NEW CONCEPT OF SHIP'S POWER PLANT SYSTEM WITH VARYING ROTATIONAL SPEED GENSETS

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Abstract
A variable speed genset is an engine driven electrical power generating system that uses proper technology to control engine speed to provide performance enhancement, fuel savings, reduced emissions and noise reduction while providing power to the load at a specified voltage and frequency. The presented system consists of asynchronous generators and a DSP controller. Numerical simulations along with experimental results obtained in laboratory desk bench were presented.
Key words: *electronic governor, parallel operation, power distribution, load sharing, VSI, variable speed generators.*

INTRODUCTION

Currently most generators installed onboard of seagoing vessels operate with a fixed rotational speed which results in constant voltage frequency on terminals (mostly 60 Hz and 50 Hz). With high rotational speeds combustion engines produce higher exhaust gases emissions. The manufacturers have started to reduce the speed on engines just to meet new emission standards. In these solutions there is a need of maintaining higher, constant revolutions when operating with low loads. This has always been a major concern with regard to the glassing of the cylinders, engine lifespan, and consumption of lubricating oil.

In recent years manufacturers are creating and testing engines (Diesel, dual-fuel or gas feeded) that allow efficient operation under low RPM’s. This feature makes gensets more environmentally friendly because of low fuel consumption along with lower exhaust gases emission. Variable speed function of the engine is dependent on electrical generator load and power consumed. There are two main types of variable speed gensets. These are based on power electronics and based on a mechanical, constant speed transmission.

The constant speed transmission employs a mechanical solution that uses a standard synchronous alternator and a variable speed engine.

Power electronics based designs use an engine driven generator along with power transistor (or controllable thyristors) inverters in back-to-back intermediate circuit connection, power electronics filters and a control scheme to create resulting voltage and current waveforms comparable to that generated by a fixed speed synchronous genset. Line side inverter performs constant voltage and frequency output during most load conditions and may also provide fault protection. In the solution with AC voltage output of line side inverter and varying rotational speed there is problem of rapid load changes which may cause a voltage collapse. The drawback of lower RPM’s of combustion engine is the lack of power reserve so in such solution some other means of power reserve must be provided. The article presents new concept of system consisted of variable speed Diesel engines propelling asynchronous squirrel-cage electrical generators which are feeding IGBT’s inverter DC intermediate circuitry.

MATERIALS AND METHODS

The main advantage of varying RPM’s generator is average fuel saving from 6% (huge cruise ships) (*Lundh, Garcia-Gabin, Tervo & Lindkvist, 2015*), to about 20-30% (small, specialized diesel-electric vessels) thus reduced emissions as fuel is burned more cleanly. Moreover, very important factor on the vessel mounted genstes is reduced noise and vibrations level (>6dB) what in the case of all-electric ship with 6 medium speed gensets results in notably noise reduction. Another advantage of such system is decreased combustion engine wear resulting in doubling time to overhaul. According to average load requirement the driving Diesel engine can be optimally sized, with peak loads supplied from external electrical energy storage unit (batteries, super or ultra capacitors). With use of direct current ship electrical distribution system overall weight and space of the equipment decreases of about 30%. As real-world applications of offshore PSV ships like “Dina Star” or “Edda Ferd” show excellent results of using variable speed generators and DC current distribution systems along with power electronics controllable converters the attempts to improve such a system are being undertaken.

