Stability and control of a ship electric grid emulator

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Synopsis

This paper presents an analysis of the frequency control and stability of the ship electric power system emulator of the School of Naval Architecture and Marine Engineering of NTUA. The emulator is an AC three-phase microgrid, comprising Generation, Distribution, Consumption, Protection and Supervising Monitoring-Control sub-systems. The generation system consists of (three) small AC synchronous generators (5 to 6 kVA each), while its loads are a passive RL load and a three-phase induction motor. The system is an electric island as its frequency and voltage are defined by its synchronous generators. The use of converter-driven three-phase induction motors as prime movers of the synchronous generators results to a particular power system, with some special characteristics in its stability and control.

Keywords: Stability; ship grid emulator; educational

1. Introduction

The mandate for reduced environmental footprint of all ships according to the resolutions of the International Maritime Organization (IMO) and the European Union, as well as other governmental bodies, has led worldwide to the development of a series of measures, all under the umbrella of the sustainable decarbonisation of the maritime sector.

The improvement of the efficiency of the entire powertrain of the ship energy systems has been under investigation during the last two decades and within this context it has been shown that the extensive electrification of ship systems, including propulsion can be one good way to reach the ultimate green target at least for certain ship types.

Within this framework of ship electrification several issues during operation need to be investigated and further clarified, such as power quality problems, stability problems and short circuit faults. To this end, a ship electric grid emulator system has been materialized at NTUA. The system is actually an AC three-phase one, comprising Generation, Distribution, Consumption, Protection and Supervising Monitoring-Control sub-systems.

The aim of this paper is to present the concept of operation of this ship electric grid emulator, but also the analysis of important operating conditions of all the aforementioned sub-systems focusing on designing more efficient and environmentally friendly ships.

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2. Description of physical system and implemented model

A simplified one-line diagram (SLD) of the system is shown in Figure 1. Dashed lines indicate future installations.

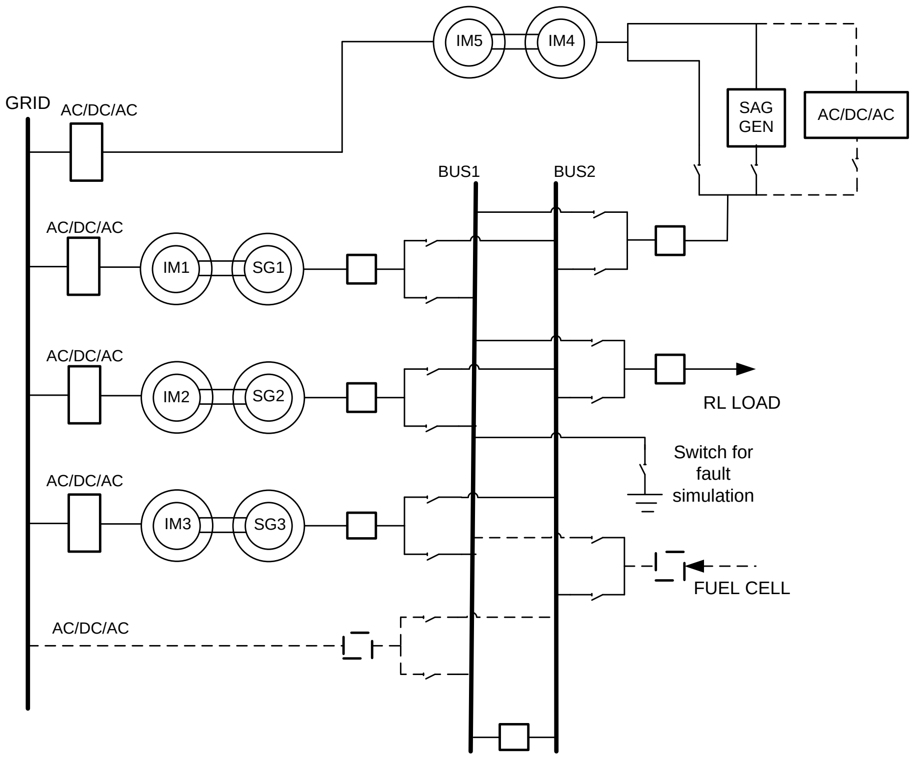

Figure 1: Single-Line Diagram of the grid emulator

The power generation sub-system comprises three synchronous generators (two of 5.9 kVA/400V/50Hz/pf=0.8 and one of 5 kVA/400V/50Hz/pf=0.8). As the generators are of low power, they produce Low Voltage (400 V), so no transformers are used in the system. Due to the difficulties of finding and installing small diesel engines, an induction motor fed by the local grid via an AC/DC/AC converter plays the role of the prime mover for each generator, while the governor operation is emulated via the power electronic inverter rotating the prime mover - electric motor. As it will be shown, this results to an adequate emulation of the droop frequency control. Also, the converter-driven AC induction motor can potentially be controlled in a way to emulate a prime mover like a diesel engine.

