DYNAMIC SIMULATIONS OF A LARGE HIGH-FREQUENCY POWER SYSTEM

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Abstract

Dynamic simulations to assess performance aspects of a large high-frequency power system have been conducted. The analysis uses a model of an 80-MW power system for an all-electric ship. The model, developed in the Matlab/Simulink environment, includes several power generation units, two propulsion power trains, an energy storage system, a high-power pulse load, and several service loads. Three case studies were addressed. The first considers the response of the power system to a high-power step load, representing a sudden request for acceleration of the ship. The second deals with the effects of a partial loss of generation during operation. The third addresses the effects of load drop on the power system.

1. INTRODUCTION

Utility-type power systems that transmit power long distances have constraints on the transmission frequency to limit losses. In contrast, multi-megawatt power systems that operate in small environments, such as an all-electric ship or a large commercial airplane, do not have this restriction because they require much shorter cables to transmit power to their loads. This distinction allows such autonomous power systems the use of frequencies higher than the conventional 60-Hz or 50-Hz.

The main advantage of using high frequencies in power systems is size reduction. This size reduction is achieved by using high-speed generators, eliminating the use of gear boxes, and using high-frequency transformers for power conversion and distribution whenever appropriate [1-4]. However, there are disadvantages as well, mainly electric losses. A compromise frequency that balances size-reduction benefits with the electric losses is therefore necessary. In this analysis, a compromise frequency of 240 Hz was selected.

It is recognized that aircraft have adopted 400 Hz components, but they require less power than ships. Ships typically require 50-100 MW or more. Larger generators turn more slowly and so would require a large number of poles. Based on generator considerations, 240 Hz was judged to be a good compromise between 60 Hz and 400 Hz.

While size reduction benefits and efficiency deterioration associated with high-frequency are well understood, another important aspect needs to be addressed. Mainly, the dynamic performance of a high-frequency, multi-megawatt, power system. A basic assessment of the dynamic behavior is necessary to determine whether a high-frequency power system for an all-electric ship is a viable choice that warrants further research and development efforts.

In this paper, we address some aspects of this issue through modeling and simulation. The modeling approach is described in section 2, , the high-frequency (HFAC) power system model is described in section 3,results of the dynamic simulations are presented and discussed in section 4, and the summary is in section 5.

2. MODELING APPROACH

The high-frequency power system considered in this analysis presents a very challenging problem to solve on desktop computers, mainly due to the long solution time it requires. The solution time is very long because a short integration time is required to solve a very large number of differential equations with a time resolution that allows the capture of crucial dynamic events, and an adequate simulation time that accounts for slower events and/or multiple events. The presence of power electronics components such as motor drives, rectifiers, and other converters, exacerbates the problem further since related switching events need to be modeled with high fidelity for a credible dynamic analysis.

One approach to solve this problem is to use supercomputers that are often available in academia and in some public and private institutions. However, accessibility is often limited and their use requires that the users develop and program their own solvers.

A second approach is to take advantage of the rapid development of multi-core technology which is enabling significant computing power in desktop computers. As in the case of supercomputers, their use also requires developing and programming solvers for the models since commercial software has not yet caught up with this new hardware development.

A third approach to mitigate the long solution time problem is to seek a compromise between a reduced resolution and a reasonable solution time. This is the approach we used in this analysis. By choosing a fixed time step of 10 µs, the solution time for a 10 s scenario is reduced from days to hours as compared to a 1 µs time step. In addition, we used a high-performance desktop computer with a large memory (24 GB RAM) and a 3.33 GHz processor speed. The drawback with this approach is that we miss dynamic events with a time-resolution shorter than 10 µs, if any.

Most of the case studies or scenarios we need to analyze do not require that the turbo-generators be ramped-up from rest, a process that takes a long time to simulate and is generally uninteresting. A computationally efficient approach we use is as follows. For each set of analyses with a particular power system configuration that does not require a change of components, an initialization run is conducted by ramping up the turbo-generators from rest to rated speed while all breakers are open, i.e., power is not supplied to the loads except for the small parasitic loads that are connected to the generators' terminals (a software requirement to maintain numerical stability). Once the run is completed, the final states are saved and used as initial conditions for subsequent analyses. The initialization run takes about nine hours to complete a 120 s ramp-up of the four turbo-generators. Using these initial conditions, typical 10 s case studies are completed in less than two hours. The choice of 10 s for the simulation time is based on the gas turbines' time response which is slow and in the range of few to several seconds. Several case studies can use the same initial conditions, thereby shortening the solution time. All three case studies presented in this paper used the same initial conditions.