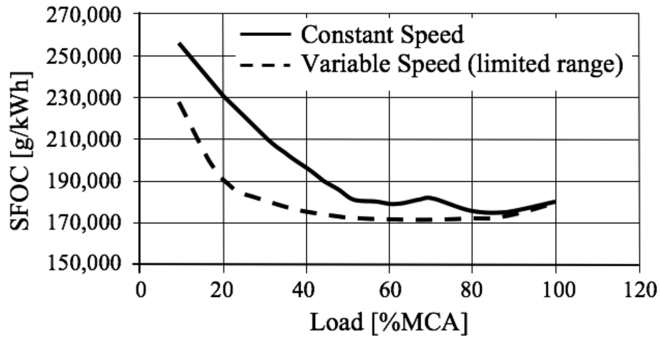

Fig. 1 Comparison of SFOC of variable speed operation efficiency against constant speed operation. (*Kozak, Gordon & Bejger, 2016*)

As it can be seen in the Fig. 1 the efficiency of presented system is notably better than one of the constant RPM’s especially under medium and low load values. This is not surprising as the typical Diesels engines are designed to operate at minimal load at level of about 60%. The problem arises when load demand excesses a little bit power of one genset and to complete operation two generators must be put into parallel operation. The dynamic changeover of load between the gensets is recognized as the best mean for removing cylinder surface carbon deposits but it is not providing

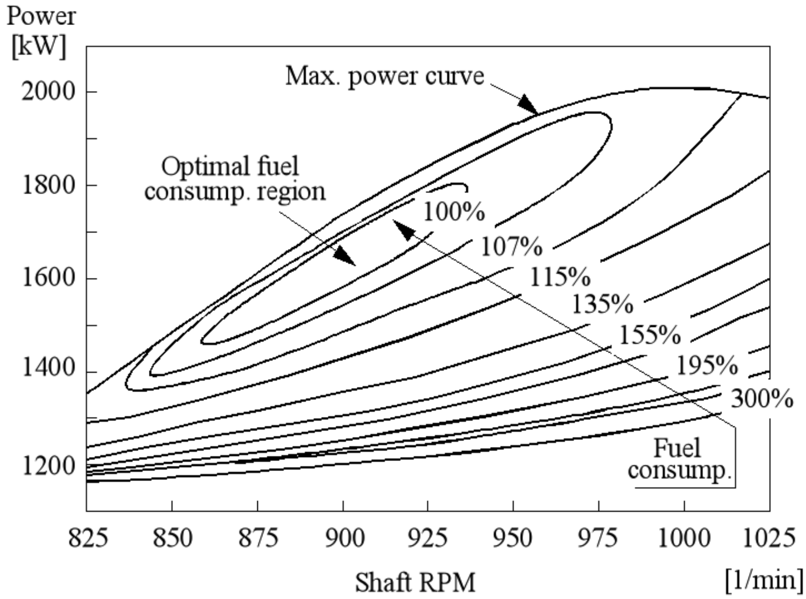

Fig. 2 Marine fuel consumption and exhaust gases emission reduction. (*Kozak, Bejger, Gałaj & Gawdziński, 2016*)

Ship electric load variability implies changing in time power generation, hence variable operation points for the generators. It is well-known that the SFOC (specific fuel oil consumption) function of a diesel generator depends solely on the generator output power and some loses. Generators fuel consumption function can be approximated by second order polynomials (*Kanellos, Tsekouras & Hatziargyriou, 2014*). This function can be expressed as:

$$FC_j(P_j) = a_{0j} + a_{1j}P_j + a_{2j}P_j^2,\ P_{jmin} \le P_j \le P_{jmax} \quad (1)$$

where P_j is the power of j-th unit.

Specific fuel oil consumption function (denoted as F_{SFOC}) is useful for the determination of the point of operation of a generator. SFOC determines generator fuel consumption per kilowatt hour. A typical SFOC is shown in Fig. 1. SFOC for given engine can be calculated as

$$F_{SFOCj}(P_j) = FC_j(P_j)/P_j = a_{0j}/P_j + a_{1j} + a_{2j}P_j\ ,\ \ P_{jmin} \le P_j \le P_{jmax} \qquad (2)$$

SFOC of combustion engine is a decreasing function of the produced power P. In the point where the most economical operation is achieved curve slope changes and increases until next maximum power.