On the other hand, the generator output voltage is regulated via installed Automatic Voltage Regulators (AVRs). It is noted that the system is essentially electrically isolated with respect to the local grid, with the exception of auxiliary circuits (e.g. the AVRs of the synchronous generators and protection relays). This allows the emulation of the electric grid of a ship, with its protection and control systems, which is the first priority of the grid emulator.

The system loads are a passive RL load and a three-phase induction motor. Similarly to the synchronous generators (but with opposite power flow), the mechanical load of the motor is another induction motor connected to an AC/DC/AC converter and acting as a regenerative brake. The ensemble of the motor and AC/DC/AC converter can be used to simulate various mechanical loads, e.g. a propeller.

The system has been modelled in MATLAB/Simulink. Induction motor and synchronous generator models have been developed in Simulink, implementing the corresponding well-known rotating electric machine equations from (Krause, 2000). The rotating shaft of each generator set is common for the induction motor and the synchronous generator. Assuming all rotating masses can be lumped as a single one, a single equation of motion has been used for each generator set, i.e. the rotor speed is common for the induction motor and the synchronous generator. The electromagnetic torque of the induction motor (resp. synchronous generator) tends to accelerate (resp. decelerate) the rotor.

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3. Frequency control

The use of induction motors as prime movers results to a particular system with respect to Frequency Control. To demonstrate the operation principle of the grid emulator, a single generator set is analysed first, as shown in Figure 2. This can refer to either a single generator set being in operation, or an equivalent for two or three generator sets.

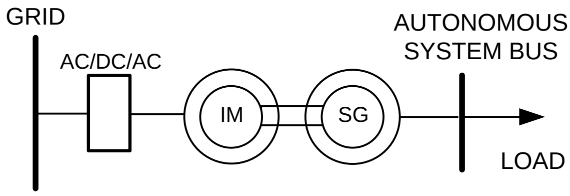

Figure 2: Single-Line Diagram of one generator set

The well-known characteristic curve of the induction motor power as a function of its rotor speed is shown in Figure 3. The induction motor is supplied with terminal voltage of nominal amplitude and frequency (50 Hz). Normal operation of the induction motor is within a narrow range close to 1 per unit (pu) rotor speed, i.e. the speed that corresponds to electrical frequency of 50 Hz, while the motor power is zero at exactly 50 Hz. For example, to supply 50% of its nominal mechanical power, the rotor speed is approximately 0.98 pu. Since the rotors of the induction motor and the synchronous generators are coupled on the same axis, the electric frequency of the autonomous system is 98% of the induction motor stator frequency, i.e. 49 Hz. The frequency of the voltage supplied to the induction motor can be adjusted, in order to have 50 Hz at the autonomous system.

