to use of medium voltage for all 3–phase systems. Only selected of high power electrical consumers use medium voltage which is generated by step–up transformers while main generators and main busbar work with low voltage. With still decreasing costs of MV machines, transformers and cables and for the sake of installation ease aforementioned topology is quite

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popular and used in some ships. Fig. 1 shows the ship system that utilizes three–phases step–up power transformer of 2.6 MVA power for start–up autotransformer and bow thruster induction motor supply. As it can be seen system is divided on low voltage (440 volts) part powered by main generators and medium voltage side fed by 0,4/6,6 kV transformer. In presented topology one generator solely can power up bow thruster motor but in many cases for the safety of operation there is a need paralleled work of two or more generators.

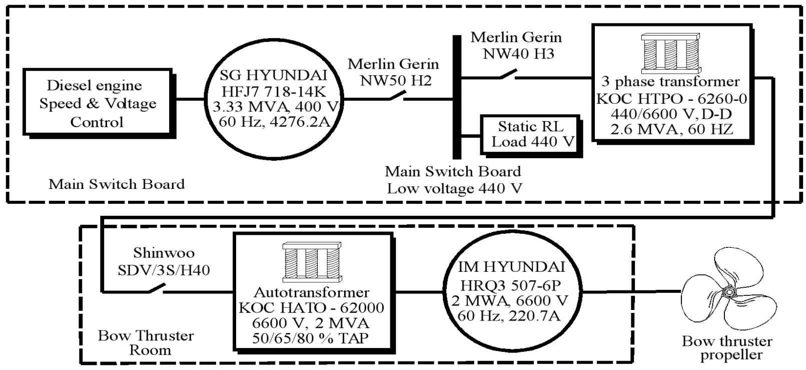

Fig. 1. Scheme of MV bow thruster supply system with use of step–up transformer

1.2. Concept of electrical grid with inverters and transformer use.

Investigated system consists of two AC generators driven by electrical motors supplied by variable speed drives, two back–to–back inverters and one 0.4/15 kV power transformer.

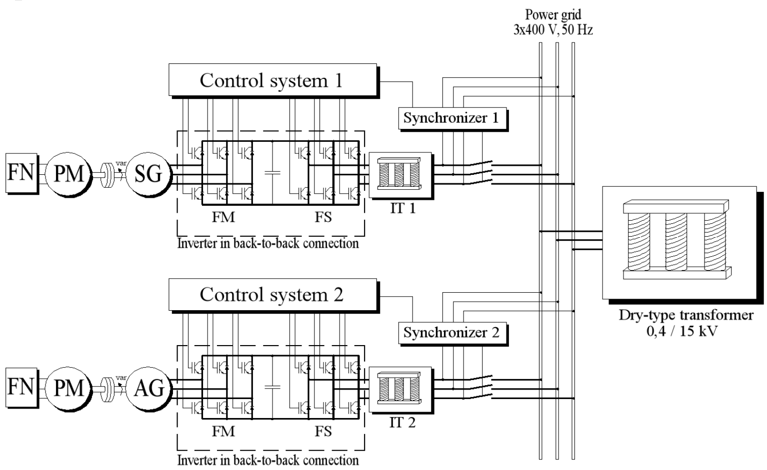

Fig. 2. Scheme of investigated system

All protections along with synchronizers and measurement facilities are enclosed in main switchboard which is central point of electrical system. The generators can rotate with varying revolutions and back–to–back inverters are intended to maintain resulting voltage parameters. One of used generator is of squirrel cage asynchronous type and second is self–excited synchronous generator [3].

1.3. Inrush currents considerations

A transformer draws inrush current that can exceed saturation current at power up. These current affects the magnetic property of the core. This feature occurs especially if the transformer has no–load with its secondary winding open or closed by huge impedance. The magnitude of the inrush current depends mainly on the point of time when the AC voltage is supplied to the transformer. When the transformer is energized, a transient overcurrent is created, which depends on the moment that the voltage is applied and the remanent induction of the magnetic circuit.

If the case of switch on of idle running transformer, when the AC voltage wave is at its peak value, there will be no inrush current drawn by the transformer and the magnitude of the current equals no–load value.