In the case of ship propelled by electrical motors optimization of the electric power generation should be performed along with the optimization of the electric propulsion power. This problem comprises problems of power generating unit priority and optimal power distribution. Unit designation decides which gensets should be to be used. Power management system calculates optimal time of operation during the examined time period, while the load sharing between each generator is calculated by optimal power dispatch. Since the electrical generators are at most operating at constant speed, power distribution capabilities are limited.

To overcome aforementioned limitation a method of proper power distribution with use of control signals coming from electronic governor and DC system consisted of induction generators co-working with VSI inverter was developed. Main difference between proposed system and existing technical solutions is use of simple electrical machine as electrical generator. Onboard of few vessels similar systems consists of self-excited generators with series connected controlled rectifiers. As an emergency power reserve battery with boost-buck converters is provided.

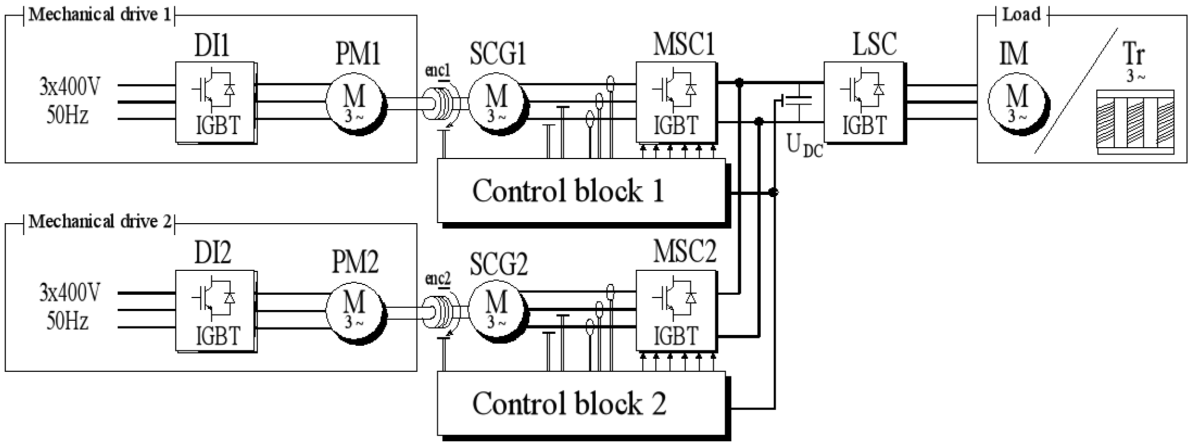

Fig. 3 Block scheme of proposed system. (*Kozak, Gordon & Bejger 2016*)

Proposed strategy of electrical generators control is based on assumption every inverter unit assigned to it's own generator can act as individual generator power management system "Slave" which cooperates with "Master" unit. While Modbus RTU communication network is assured, system can easy cooperate with combustion engine governor and control unit to maintain optimal point of combustion engine work thus to achieve best work parameters. As alternating voltage sources there are used 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. As it can be seen in Fig. 3. both inverters are in back-to-back connection (with DC intermediate circuits) which can be extremely useful in case of both direction power transfer. In proposed solution electrical energy is distributed with means of direct current, but most of consumers need inverters to work properly, so in there can be add line side converter (LSC).

Proposed system consists of two real-time controlled inverters where digital signal processor can be programed with use of VisualDSP++ 5.0 programming high-level language. FPGA (field-programmable gate array) is programmed by Altera Quartus II software. FPGA digital circuit controls switching strategy of IGBT (insulated gate bipolar transistor) transistors in space vector pulse width modulation (SVPWM) and provides handling of analog to digital sensors. DSP circuitry calls FPGA in software interruptions and reads values of measured current and voltages for control purposes. After calculation loop is done DSP sends voltages data in α-β coordinates to execute by FPGA, which enables switching of IGBT transistors. FPGA software inherently cares of power electronics dead time so every change of power devices state must be preceded by short (usually few of μs) delay.