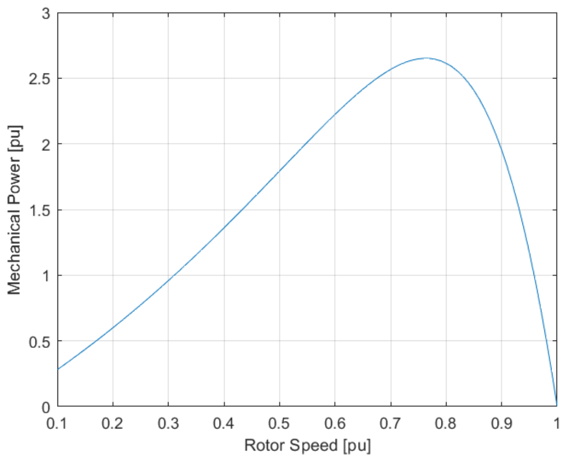

Figure 3: Power – Rotor Speed characteristic curve of induction motor

3.1. Primary Frequency Control: Step Increase of Load

To demonstrate the primary frequency control of the grid emulator, we simulate a step increase of the load, starting from an operating point with the two 5.9 kVA generators in operation (SG1 and SG2), initially supplying an RL load of 4.17 kW. At t=2 s, a 10% step increase of the load is simulated. Figure 4(a) shows that the two generators equally share the load increase, as expected since they are identical. Figure 4(b) shows the stator frequency of the two induction motors that drive the two generators (constant at 50 Hz), as well as the electric frequency that corresponds to the rotor speeds of the two generators. The common frequency of the two synchronous generators is the autonomous system frequency. After the load increase, the autonomous system frequency drops, which is the expected result of primary frequency control (Kundur, 1994). On a 5.9 kVA base, the droop of each generator can be calculated at approximately 3.2%. Therefore, the induction motor of each generator operates as an equivalent turbine with its governor and droop control. Approximating the characteristic curve of Figure 3 to be linear at the normal operating region, its slope defines the droop of the equivalent governor, defined as:

$$R = \frac{\Delta f}{\Delta P}$$

, where Δf is the steady-state change of the frequency in pu and ΔP is the steady-state change of active power in pu. On a 5.9 kVA base, the droop of each generator can be calculated at approximately 3.2%.

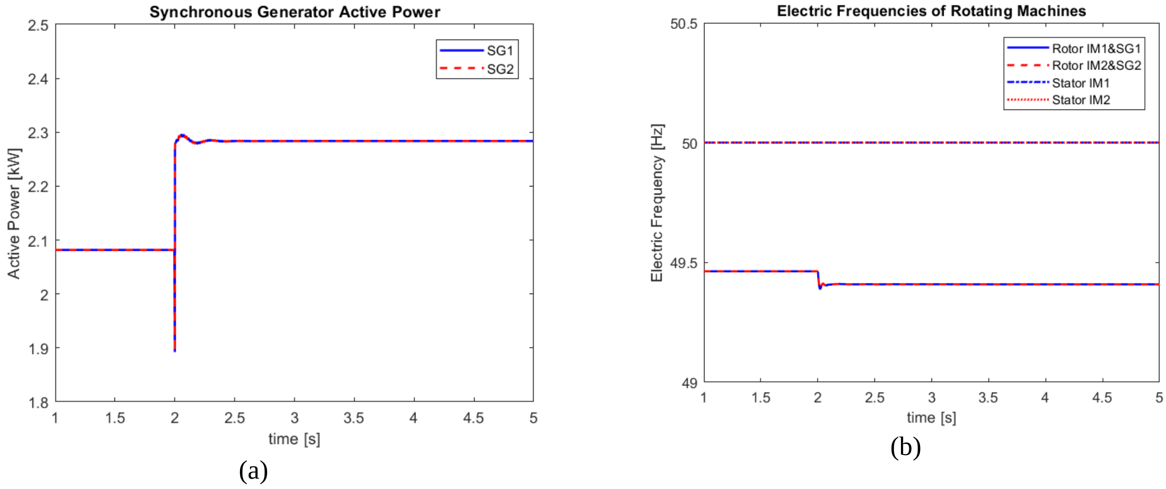

Figure 4: Response to a load step change: (a) Active power of synchronous generators and (b) rotating machines' frequencies

3.2. Secondary Frequency Control: Step change of induction motor frequency

Next, the system response to a step change of the electric frequency of the voltage applied to one of the induction motors (IM2) is examined. This results to a shift of the corresponding power-speed curve of Figure 3 to the right, so that zero power corresponds to 51 Hz. Figure 5 shows the original curve (blue, continuous), together with the shifted curve (red, dashed).