3. HFAC POWER SYSTEM MODEL

The top-level model of an 80 MW, 240 Hz, 4.16 kV high-frequency power system (HFAC) is shown in Figure 1. It is consistent with the baseline architectures developed by the Electric Ship Research and Development Consortium [5]. The model was developed in the Matlab/Simulink environment and includes four turbo-generators, two propulsion power trains, a radar load, a high-power pulse load, a super-capacitor energy storage system, four load zones with a total of 22 loads, several power conditioning modules, cables, and breakers. The loads include constant impedance, constant power, and uncontrolled motor loads.

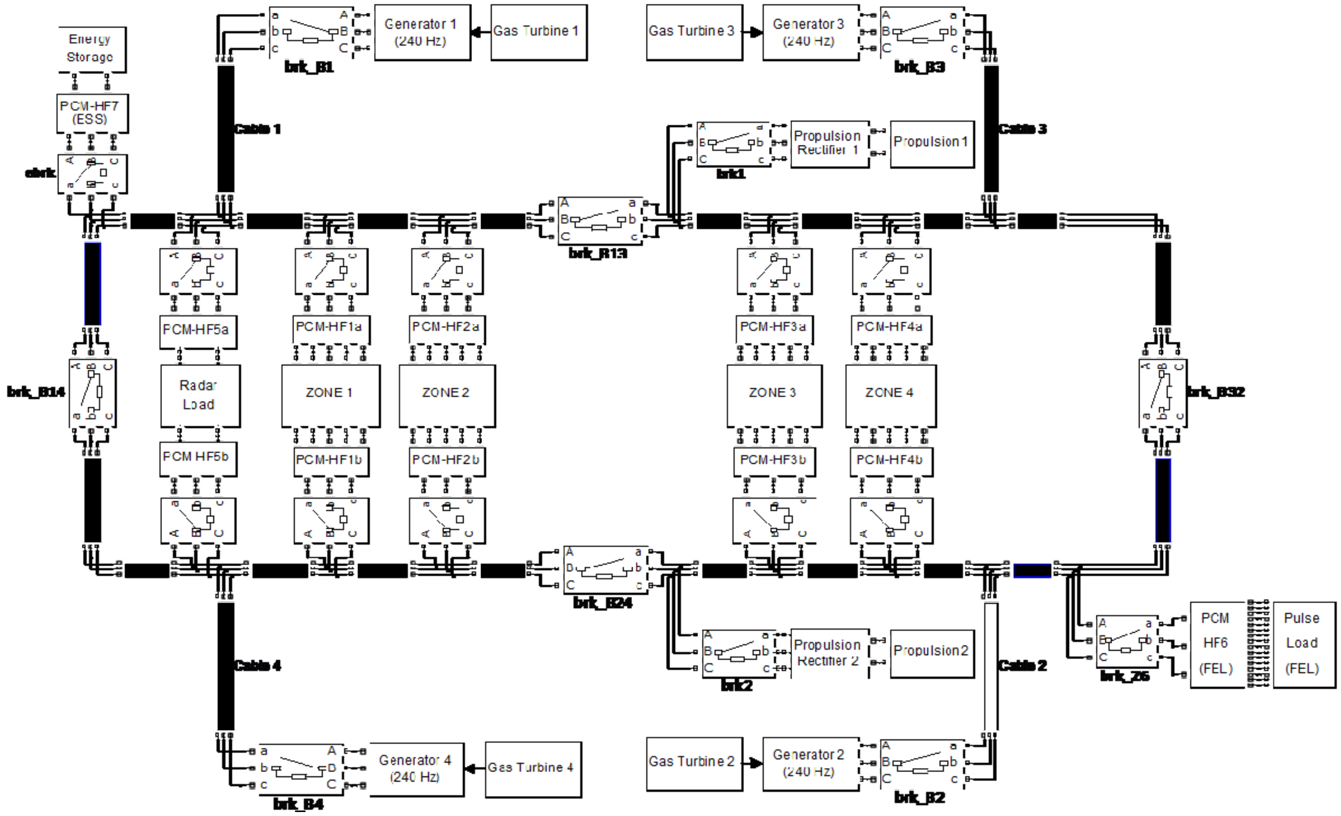

Figure 1. High-frequency power system model

4. DYNAMIC SIMULATIONS

The goal of this study was to assess the ability of the model to predict the dynamic behavior of the power system under prescribed conditions. These prescribed conditions, often called scenarios or case studies, represent realistic events that are expected to occur during operation of the power system and are deemed crucial for predicting its performance. Three case studies were selected for this study.

