

## Motor Control of Two Flywheels Enabling Combined Attitude Control and Bus Regulation

Barbara H. Kenny

21 April 2004

Presented at the 2004 Space Power Workshop

This presentation discussed the flywheel technology development work that is ongoing at NASA GRC with a particular emphasis on the flywheel system control. The “field orientation” motor/generator control algorithm was discussed and explained. The position-sensorless angle and speed estimation algorithm was presented. The motor current response to a step change in command at low (10 kRPM) and high (60 kRPM) was discussed. The flywheel DC bus regulation control was explained and experimental results presented. Finally, the combined attitude control and energy storage algorithm that controls two flywheels simultaneously was presented. Experimental results were shown that verified the operational capability of the algorithm.

Overall, the presentation demonstrated that GRC has an operational facility that shows high speed flywheel energy storage (60,000 RPM) and the successful implementation of an algorithm to simultaneously control both energy storage and a single axis of attitude with two flywheels.

# Motor Control of Two Flywheels Enabling Combined Attitude Control and Bus Regulation

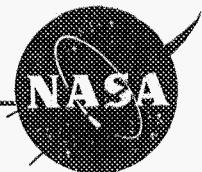
Dr. Barbara Kenny

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21 April 2004

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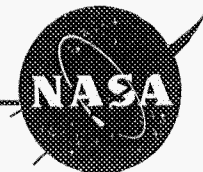


# Outline of Presentation

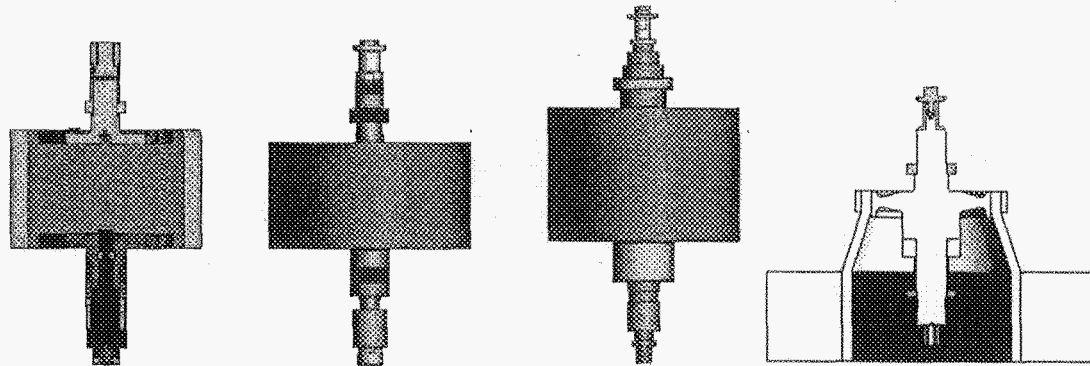
- NASA GRC flywheel development
- NASA GRC flywheel test facility
- Control algorithms
- Motor control
- Full speed/power bus regulation
- Single axis attitude control and bus regulation
- Conclusions and future work

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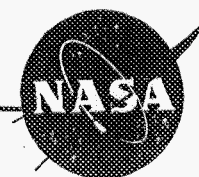
# NASA GRC Flywheel Research



Flywheel Unit	HSS	Dev1	D1	G2	G3
<b>Rotor Composition</b>	Steel Hub	Single Layer Composite	Multilayer Composite	Multilayer Composite	Composite Arbor
<b>Energy</b>	17 wt-hr	300 wt-hr	350 wt-hr	581 wt-hr	2136 wt-hr
<b>Specific Energy</b>	1 W/kg	23 W/kg	20 W/kg	26 W/kg	80W/kg
<b>Motor/Generator</b>	PM 4 pole 165 Vrms l-l active cooling	PM 4 pole 165 Vrms l-l active cooling	PM 2 pole 80 Vrms l-l active cooling	PM 2 pole 80 Vrms l-l active cooling	PM 4 pole 60 Vrms l-l passive cooling
<b>Magnetic Bearings</b>	Radial+Combo PM bias 4 pole no redundancy 55lbf (245N)	Radial+Combo PM bias 4 pole no redundancy 55lbf (245N)	Radial+Combo PM bias 4 pole no redundancy 55lbf (245N)	Radial+Combo PM bias 6 pole radial redundancy 70lbf (310N)	Radial+Combo PM bias 6 pole radial & axial redundancy 80lbf (356N)
<b>Peak Tip Speed</b>			750 m/s	750 m/s	1100 m/s
<b>Operational Speed Range</b>	0-60 krpm	20-60 krpm	20-60 krpm	20-60 krpm	25-50 krpm