The asymmetry and the current value are maximum when the transformer is energized, at the moment the voltage reaches zero, and when the remanent induction on the same phase is maximum. The overcurrent is due to the saturation of the magnetic circuit, which causes a very high magnetizing current.

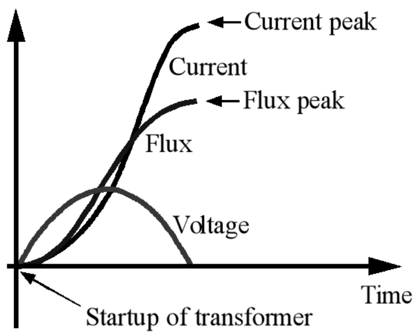

Fig. 3. Inrush currents with transformer startup at zero voltage

It is shown that:

$$B_{max} = 2\,B_n + B_r \qquad (1)$$

where: B_{max} – maximum induction reached, B_n – value of nominal induction, B_r – remanent induction.

This short duration overcurrent is referred to as an inrush current. The inrush current can be depicted as follows:

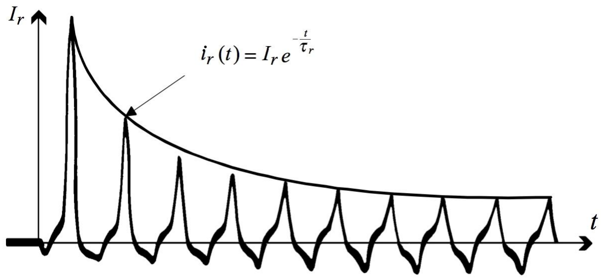

Fig. 4. Transformer startup inrush current waveform [4]

The peak value of the inrush current is damped according to an exponential law:

$$i_r(t) = I_r e^{-\frac{t}{\tau_r}} \tag{2}$$

where: $i_r(t)$ – peak value of the current in relation to time, I_r – maximum peak value, i.e. the first peak, τ_r – time constant.

The maximum peak value I_r is defined in relation to the nominal current I_n value of the transformer:

$$n_r = \frac{I_r}{I_n} \tag{3}$$

The no–load inrush current values are in most cases known. Experience has shown that the on–load transformer inrush current value is roughly the same.

2. CONTROL OF BACK-TO-BACK INVERTERS

2.1. Control of synchronous generator

The 5,5 kW slip–ring synchronous generator was used as one of test objects. 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 voltage regulator in synchronous generator there is no need to independent control of reactive current control so as control algorithm the field oriented control was chosen to utilize. With the use of this method active and reactive currents can be independently controlled. Constant value of DC link voltage U_{DC} is ensured by active current i_{sq} control loop, while reactive current i_{sd} is set to zero.

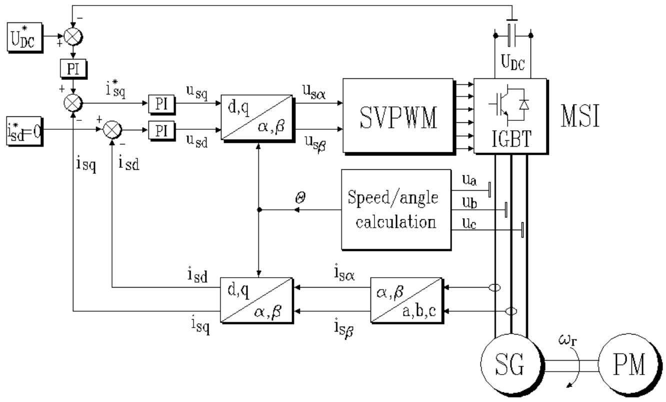

Fig. 5. Scheme of synchronous generator control

To proper operation of algorithm there is need for rotating frame angle θ calculation. It is done in sensorless way by measurement excited generator terminal voltages. Those voltages are roughly sinusoidal waveforms so by applying PLL or zero–crossing sensing it is possible to calculate rotational speed and frame reference actual angle. Value of θ angle is needed by Park and Clarke transforms for real–time operation.