4.1. Case Study 1: Sudden Acceleration

Propulsion load is the largest consumer of power in an all-electric ship. It consumes ~90% of installed power at full load but uses much less power when in cruising mode: ~17% of installed power only. In a situation where the ship needs to take evasive actions, a sudden acceleration to bring the ship to full speed may be required. This results in a fast transfer of a large amount of power, up to ~60 MW, from the distribution bus through which all other loads are also supplied. What is the dynamic behavior of the power system under such conditions? The aim of this first case study is to answer this question. The simulation sequence of events was as follows:

1. Establish steady state condition just before time t = 7s
   - The ship is now sailing at cruising speed with propulsion consuming: ~14 MW
   - Radar in cruising mode: ~2.85 MW
   - Pulse load in operational readiness mode: ~1.45 MW
   - Zonal loads in cruising mode: ~6.05 MW
   - Total initial load power: ~24.4 MW, available power: ~55.6 MW
2. Initiate acceleration at time t = 7 s
   - Increase propulsion power command from 14 MW to 60 MW (an increase of 46 MW)
   - Allow the propulsion motor speed to increase to maximum speed allowed by available power and propeller loading condition
3. Stop simulation at t = 10 s

These are expected to be reasonable in future ships, but are not intended to be representative of any present ship.

To establish the steady state condition by time t = 7 s, the following simulation sequence is applied:

1. Start simulation at time t = 0 s using saved initial conditions
2. Close all four generator breakers at t = 0.1 s
3. Connect all four generators in parallel: close all four ring bus breakers, at t = 0.5 s
4. Supply power to zonal loads, radar load, and pulse load (up to standby mode only, no high-power pulse) between t = 2 s and t = 4 s
5. Assign 14 MW of power to propulsion load at t = 4 s, assuming the ship has an initial speed close to cruising speed; this will bring the propulsion to steady state condition very quickly
6. The ship is in steady state by t = 7 s

Several data sets are recorded during the run and three particular parameters are considered first. These are gas turbines' speeds to assess controllability and frequency change, bus voltage to assess stability and amplitude changes, and load sharing among the four generators to further assess controllability.

4.1.1 Turbo-generators' Speeds

Figure 2 shows the four gas turbines' speeds during the simulation. Note that ~2 s after the generators were connected in parallel, the turbines' governors were able to bring the turbines' speeds to a common value and keep them under control through the sudden acceleration with the clear large speed drop and slow recovery. The important result is that the sudden acceleration requiring an extra 45 MW of power for the propulsion load didn't cause a loss of turbine control. In addition, the transient difference in shaft speeds is less than 2%.

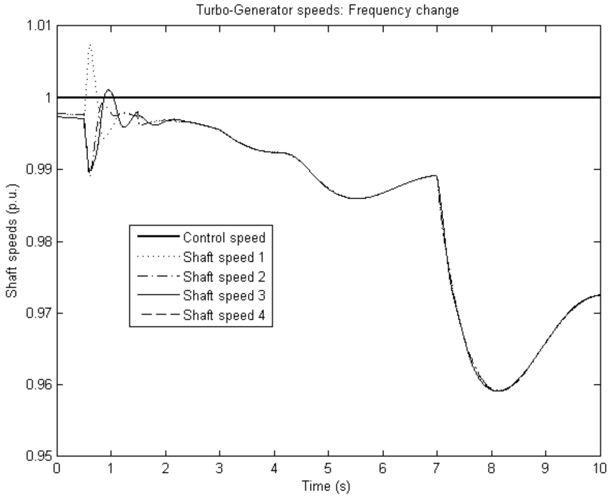

Figure 2. Turbo-generators speeds

4.1.2 Bus Voltage

Figure 3 shows bus voltage during the simulation. The changes seen in the voltage trace are best understood by following the sequence of event given in section 4.1. A large voltage sag is clearly apparent during the sudden acceleration beginning at t = 7 s. An expansion of the voltage trace around the sudden acceleration is shown in Figure 4. The amplitude drops by ~15% and the frequency drops to ~230 Hz.