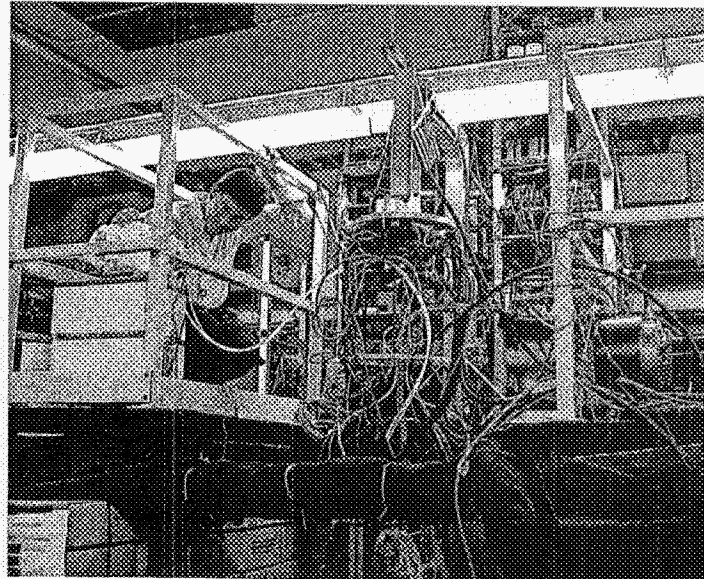
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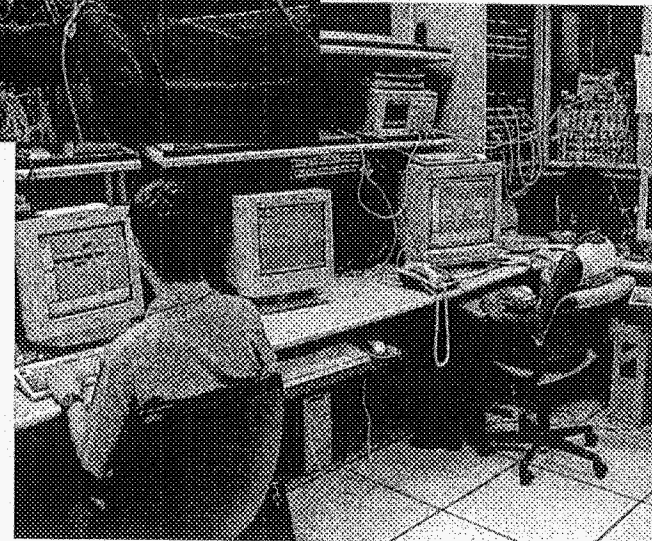
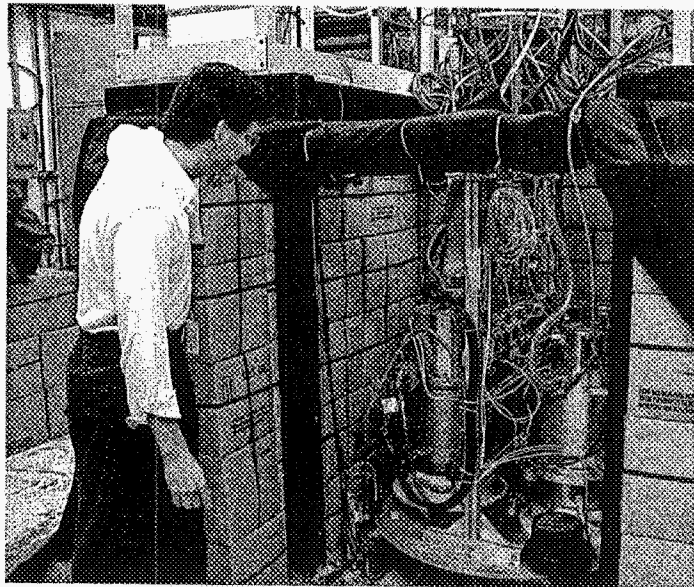


# Dual Flywheel Test Facility

## Electronics



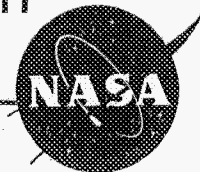
## Flywheel modules



## Control Room

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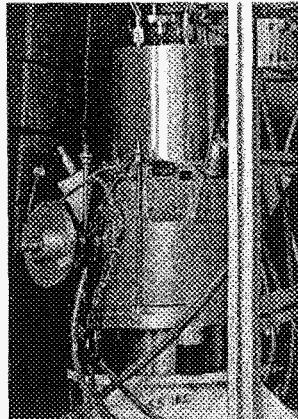
at Lewis Field



# Flywheel Modules

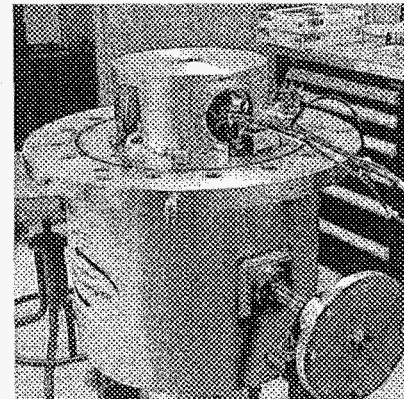
- D1 Flywheel Module

- Rotor
  - 350 Whr - Toray 4 ring rim
  - Monolithic steel hub
- Motor/Generator
  - 1kW, 80V I-I, 2 pole Ashman Technology
- Magnetic Bearings



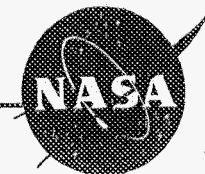
- High Speed Shaft

- Rotor
  - 17 Whr – no rim
  - Monolithic steel hub
- Motor/Generator
  - 3kW, 220V I-I, 4 pole Ashman Technology
- Magnetic Bearings

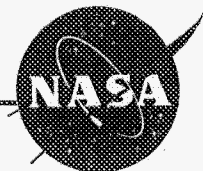
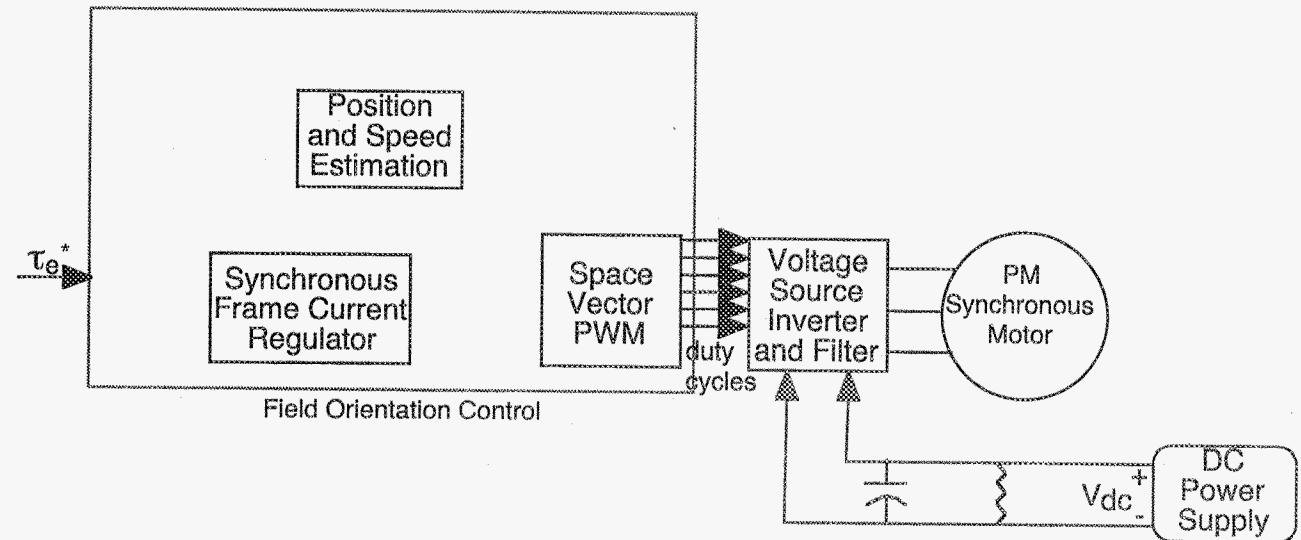