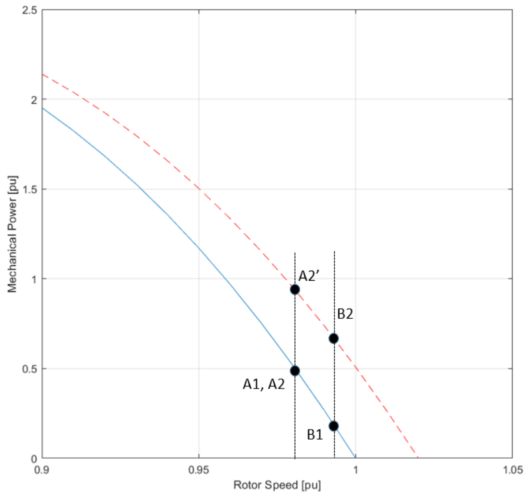

Figure 5: Power – Rotor Speed characteristic curves of induction motors

If the two motors initially operate at the same operating point (A1, A2) and at equilibrium (i.e. their output power matches the load), they provided equal mechanical power. Given that their rotors are synchronised via the autonomous system, they have the same rotor speed at equilibrium. Assuming that after the step change of its stator electrical frequency, IM2 maintains the same rotor speed, it would operate at point A2', while IM1 remains at A1. However, there is no equilibrium under these conditions, since the total sum of power from IM1 and IM2 exceeds the load power. Therefore, the motors will accelerate, i.e. their operating points will move to the right. An equilibrium is possible at operating points B1 and B2, where the total power sum is the same with the initial equilibrium point.

The dynamic response of the system is shown in Figure 6. Figure 6(a) shows the active power of each synchronous generator, while Figure 6(b) shows the frequencies of the rotating machines. In the latter, the applied step change can be seen in stator frequency of IM2.

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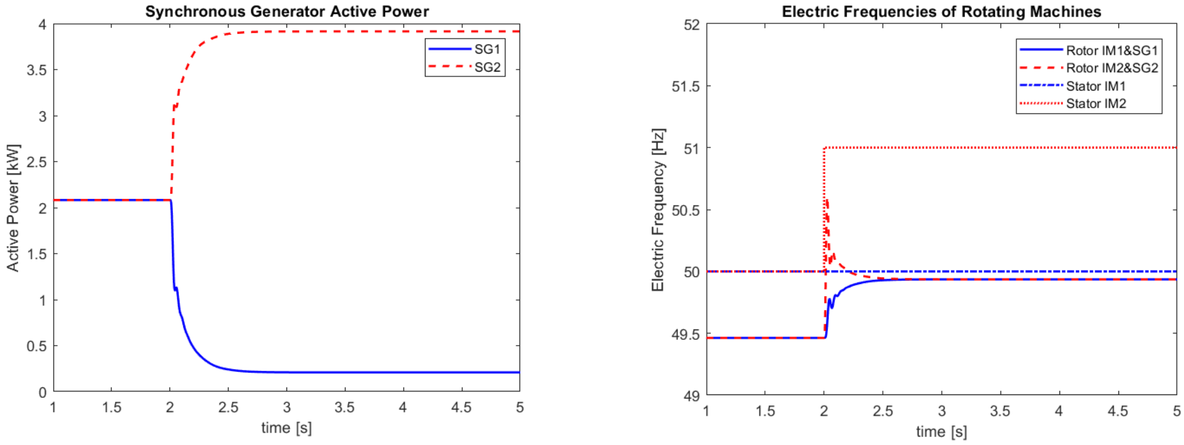


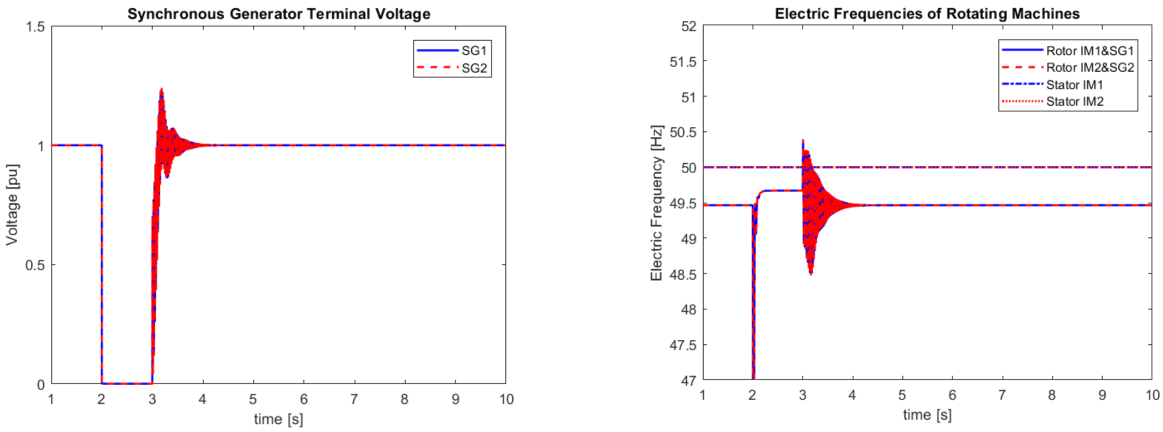
(a) (b)