The voltage trace during the acceleration event appears noisier, indicating a large harmonic content. This is not surprising given the fact that a very large amount of power is extracted from the bus through two six-pulse rectifiers. The extent of this bus pollution can be estimated further by calculating the THD level.

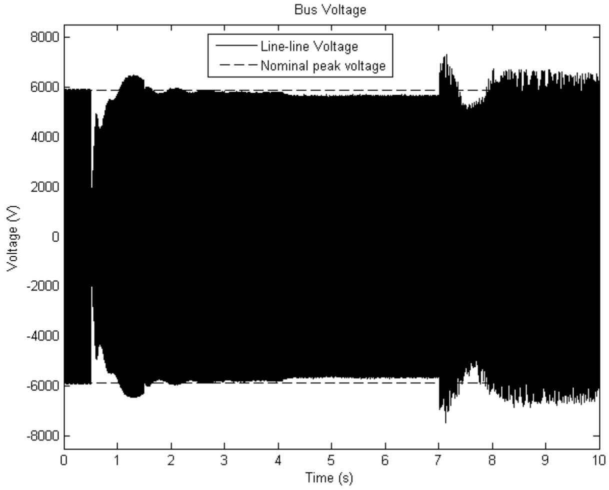

Figure 3. Bus voltage before and after sudden acceleration

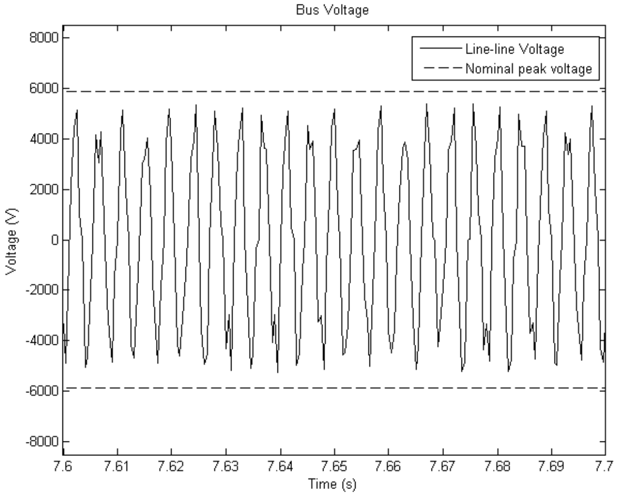

Figure 4. Voltage and frequency change during sudden acceleration

4.1.3 Load Sharing

Figure 5 shows load sharing among the four generators during the sudden acceleration event. This result indicates that proportional load sharing is established once steady state is obtained and is maintained during the sudden acceleration event. The four generators consist of two identical large generators and two identical but smaller generators. This explains the appearance of only two traces instead of four. In addition, a large spike appears in the power traces for a short period of time at the beginning of the sudden acceleration. This is also seen in the propulsion motor output power and torque traces. It is possible to design machines that are capable of producing higher power levels than their rated values, but for a short period of time. Motor control parameters can also be adjusted to reduce the amplitude of this spike.

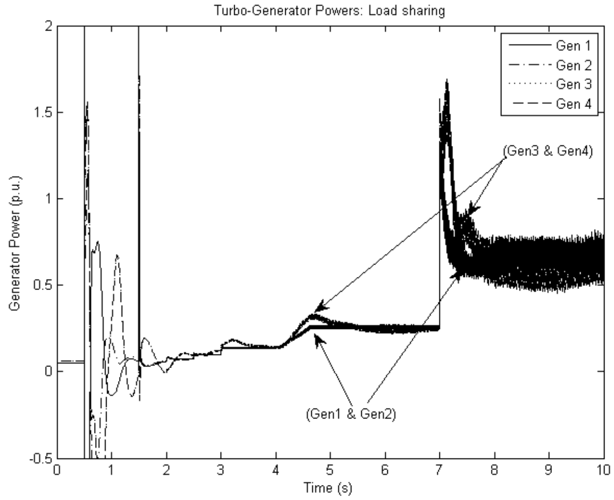

Figure 5. Load sharing during the sudden acceleration event

4.1.4 Propulsion Motors

Speed and power of one of the propulsion motors are shown, respectively in Figure 6 and Figure 7. Motor speed reaches the speed value of ~73 rpm, which corresponds to a ship cruising speed of ~20 knots, relatively quickly. This is so because the initial ship speed was set very close to 20 knots when the propulsion started at t = 4 s. Notice the spike in motor power trace at the start of the sudden acceleration.