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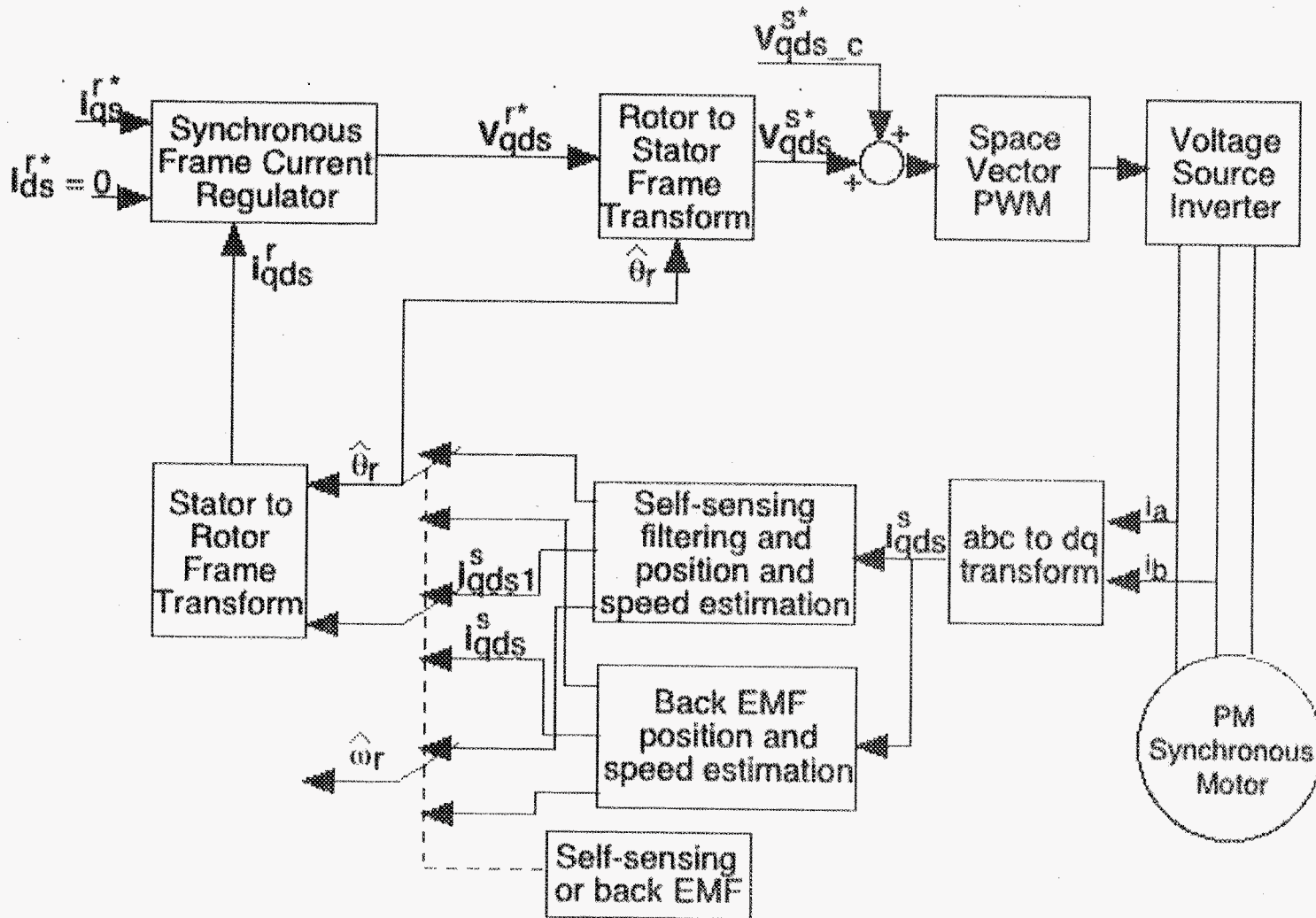


# Motor and Flywheel Control Algorithms



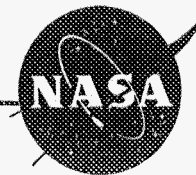


# Motor Control



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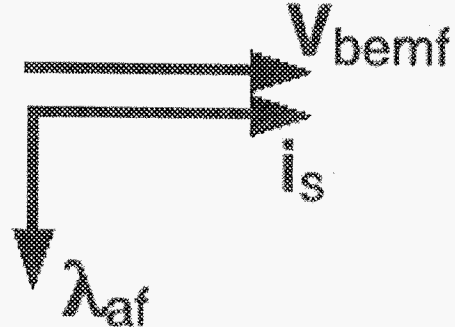


# Field Orientation (Vector Control)

- Control motor current relative to rotor magnetic flux
  - Stator current vector perpendicular to rotor flux vector and in phase with back EMF voltage
- Control done in rotor reference frame
  - Control variables become dc quantities:  $i_{qs}^r, i_{ds}^r$

## Motor torque

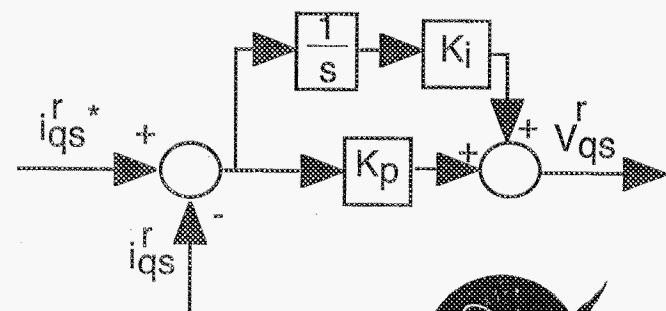
$$\tau = \frac{3}{2} \frac{P}{2} i_{qs}^r \lambda_{af} \text{ if } i_{ds}^r = 0$$



