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Presented is a comprehensive power model for the Flywheel Attitude Control, Energy Transmission, and Storage (FACETS) system located at the Air Force Research Laboratory Space Vehicles Directorate at Kirtland AFB, NM. The system consists of three advanced flywheel units and the Agile Multi-Purpose Satellite Simulator (AMPSS). The purpose of FACETS is to demonstrate integrated attitude control maneuvers and energy storage. The FACETS power model is constructed using blocks provided in the Matlab Simulink package. Several electrical elements are represented by state space averaged models using Cuk's methods for averaged power converters. The model is demonstrated over an orbital profile derived from a notional space radar application. The model is verified by comparing the performance to previous power subsystem simulations produced by the FACETS program.

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Simulation of Flywheel Energy Storage System

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Abstract—Presented is a comprehensive power model for the Flywheel Attitude Control, Energy Transmission, and Storage (FACETS) system located at the Air Force Research Laboratory Space Vehicles Directorate at Kirtland AFB, NM. The system consists of three advanced flywheel units and the Agile Multi-Purpose Satellite Simulator (AMPSS). The purpose of FACETS is to demonstrate integrated attitude control maneuvers and energy storage. The FACETS power model is constructed using blocks provided in the Matlab Simulink package. Several electrical elements are represented by state space averaged models using Cuk's methods for averaged power converters. The model is demonstrated over an orbital profile derived from a notional space radar application. The model is verified by comparing the performance to previous power subsystem simulations produced by the FACETS program.

INTRODUCTION

Flywheels have become increasingly popular in pulse power applications over traditional electrochemical batteries. The efficiency has grown due to advances in composite rotor design and magnetic bearings [1]. The high hoop strength of carbon composite rotors, compared with their metal counterparts, allows wheel speeds to increase as high as 60,000 rpm in some cases. Magnetic bearings reduce parasitic energy losses enabling long term energy storage.

The FACETS program, located at the Space Vehicle Directorate of the Air Force Research Laboratories at Kirtland Air Force Base, NM, employs three flywheel units and the Agile Multi-Purpose Satellite Simulator (AMPSS). The flywheels have a maximum angular velocity of 40,000 rpm allowing them to kinetically store 1kWhr each. An air bearing supports the entire AMPSS test article, allowing for three-axis rotational motion while minimizing external damping.

POWER PROFILE

A notional space radar application was selected for the FACETS mission profile. Space radar requires extremely large pulse power and therefore is an ideal application for flywheel technology. A space radar power profile is shown in Figure 1.

The FACETS power system operates in three modes; charge, discharge and standby. The charge mode takes place while the spacecraft is in view of the sun and the power demands are lower than the incoming solar power. In this mode, the solar arrays provide the power to spin-up the flywheels and power the housekeeping of the spacecraft. The discharge mode takes place during eclipse or high power demand

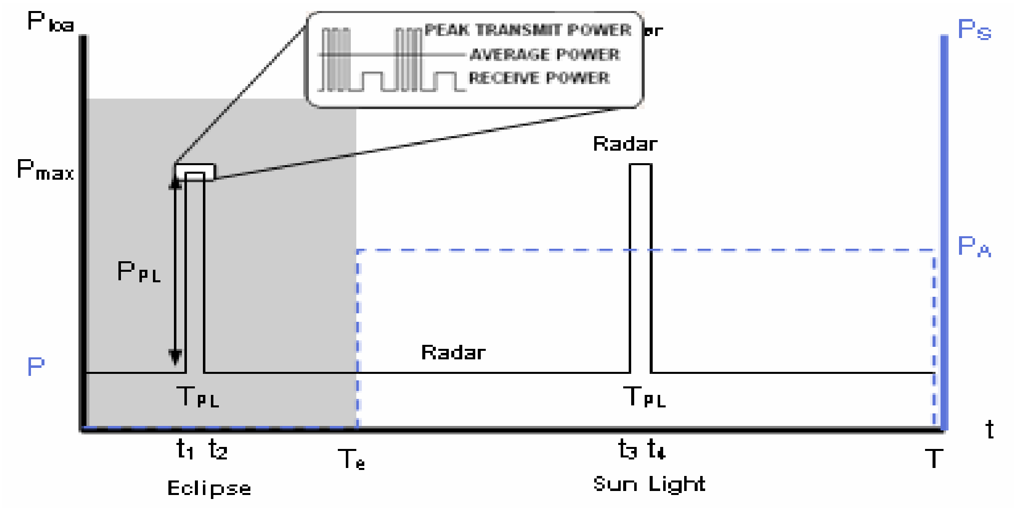


Fig. 1 Approximate Power Profile for Space Radar

periods. During this mode the flywheels provide power to the spacecraft and space radar systems. The third mode, standby, occurs when sunlight is available but the wheels have reached their maximum rated spin speeds.