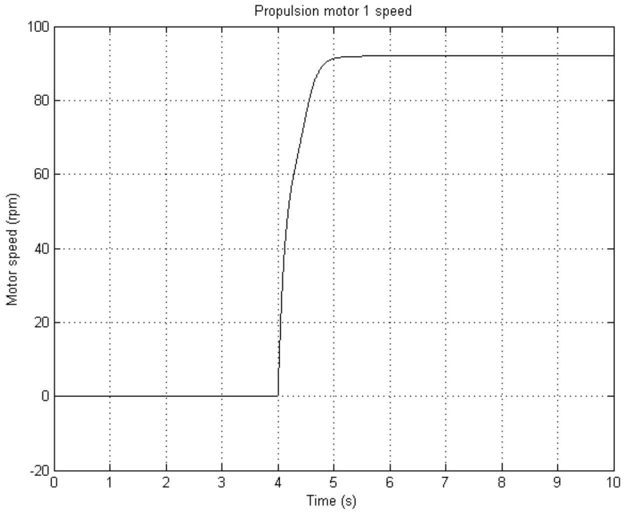

Figure 6. Propulsion motor speed during the sudden acceleration event

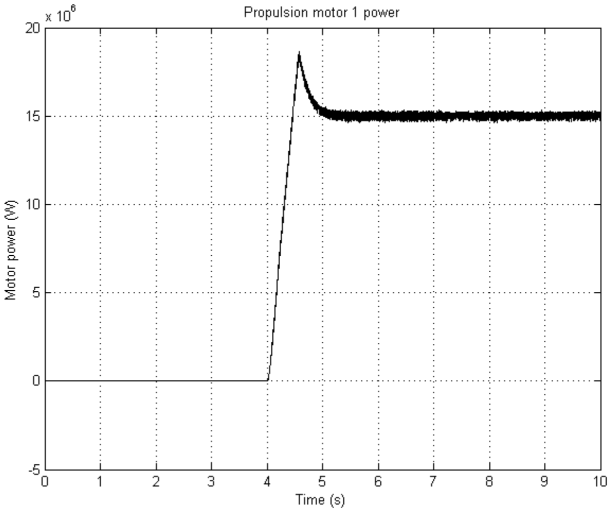

Figure 7. Propulsion motor power during the sudden acceleration event

4.2. Case Study 2: Partial Loss of Generation

In the second case study, one of the large generators was taken offline during normal operation by tripping its breaker open. This is breaker brk_B1, located at the top left corner of Figure 1. The simulation sequence swas as follows:

1. Establish steady state condition just before time t = 7 s. This is identical to the previous case except that the propulsion power is ~30 MW.
   - The ship is now sailing at ~25 kn with propulsion consuming: ~30 MW
   - Radar in cruising mode: ~2.85 MW
   - Pulse load in operational readiness mode: ~1.45 MW
   - Zonal loads in cruising mode: ~6.05 MW
   - Total initial load power: ~40.4 MW, available power: ~40.3 MW
2. Initiate generator loss at time t = 7 s
   - Open breaker brk_B1
   - Available power is now: ~4.3 MW
3. Stop simulation at t = 10 s

4.2.1 Turbo-generators' Speeds

Figure 8 shows the change in the turbo-generator shaft speeds during the generator loss event. As expected the speed of the tripped generator increases at the start of the event but the gas turbine governor prevents it from increasing further. The speeds of the three other generators decrease as they pick-up more load but remain under good control.