- Similar to dc motor control
- Fast torque response

## Currents regulated using PI controllers in rotor reference frame

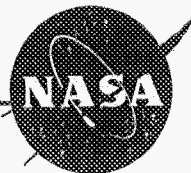
- Synchronous frame current regulator
- Bandwidth  $\sim 1\text{kHz}$



## Needs rotor position information

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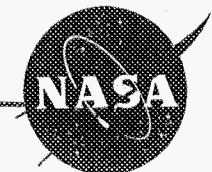
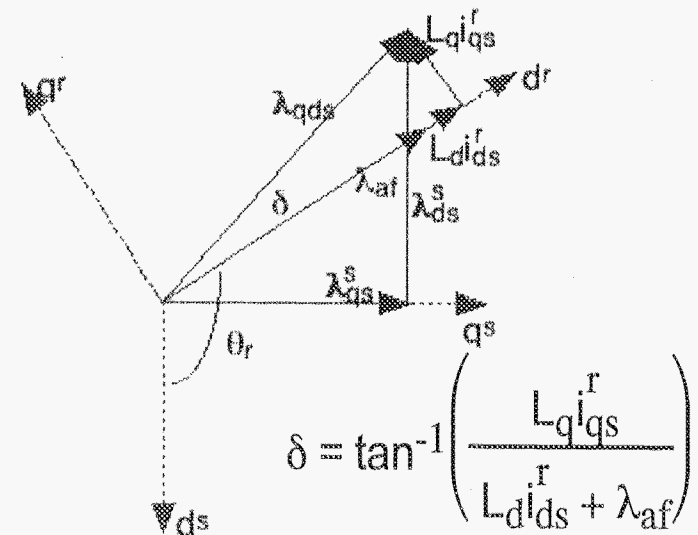
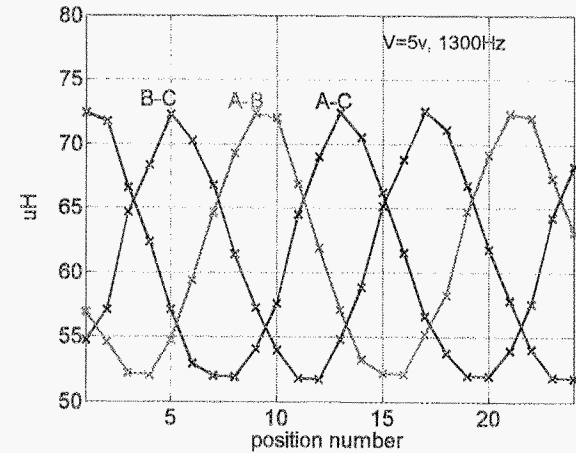
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# Sensorless Control

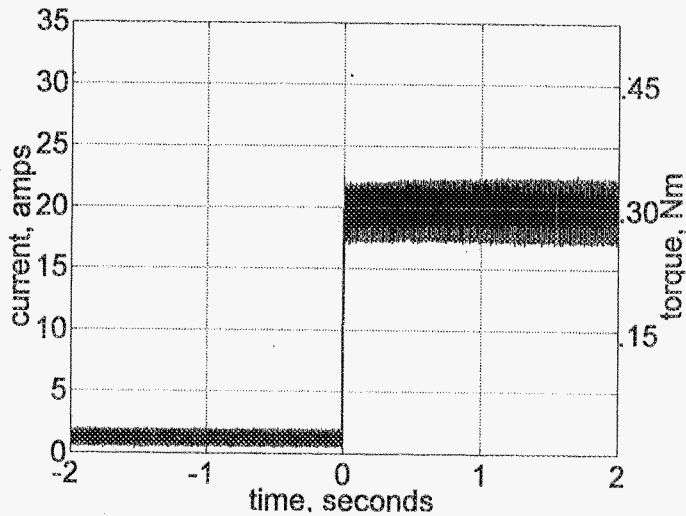
- Rotor position and speed are estimated
- Signal injection technique for starting and low speed
  - High frequency voltage added to fundamental
  - Position information contained in resulting high frequency current
  - Requires magnetic saliency on rotor
- Back EMF technique for higher (operational) speed
  - Stator flux vector determined from integrating the motor phase voltage
  - Rotor flux related to stator flux through machine inductances and phase currents

Motor Inductance

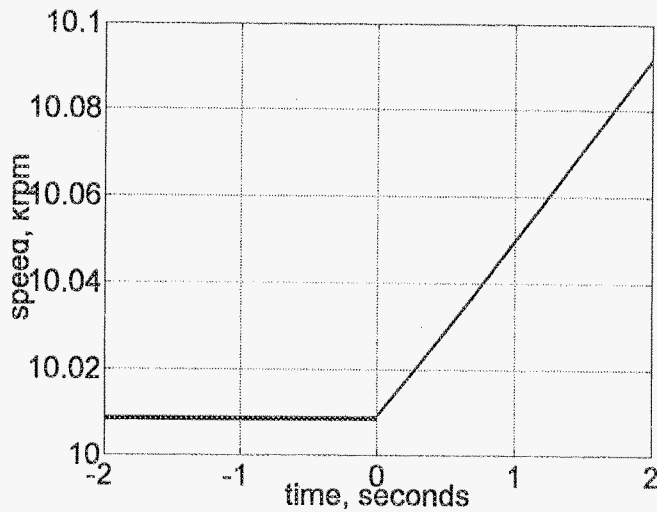


# Current Regulation: 10 krpm

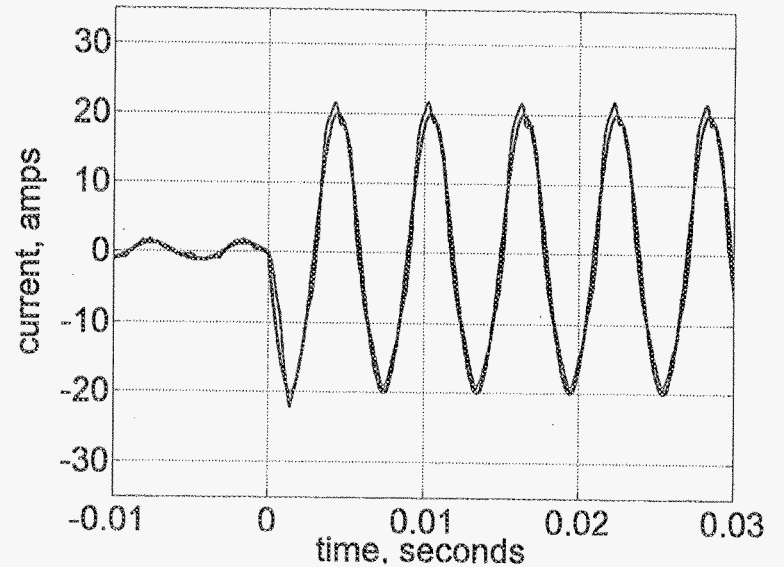
**Current Magnitude and Torque Response**