Figure 6: Response to a step change in the frequency of the voltage applied to IM2: (a) Active power of synchronous generators and (b) rotating machines' frequencies

As expected, the results of Figure 6 show that SG2, which is driven by IM2, takes now a higher share of the load power, while the autonomous system settles at a higher frequency. Therefore, adjustment of the difference of stator frequency of IM1 and IM2 provides a means for regulating power sharing and system frequency.

4. Large-disturbance stability

In this section, the response of the autonomous system to three-phase faults is examined from the stability point of view. A three-phase fault is simulated at the AC bus of the autonomous system by decreasing temporarily the load inductance to a very small value at t = 2 s. The terminal voltages of the two synchronous generators, shown in Figure 7(a), are identical as they are connected at the same AC bus, without transformer. Figure 7(b) shows the rotor speeds (frequencies) of the two machines. It can be seen that the system reaches a steady-state equilibrium during the fault at a higher rotor speed.

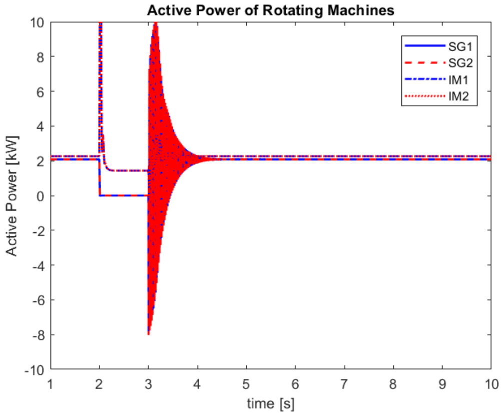


(a) (b)

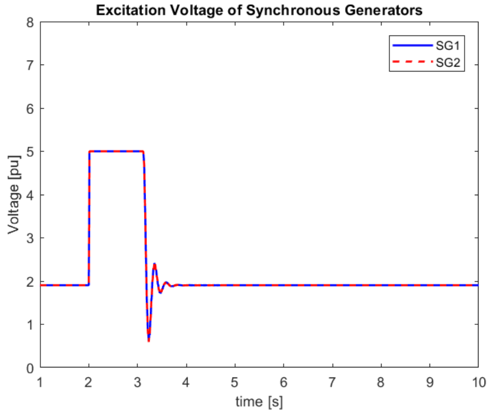
Figure 7: Three-phase fault response: (a) Synchronous generators' terminal voltage (a) and rotating machines' frequencies

Figure 8(a) shows the active power of the rotating machines. During the fault, the power into the induction motors reaches a new steady-state value. As the active power of the synchronous machines is zero during the fault, all the power of induction motors is consumed in losses. Figure 8(b) shows that during the fault the excitation voltage of the synchronous generators is limited to its maximum value.

As in common autonomous systems, the risk of loss of synchronism is very small, since the generators accelerate together. However, in the specific system, overfrequency also appears not to be of concern. Indeed, as the power in an out of the induction motors is reduced, their speed is increased, however it is limited at their stator frequency which corresponds to zero mechanical power.



(a)



(b)

Figure 8: Three-phase fault response: Synchronous generators' (a) active power (a) and excitation voltage

5. Conclusions

This paper presented an analysis of the frequency control and stability of the ship electric power system emulator of the School of Naval Architecture and Marine Engineering of NTUA. The emulator is an AC three-phase islanded microgrid, comprising Generation, Distribution, Consumption, Protection and Supervising Monitoring-Control sub-systems.

It was shown that the use of converter-driven induction motors as prime movers for the synchronous generators results to a peculiar system with special characteristics. The slope of the induction motor power-speed curve defines the droop of the equivalent prime mover (primary frequency control), while modifying the stator frequency of the induction motors can be an effective way for power sharing and secondary frequency control.

Finally, the autonomous system response to three-phase faults has been analyzed and it has been shown that it reaches a steady-state equilibrium if the fault duration is high enough. Therefore, no risk of either losing synchronism or overfrequency occurs.

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