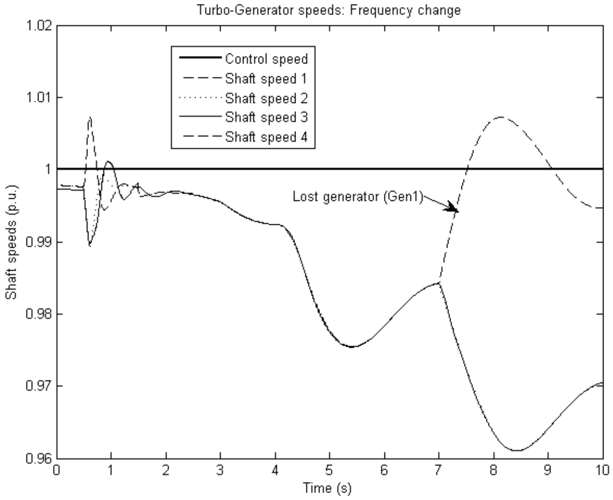

Figure 8. Turbo-generators speeds, green curve is speed of dropped generator

4.2.2 Bus Voltage

Figure 9 shows the change in the bus voltage during the simulation event. As indicated earlier, the changes in the voltage signal can be easily correlated with the corresponding simulation sequence. A drop in bus voltage is observed just at the start of the transient event. The voltage recovers some after the transient event, but settles at a smaller voltage value. This is acceptable since each of the remaining generators is supplying a higher load requiring higher current and resulting in a higher voltage drop across the machine impedance. In principle, the excitation system should have been able to maintain voltage close to the nominal value, indicated by the dashed lines in all voltage traces. This indicates that the exciter parameters will need to be re-adjusted.

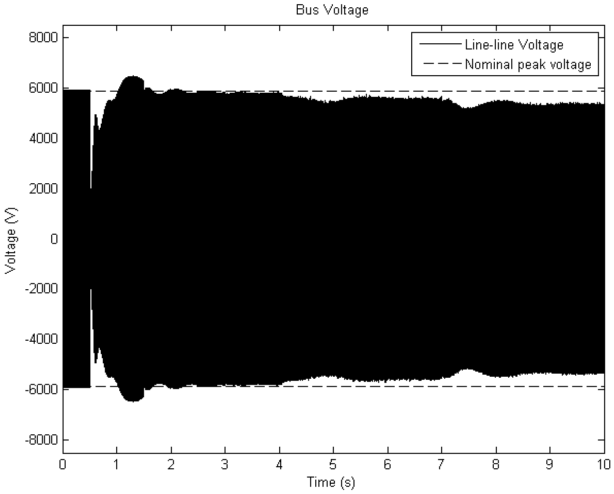

Figure 9. Bus voltage

Further expansion of the voltage trace just after the transient event is shown in Figure 10. It clearly shows a voltage drop and less harmonic content than in the previous case.

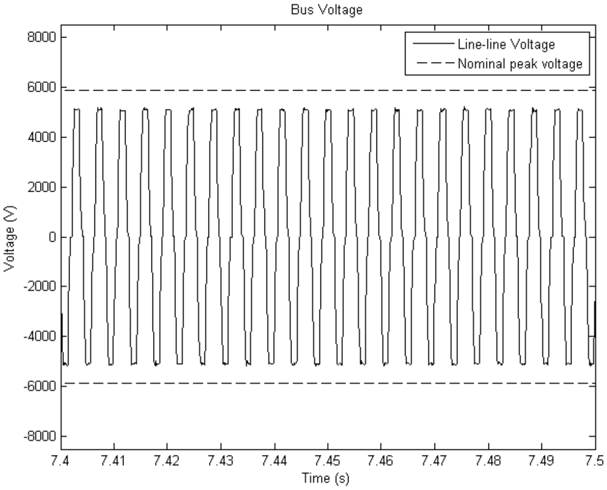

Figure 10. Bus voltage drops after a loss of a generator

4.2.3 Load Sharing

Figure 11 shows load power distribution among the four generators before the loss event and among the remaining three generators afterward. This result indicates that the remaining generators successfully picked up the load rejected by the lost generator and re-established proportional load sharing only a few seconds after the transient event.

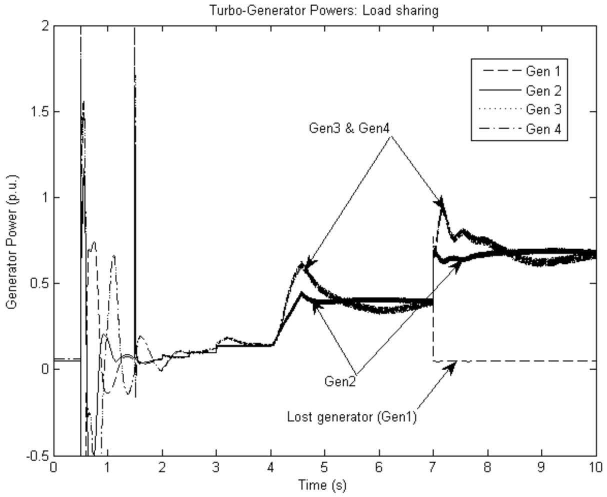

Figure 11. Load sharing during the generator loss event

4.2.4 Propulsion Motors

The speed and output power of one of the propulsion motors are shown in Figure 12 and Figure 13, respectively. Both traces show that the motor is basically unaffected by the generator loss event.