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

Considering Diesel engine governor inputs and outputs as main control unit the RPM's and engine mechanical torque would be the best choice of control signals. Such signals are inputs of electrical power management system with means of Modbus protocol.

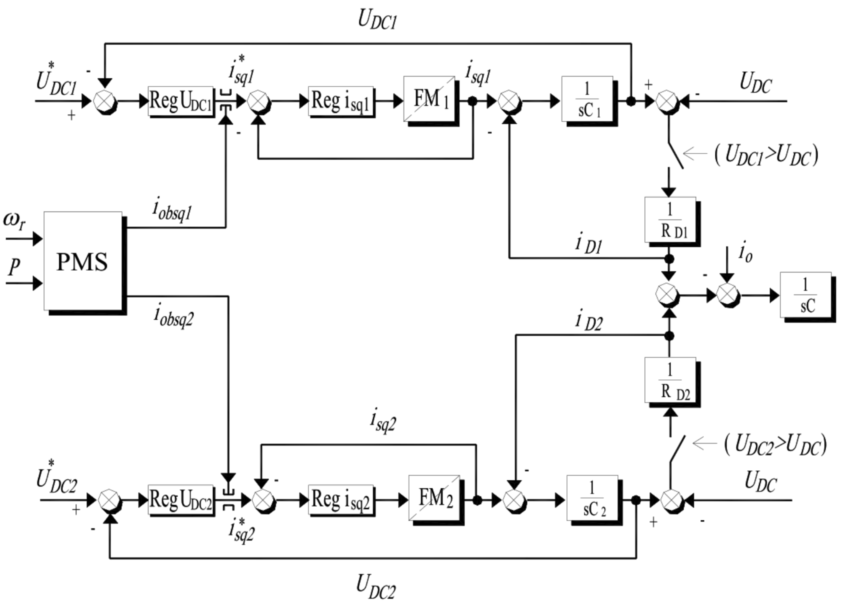

Fig. 4 Control system of proposed system.

The core of presented system are signals of available power P and rotational speed ω_r of working in parallel generators incoming into PMS (power management system). The data is proportional to incoming available power of each genset and consist of limited power and rotational speed of generators. Based on incoming data DSP is performing real-time calculations of power distribution between generators. There are Diesels engines torque maps (*Seung-Hwan, Jung-Sik, Joon-Hwan & Seung-Ki, 2015*) with optimal fuel consumption regions and forbidden areas in the form of tables embedded into software code. The data fill of tables would come from information provided by engines manufactures. The algorithm of power distribution seeks for optimal Power/RPM's ratio with use of (1) and (2) closest to optimal region of SFOC for each genset. In the case of two-way communication between PMS and EEG (engine electronic governor) power management system is capable to transmit RPM's control commands. Because of complexity of design and used algorithms it is worth to note that not only one configuration exists and finding the best parameters can be achieved in many ways. In proposed system knowledge of total electrical load of generators is crucial to work out proper Diesel engines control signals.

In the case of very simple to maintain asynchronous squirrel cage generator (SCG), task of excitation and stable work, is far more complicated than in other type of self-excited generators. Firstly, DC link capacitors have to be charged from external source. With energy stored in capacitors of intermediate circuit generator is put into operation and initially takes energy from energy banks for machine magnetization purposes. Decoupled control of magnetizing and active current is provided by means of programmed machine side inverter. After voltage build-up the DC busbar voltage is maintained by outer-loop control algorithm.

As control method algorithm the field oriented control (FOC) was chosen as perfectly fit to such a task. In a manner of this method 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 value motor magnetizing current.