2.2. Control of asynchronous squirrel cage generator

In case of asynchronous squirrel cage generator, which is regular squirrel cage motors task of excitation and stable work, is more complicated than in other type of electrical generators. Intermediate circuit capacitors must be charged from some external source. With energy stored in capacitors, generator is put into operation and initially takes energy from electrolytic capacitors for magnetization purposes. Small amount of electrical charge is needed also to cover mechanical losses [8]. Decoupled control of magnetizing and active current is provided by means of properly programmed machine side inverter. After initial voltage build–up the contactor opens its contacts and the voltage of DC bus is maintained by control algorithm. As a control method algorithm the field oriented control was chosen to utilize. Such control loop allows independent active and reactive currents control with means of plain digital PI controllers. Active current i_{sq} control loop in d–q coordinates provides constant DC link voltage U_{DC} value. So called reactive current i_{sd} is set to value nearly equal of idle running motor current.

The core of field oriented control is use of transformations calculated in real–time. Using of space vector properties gives the possibility of projection sinusoidal balanced three phase quantities to *d–q* plane as easy to control constant values of currents, voltages and fluxes.

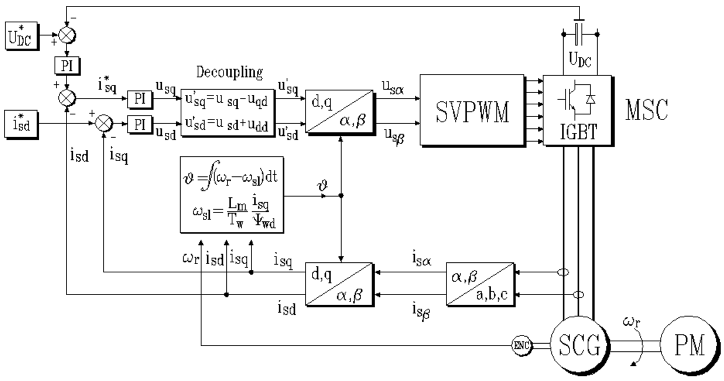

Fig. 6. Scheme of asynchronous generator control loop

Similarly, to synchronous generator FOC control rotating frame angle denoted in Fig. 6. as ν must be calculated. For this purpose, some well-known sensored or sensorless algorithms can be used. In this particular experimental setup system with encoder was used, so the calculations were simple and utilized so-called current model of asynchronous machine.

2.3. Control of line side inverters and power distribution

Voltage line side inverters are main source of alternating current for ship electrical grid. In back-to-back inverter connection it is crucial to maintain constant value of DC link voltage to ensure stable work and proper power distribution [6]. Both of line side inverters have implemented the same control algorithms. There are provided two modes of operation: island type (one generator–inverter set feeding grid) or parallel work of two inverters. In the first mode when only one generator powers up the grid, line inverter has to control over the frequency and amplitude of voltage. In case of of demanded power increase, another generator set is put into operation. After a synchronization resulting in closing circuit breaker, control algorithm of inverters changes.

One of parallel working inverters (master) holds frequency and amplitude values on constant level, while second one (slave) carries out an algorithm of active and reactive power distribution.

The amount of power not covered by generator working in power sharing mode is covered by the second one. For proper operation of power distribution regulators actual value of net frequency must be provided constantly. For this purpose, in presented system phase locked loop algorithm was used but in case of distortions appearance other methods should be used [7].

3. EXPERIMENTAL RESULTS OF STARTING UP THE TRANSFORMER AND PARALLEL OPERATION OF INVERTERS

First test was done for transformer starting up with restricted voltage level to prove reliability of step voltage supply in order to get inrush current reduction. While closing circuit breaker first generator was driven by prime mover with constant rotational speed of 314 rad/s. Line side inverter AC voltage was set to 250 V just to obtain low inrush currents values and prevent protection trip off. After successful connection of load (idle transformer 0,4/15 kV, 20 kVA), voltage was increased to nominal 400 volts.