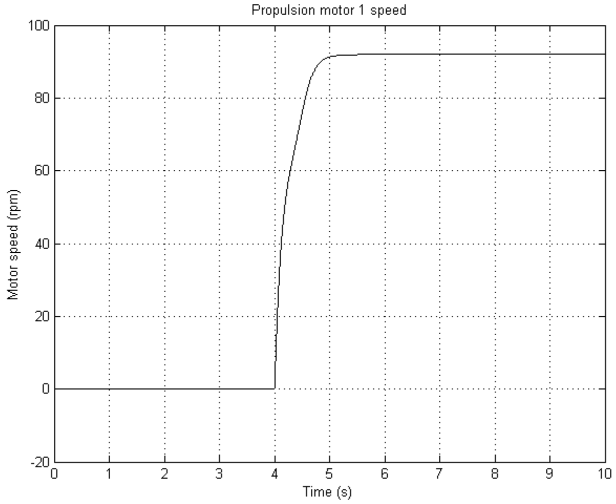

Figure 12. Propulsion motor speed during the loss of a generator

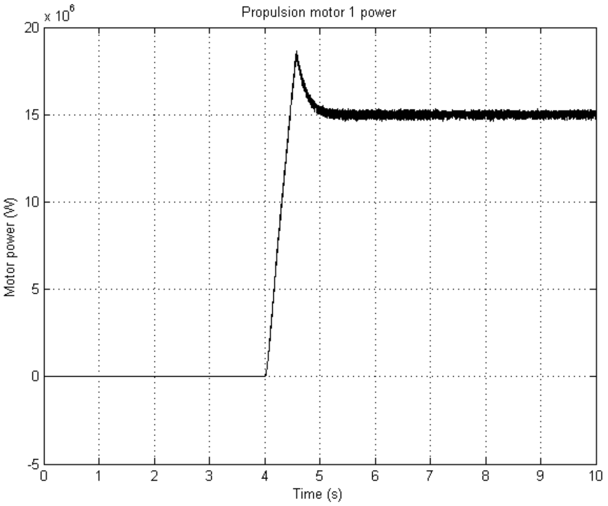

Figure 13. Propulsion motor output power during the loss of a generator

4.3. Case Study 3: Load Drop

In the third case study, a set of loads are suddenly disconnected from the main ring bus during normal power system operation. This is achieved by opening the breakers supply loads in zone 2 and zone 3 corresponding to a total load drop of ~3.8 MW. The simulation sequence of events is similar to case study 2 with the transient event initiated at time t = 7 s.

The results show no significant disturbances in the power system during the transient events. Generator shaft speeds, bus voltage, and load sharing distribution are shown in Figure 14, Figure 15, and Figure 16, respectively. A more interesting case to study would be to disconnect a much larger load such as the propulsion load. This will be considered in future work.