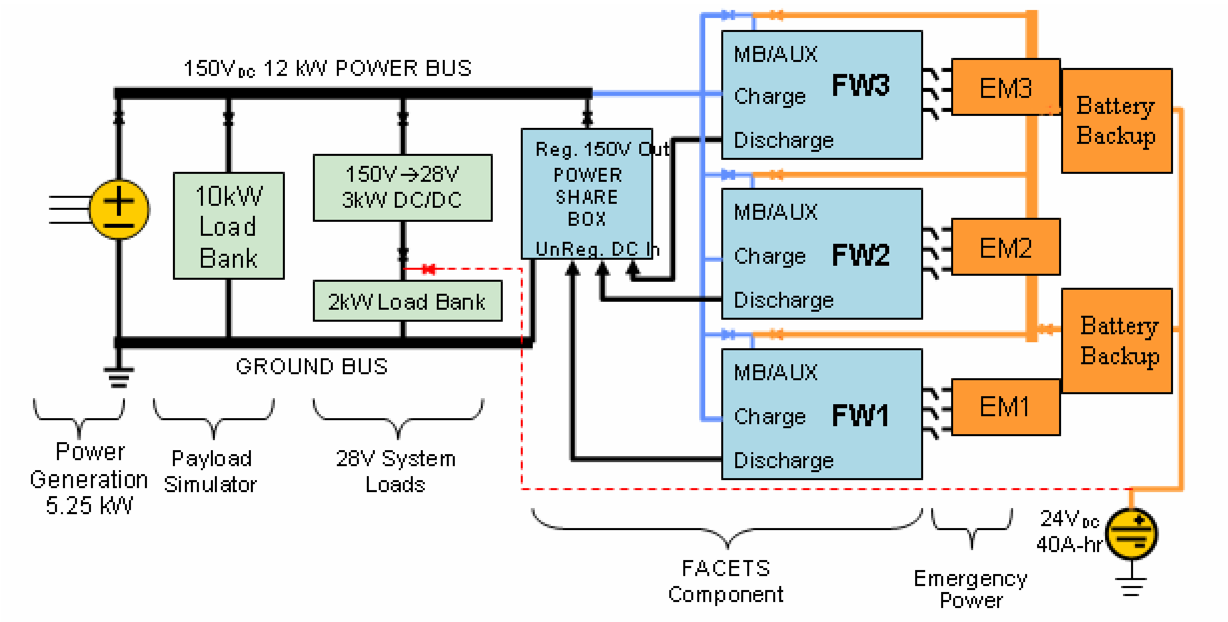


Fig. 2 FACETS Power Subsystem

POWER SUBSYSTEM

The FACETS power system is shown in Figure 2. The power subsystem consists of three flywheel units connected in parallel to the 150V main bus. The solar array is connected to the main bus as well. The main bus is connected to the 28V bus through a buck converter to provide housekeeping power for the spacecraft. In charge mode the flywheels are connected to the main bus via the buck converter. The buck converter sets the DC voltage of the inverter which determines the rate at which the wheels spin up. In discharge mode the wheels are connected to the main bus via the rectifier and boost converter. In standby mode, the wheels are not connected to the main bus.

FACETS Power System Model

The FACETS power system was modeled using Matlab Simulink. The motor and three phase inverter were modeled using the Permanent Magnet Synchronous Machine and the Universal Bridge Simulink blocks respectively. High fidelity electrical models of the DC/DC converter and three phase rectifier were too computationally intensive and were replaced with state space averaged models using Middlebrook's method [2,3]. These proved to be overly idealized; boosting voltages that were well outside the realistic range. Therefore Middlebrook and Cuk's state space averaging method [4,5] was used to account for parasitics in the converter and produce a realistic voltage range. This method was used to model the three phase rectifier and the PWM controller on the inverter.

A. Model Implementation

In the model, power comes from the solar panel via the Signal Builder block and a controlled voltage source. This allows the simulation to accurately model the output of the solar panel for an orbital period. The solar panel is connected to the spacecraft's primary 150V bus which has a nominal internal resistance. In charge mode, the bus sends power to the PWM controller which acts as a buck converter. This controls the DC voltage that is tied to the inverter which in turn provides control over the rate at which the wheels spin up. This rate is important for attitude control maneuvers, as disturbance torque can be controlled. After the PWM controller, the output DC voltage enters the three phase inverter. The gates of the inverter are controlled by Decoder Blocks which are tied to the Hall sensor outputs of the motor. These blocks allow the BLDC motor to retain the correct synchronicity even when the load is changed. Between the inverter and the motor there is a motor/generator block, described in Figure 3, which allows the simulation to switch between charge, discharge, and standby modes. The power subsystem of FACETS does not employ a bidirectional converter for the motor and must separate from the inverter in order to discharge through the rectifier.