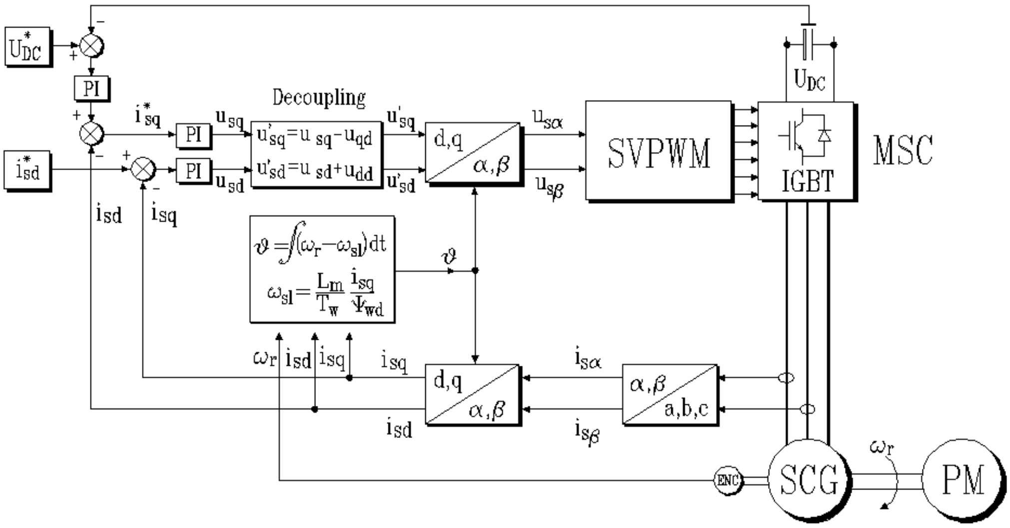

Fig. 5 Scheme of squirrel cage asynchronous generator FOC control *(Kozak, Gordon, Bejger 2016).*

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 $\overline{x}_S$ representing aforementioned quantities can be expressed by two-phase magnitudes called x_α and x_β in the real-imaginary complex plane.

RESULTS AND DISCUSSION

To verify assumptions made, proposed system was simulated. All simulations including discretized asynchronous generators models were prepared in VisualDSP++ language. Control algorithms and procedures were coded in a manner that gave possibility to move straight the source code into DSP processor. Some parameters tuning was applied and simulations results were obtained.