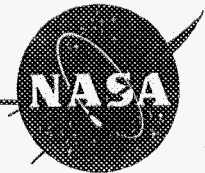
**Flywheel speed**



**Motor Phase Current**

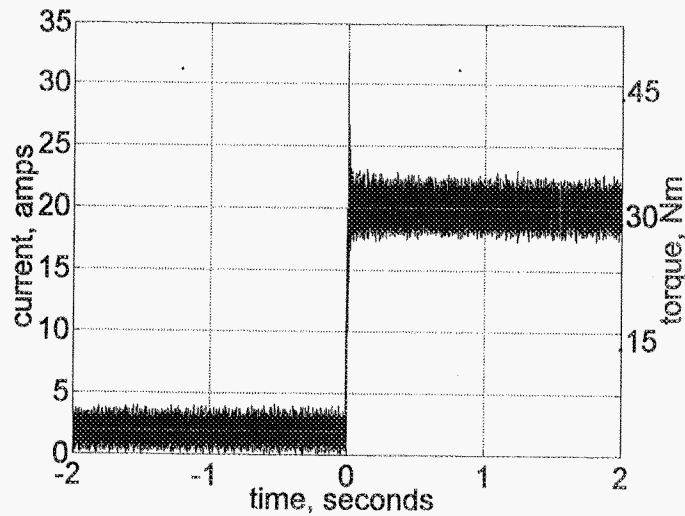


- 1 kHz torque response

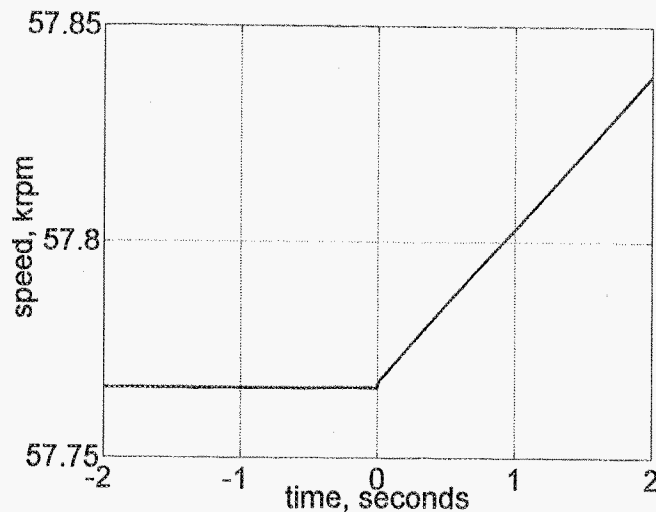


# Current Regulation: 60 krpm

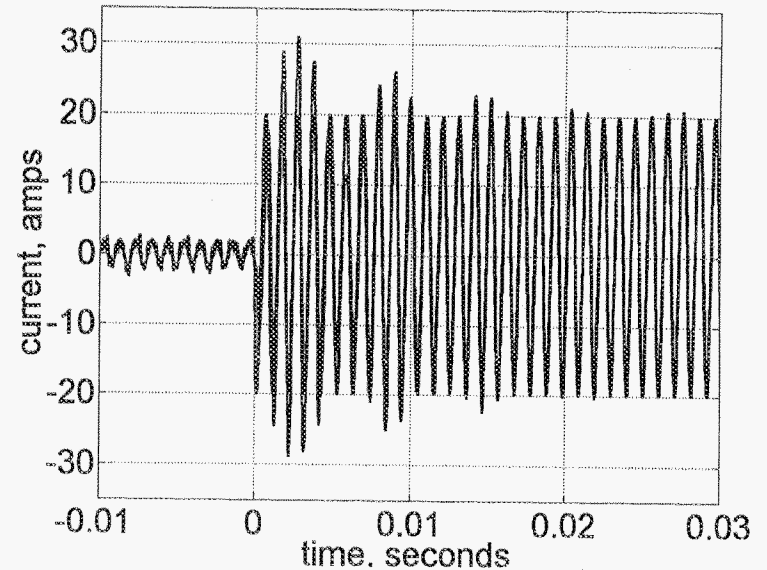
**Current Magnitude and Torque Response**