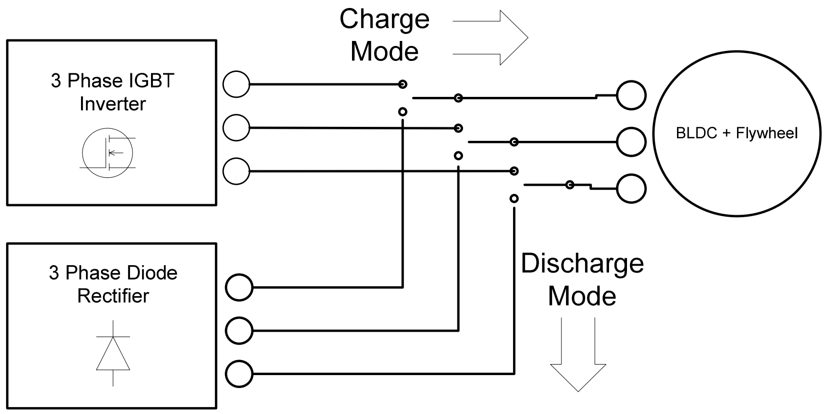


Fig. 3 Motor/Generator Switch

The motor/generator switch was difficult to implement since switches in Simulink do not emulate actual power switches. Since Matlab is an ODE solver, only the state derivatives and not the states themselves can be adjusted. Therefore the states, inductor current and capacitor voltage, cannot be changed instantaneously when the mode of operation changes. Ideal switches were used in this block since parasitics at this point of the system were not a focus.

In discharge mode the motor is connected to the state space averaged rectifier. The rectifier is tied to the boost converter. The angular velocity range for the wheel ranges between 16,000 rpm and 40,000 rpm. This produces an output range for the rectifier between 60 and 150V.

One problem that occurs with combining SimPowerSystems elements with averaged elements is that the model is not entirely electrical. The averaged models use the standard numeric signals from Simulink while the SimPower elements use a special electrical signal, normally used in simulators such as PSim or PSpice. With these mixed signals, the motor model employed as the flywheel unit does not experience power drawdown. Thus feedback is forced from the boost converter to the motor model. The amount of power that the boost converter draws is calculated and used to feed a negative torque to the motor given by,

$$T = \frac{P}{\omega}\ \text{, where } P = VI$$

Thus, in discharge mode, the wheel will spin-down according to how much power the boost converter draws.

Model Verification

In deciding on the parameters to verify the model, [6] was used primarily. Here, the model was built with transfer functions in an idealized manner, much like the first attempt for the boost converter. The power requirements were set and the wheel speeds reacted accordingly. The wheel was spun up in a constant torque manner due to the constant voltage and current supplied by the PWM controller and inverter. The wheel spun down in a constant power manner whenever the model went into an eclipse or the radar turned on.

As shown in Figure 4, the wheel was spun from standstill until the model reached its rated speed. The instant the model goes into eclipse the wheel speed begins to drop as it supplies the power to the main bus. Here it can be seen that the bus voltage is slightly below 150V due to the parasitics modeled in the boost converter. This could be overcome by setting the output voltage of the boost converter slightly higher than 150V. When the model is in sunlight again, the motor/generator switch connects the BLDC drive to the inverter and the flywheel spins up once again.

Transients can be seen in the transition between charge and discharge. In Figure 4b, the bus voltage experiences spikes of approximately 100V for short durations as the main bus is connected to both the solar array and the boost converter.

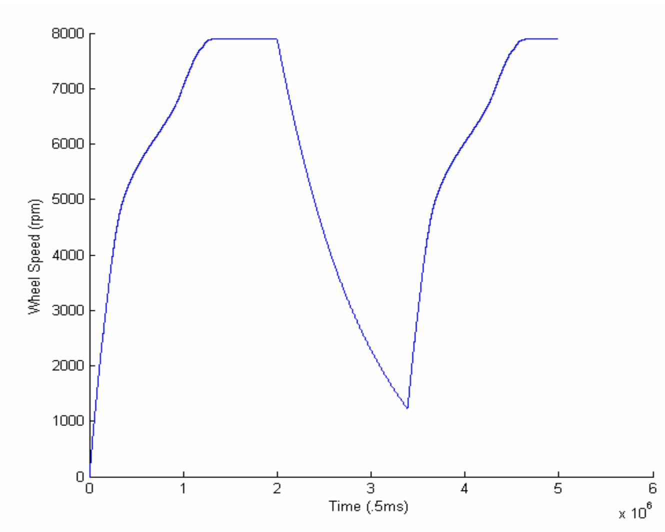
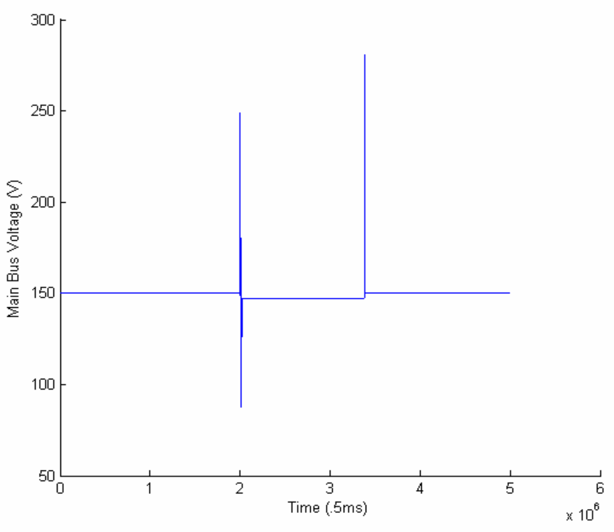


Fig. 4 a) Flywheel Speed



b) Main Bus Voltage

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