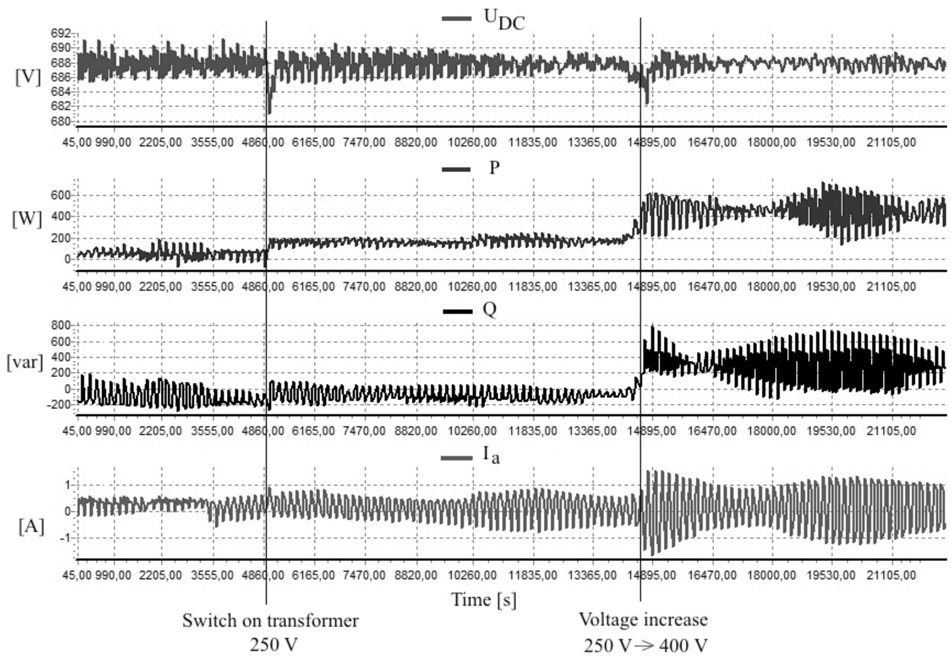

Fig. 7. Waveforms of voltages, power and phase current while transformer switch on

The use of reduced switch on voltage led to substantial reduce of inrush currents from roughly 18 amperes to 5 amperes in the worst case of 0 value of voltage switch on. Some other inrush currents limit methods were introduced in [4] including use of ramp of voltage value while magnetizing transformer.

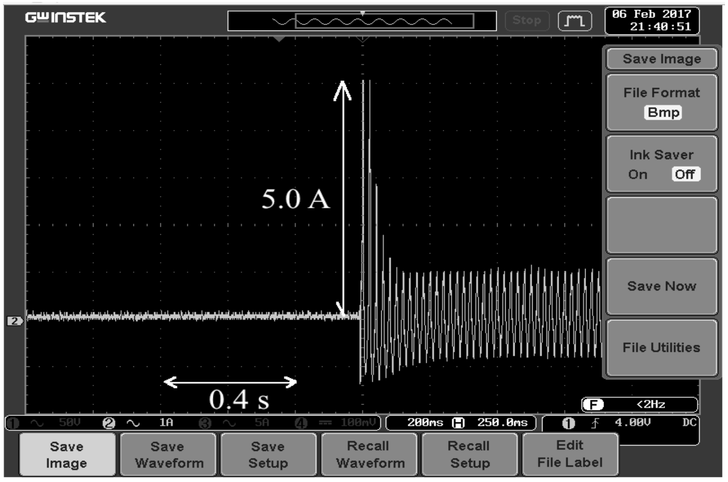

Fig. 8. Waveforms of decreased inrush currents in no–load transformer supply with reduced voltage 3x250 V, 50 Hz

Some oscillations of active (P) and reactive (Q) power occurrence can be noticed right after closing circuit breaker of second generator. These oscillations are caused by improper settings of PI regulators and especially proportional gain setting.