**Flywheel speed**



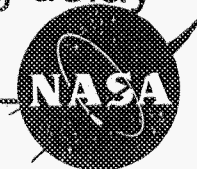
**Motor Phase Current**



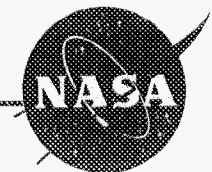
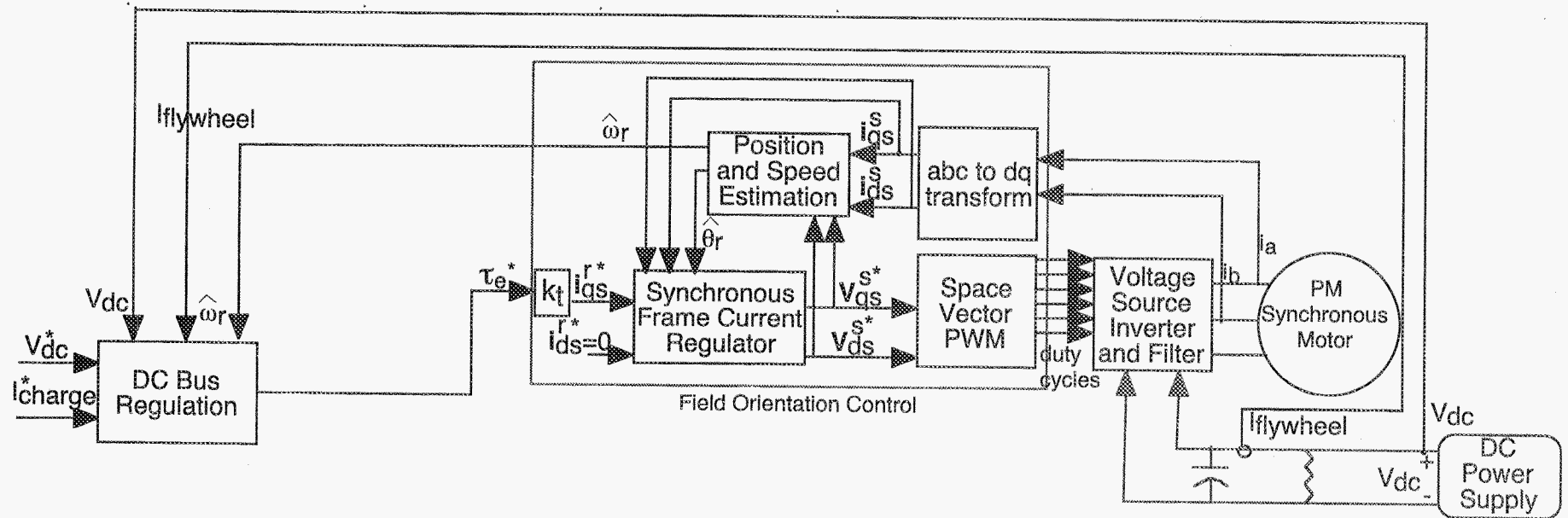
- Regulates current but oscillatory response
- Improvements
  - Back EMF decoupling
  - Include dynamics of AC filter
  - Include sampling delay

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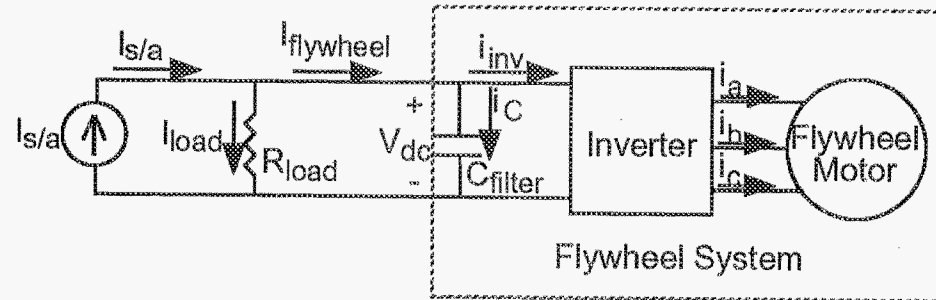


# Motor and Flywheel Control Algorithms



# Flywheel Bus Regulation Control

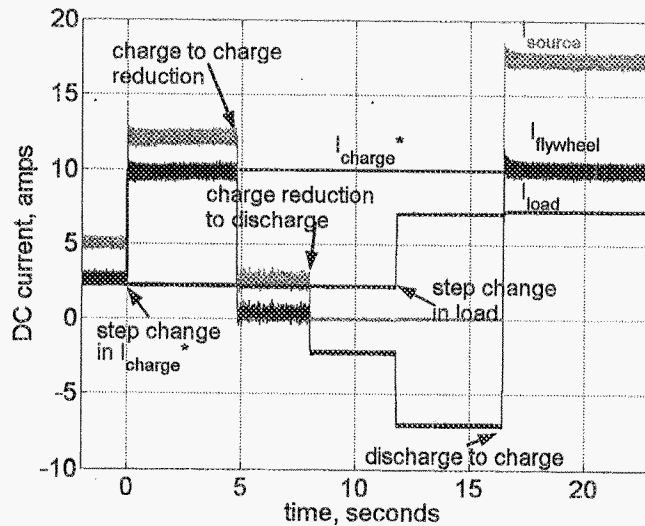
- Charge
- Charge Reduction
- Discharge



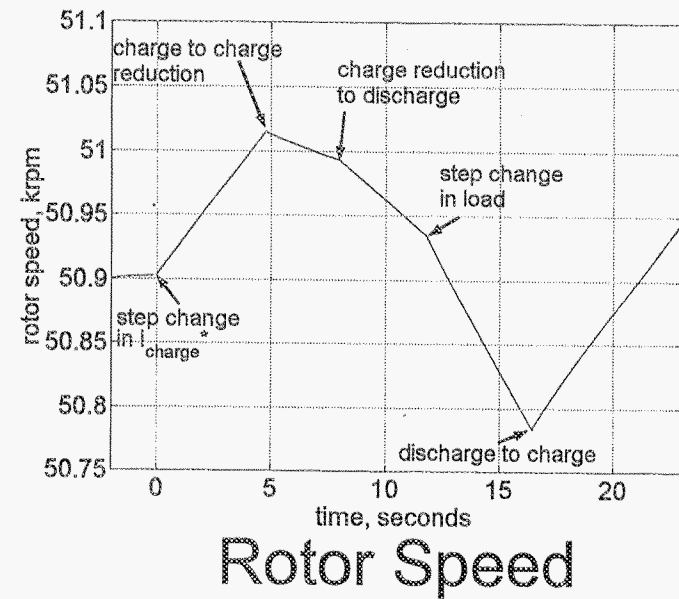
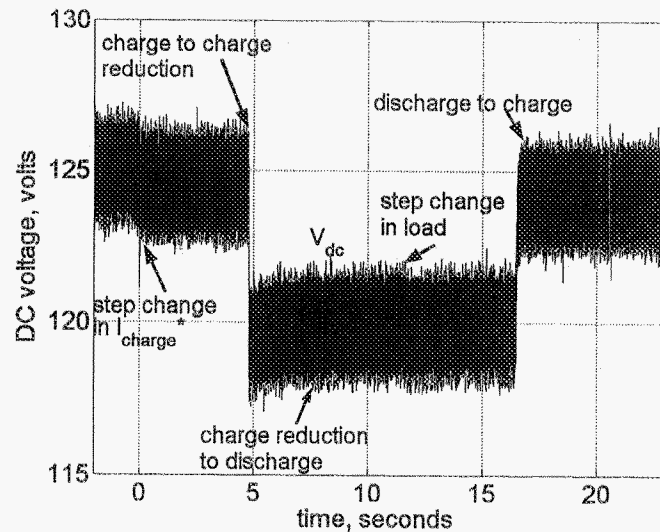
<u>Mode</u>	<u>Current</u>	<u>DC Bus Voltage</u>
Full Sun "Charge"	$I_{s/a} = I_{load} + I_{charge}^*$ $I_{flywheel} = I_{charge}^*$	Regulated by solar array system
Partial Sun "Charge Reduction"	$I_{load} + I_{charge}^* > I_{s/a} > 0$ $I_{charge}^* > I_{flywheel}$	Regulated by flywheel system
Eclipse "Discharge"	$I_{load} = - I_{flywheel}$ $I_{flywheel} < 0$	Regulated by flywheel system