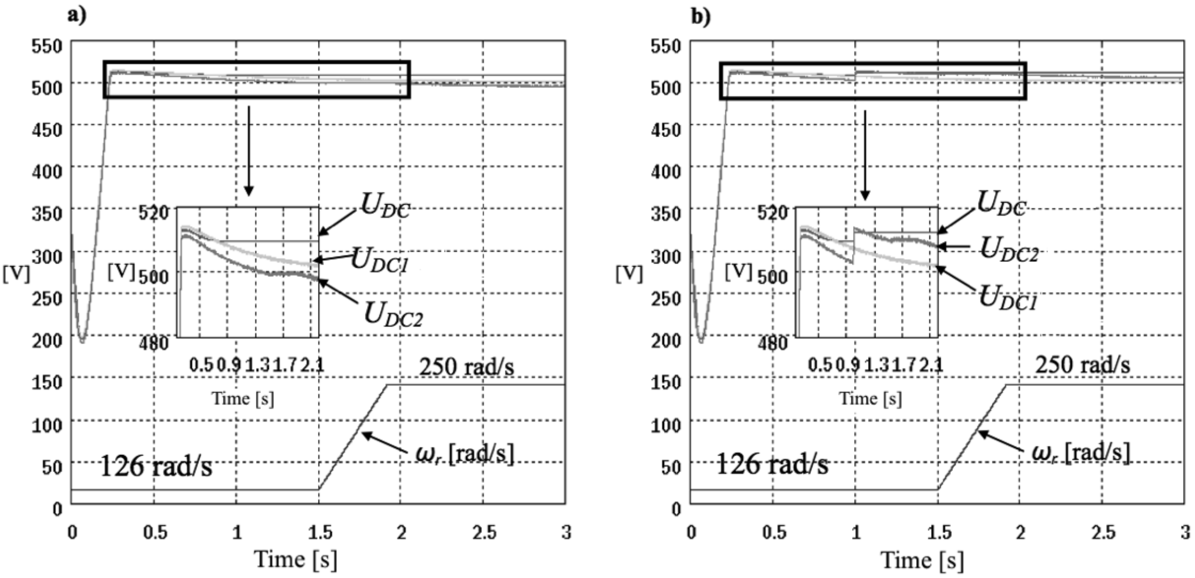

Fig. 6 Simulation results of start-up and parallel operation of two squirrel cage generators.
a) without power sharing algorithm enabled b) with automatic power sharing enabled.

For purpose of further researches laboratory test bench was created. System consists of two generators with outputs of power 1kW and 4kW respectively. Both of them are tied up to IGBT inverters controlled by one FPGA/DSP unit. LEM current and voltages transducers perform measurements. Field programming array FPGA works in DSP interrupts. In an interrupt call DSP is sending voltage waveforms of 16-bit length to FPGA. In the same time DSP reads values from analog-digital converters that are fed with data by LEM transducers. In FPGA space vector modulation program is executed in an endless loop. Auctioneering diodes are soldered on separate PCB along with electrolytic capacitors bank.

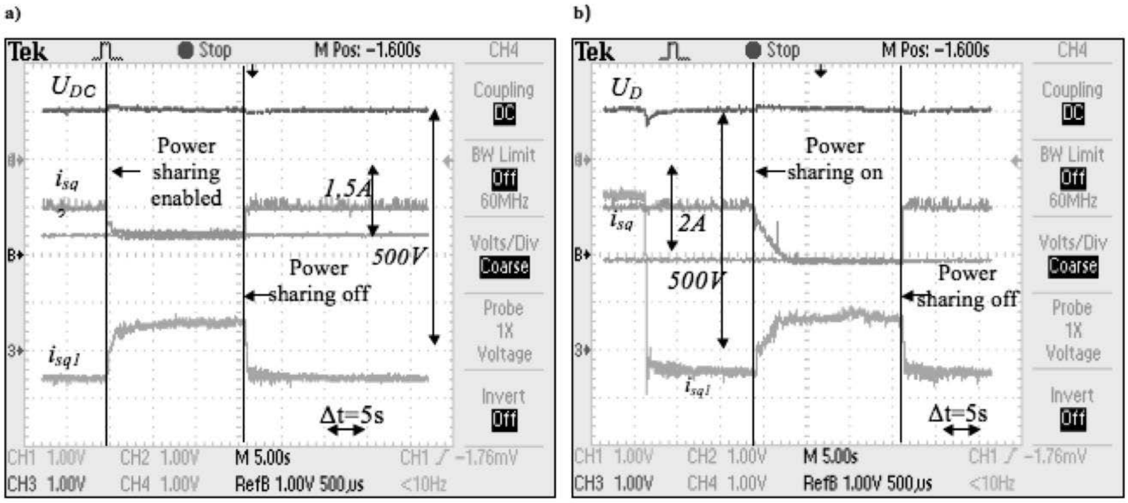

Fig. 7 Experimental results of power sharing in parallel connection of two asynchronous generators. a) current limit set to 1,5A b) current limit set to 2A

As a load commercial inverter was attached to DC link. To maintain power sharing, voltage of one generator was slightly raised and resulting generator current was limited to value incoming from external source (EEG). Next generator in parallel provided power for remaining load. This kind of system gives possibility to connect another generator and easy control of power distribution, current flow.

CONCLUSIONS

Presented system allows easy and stable distribution of electrical power and long-term cooperation of different electrical sources such as electric generators working in parallel with changing in wide range of angular speeds. Proposed algorithms and methods are still under development by adding new generators (e.g. reluctance machine), applying and testing new control algorithm cooperating with external control signals (electronic governor).

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