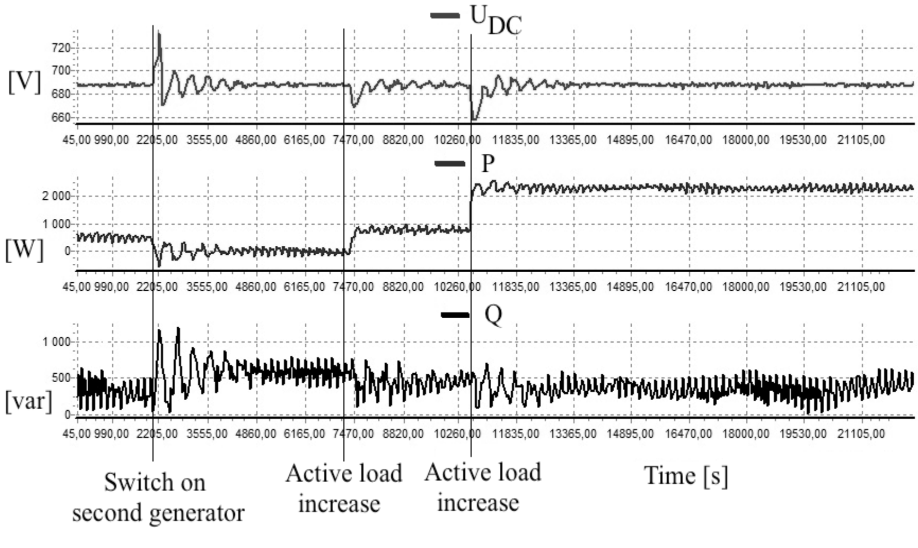

Fig. 9. Waveforms of voltage, active and reactive power of "master" generator while connection of "slave" genset and changing active load

Generator denoted as “slave” works in limiting current mode thus good active and reactive power distribution is achieved. In the case of discussed system “slave” genset has limits set to 400 W and reactive power is set to lag 500 var. All remaining power is taken over by “master” generator (Fig. 9). In the real world applications reactive power is distributed in proportion to the nominal power of generators and this setting is fixed for good.

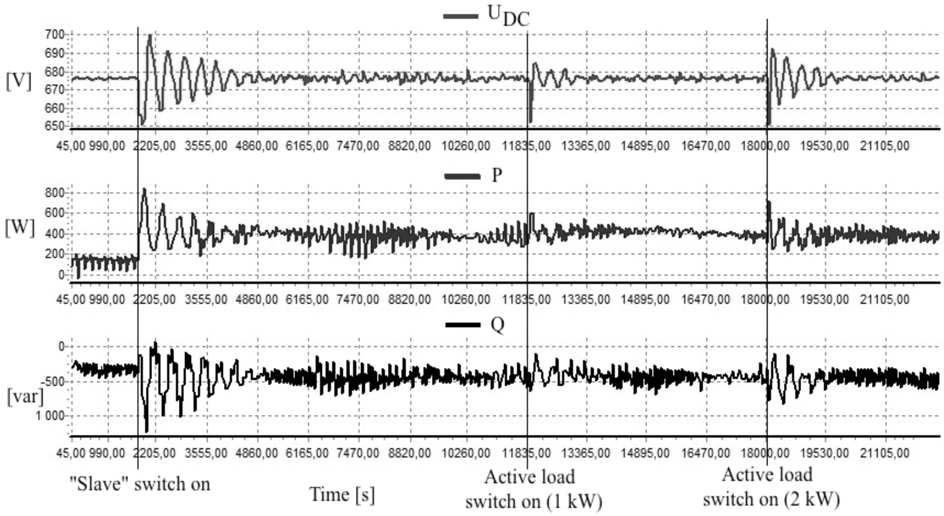

Fig. 10. Waveforms of voltage, active and reactive power of “slave” generator during parallel operation and active load changes

There have been conducted extensive tests on lab test bench for active and reactive load takeover and drop along with rotational speed changes of generators. Presented system have shown good static and dynamic features. Some tests of parallel operation of two generators along with inland power grid were performed and results showed near excellent control of active and reactive power distribution.

4. CONCLUSIONS AND FURTHER WORK

In the presented paper experimental results of supplying 0,4/15 kV transformer from two rotating with different speed generators were shown. Inrush currents limiting method by means of decreased voltage while supply switching on line side inverter was introduced and proved its benefits. Process of active and reactive power distribution between two VSI parallelized inverters was shown. Conducted tests has proven good stability and fast response of inverters cooperating with electrical generators of different types rotating with changing RPM's. Presented method can be successfully used for parallel supplying not only transformers but all consumers in case of electrical ship network. Further work will cover stability issues related to use of digital and software regulators and filters. As it can be seen in obtained results fast response time improving and tuning of parameters is still a must and researches will be continued. All experimental tests have been done in "Green energy" lab at Maritime University of Szczecin.

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(Received: 15. 02. 2017, revised: 28. 02. 2017)