# Experimental Results

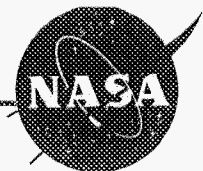
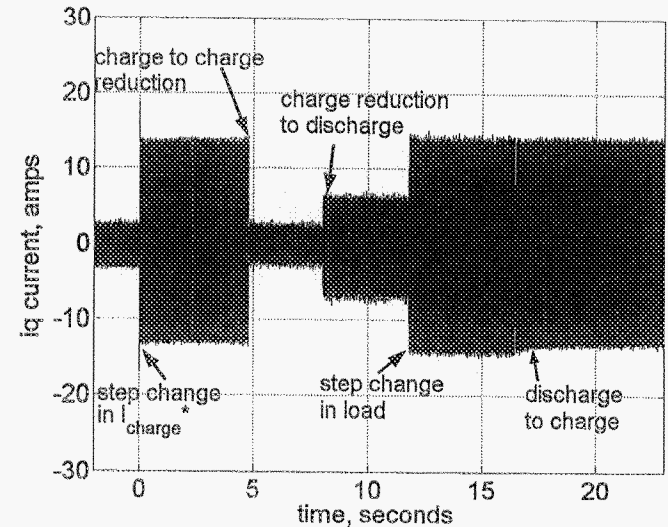
## DC Currents



## DC Bus Voltage



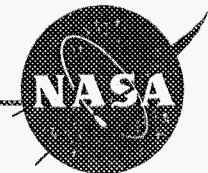
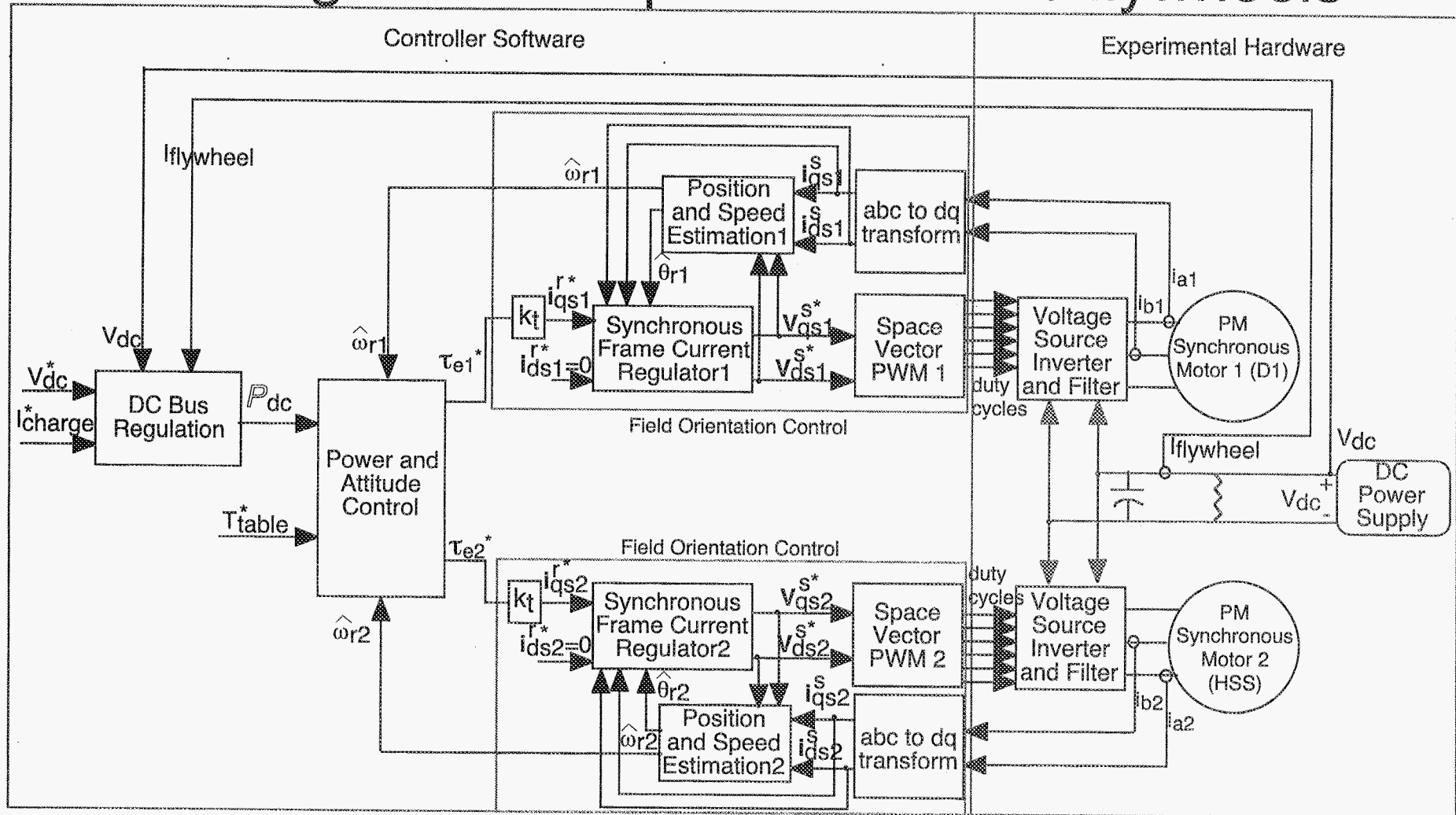
## Rotor Speed