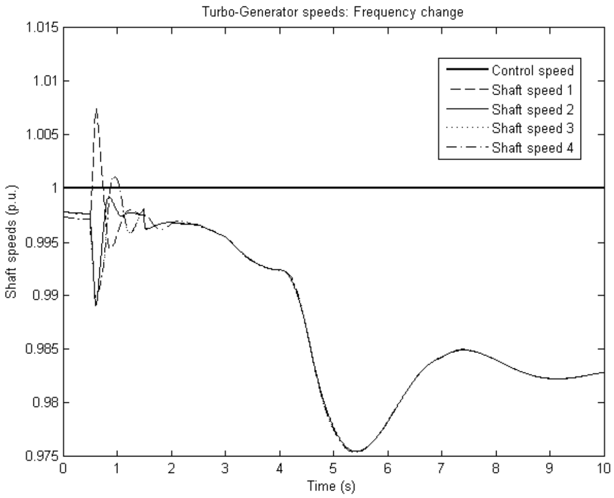

Figure 14. Turbo-generators speeds during load drop event

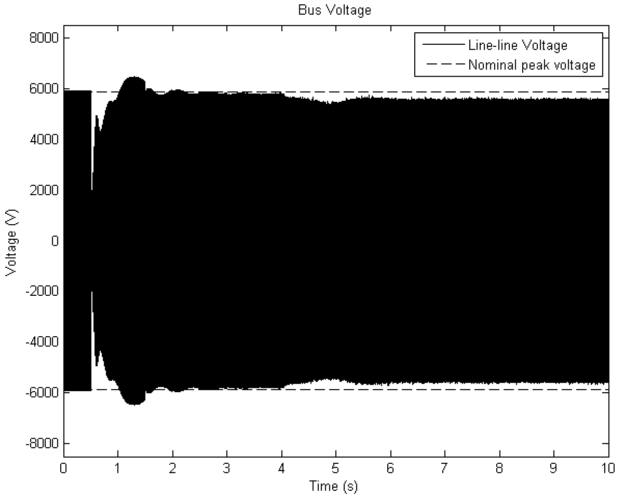

Figure 15. Bus voltage during load drop event

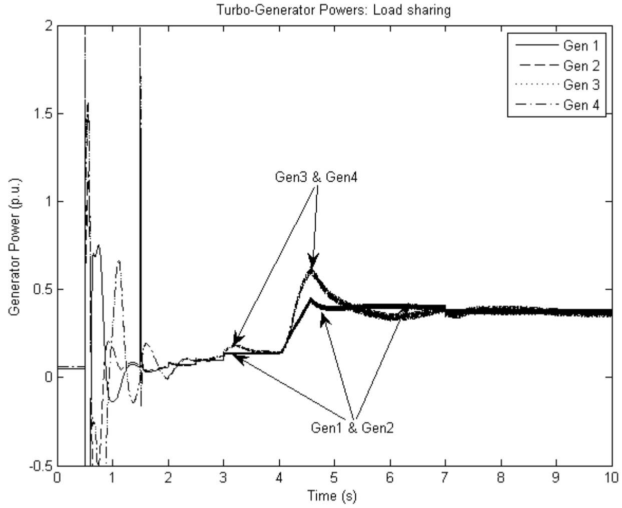

Figure 16. Load sharing during load drop event

5. SUMMARY

Dynamic simulations of a 240 Hz high-frequency power system have been conducted. The analysis used a model of an 80-MW power system for an all-electric ship developed in the Matlab/Simulink environment. Three case studies were considered. The first case addressed the response of the power system to a sudden acceleration. The second case considered the effects of a partial loss of generation during operation. The third case addressed the effects of a sudden load drop on the power system. For the first and second cases, the power generating units remained under control, while bus voltage dropped but didn't collapse. Proportional load sharing among the operating turbo-generators was successfully re-established a few seconds after the transient events. For the third case, the results show no significant effects on the power system when a 3.8 MW load is suddenly disconnected from the main bus while the system is operating at 50% capacity. Further dynamic simulations are planned in future work.

ACKNOWLEDGEMENT

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BIOGRAPHIES

Dr. Robert E. Hebner is the Director of the Center for Electromechanics at the University of Texas at Austin. The Center develops advanced energy technology and teams with companies to get the technology to market. Previously, he was acting Director of NIST with an annual budget of about $750 million. He worked in OMB on the technology portions of the Administration's 1990 budget and at DARPA to advance semiconductor manufacturing. He has extensive experience in measurement systems needed to support global trade and in developing government technology programs to stimulate the economy. He is a fellow of the IEEE.

Dr. Joseph H. Beno has served as program manager of the Electric Vehicle, Space Power, and Off-road Mobility programs since 1993 and is also an Associate Director at the University of Texas at Austin Center for Electromechanics. During this time, he served as PI or co-PI on numerous research programs from Government and commercial sponsors to address major technology thrust areas in precision actuator and telescope systems technology, active suspension systems, advanced controls, high performance magnetic bearings, high-speed rotating machines, and high speed composite flywheel energy storage systems. His typical programs include both Government and non-Government applications and combine users, manufacturers, research organizations, and Governmental organizations to develop prototype hardware that can be transferred to industry.

Prior to joining UT-CEM, Dr. Beno served for 22 years as a career Army Officer, retiring as a Lieutenant Colonel. He has authored or co-authored over 35 refereed/archival publications, holds two patents, and has one patent pending concerning active suspension actuator technology. His primary areas of expertise include high performance actuator technology, electromechanical system analysis/simulation, active suspension system technology, flywheel energy storage system technology, control systems, and program management.

Dr. A. Ouroua has BS, MS, and PhD degrees in physics and works as an analyst of electromechanical systems.