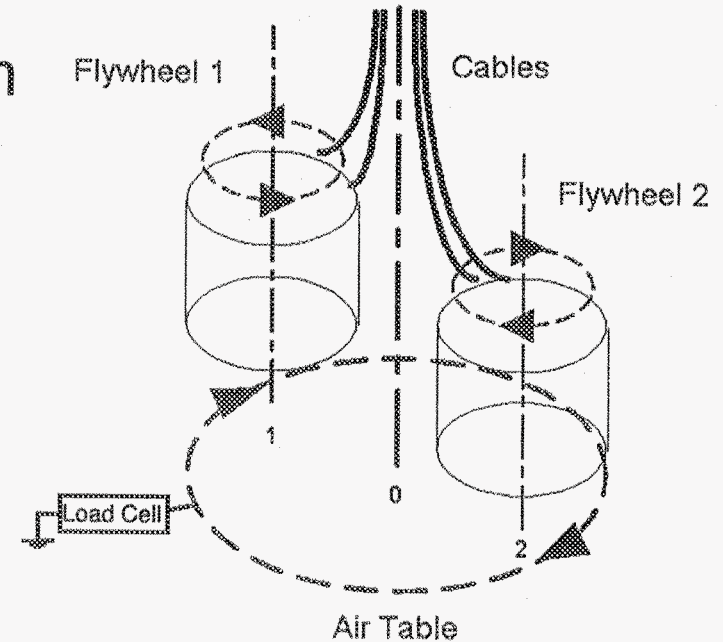
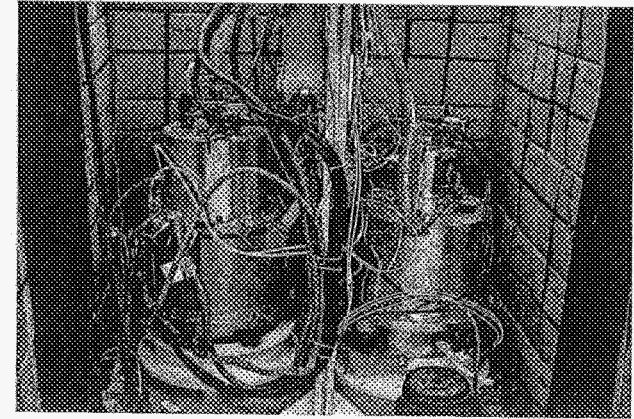
# Attitude Control and Bus Regulation

- Change outer loop to control two flywheels

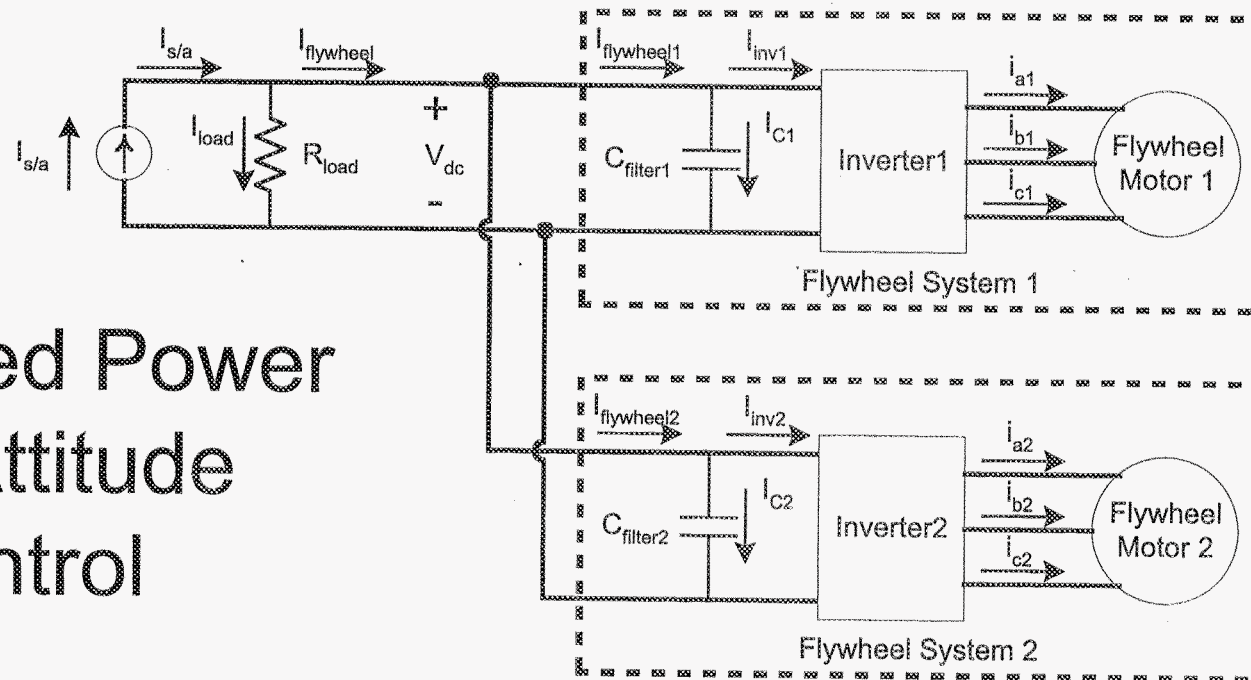


# Attitude Control and Bus Regulation

- Single axis system
- Objective: control axial torque and DC power simultaneously.
  - DC power command results from DC bus regulation algorithm
- Commanded table torque and DC power translated to two motor current commands.



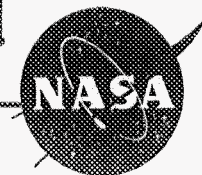
# Integrated Power and Attitude Control



<u>Mode</u>	<u>Current</u>	<u>DC Bus Voltage</u>
Full Sun "Charge"	$I_{s/a} = I_{load} + I_{charge}^*$ $I_{flywheel} = I_{charge}^*$	Regulated by solar array system
Partial Sun "Charge Reduction"	$I_{load} + I_{charge}^* > I_{s/a} > 0$ $I_{charge}^* > I_{flywheel}$	Regulated by flywheel system
Eclipse "Discharge"	$I_{load} = -I_{flywheel}$ $I_{flywheel} < 0$	Regulated by flywheel system

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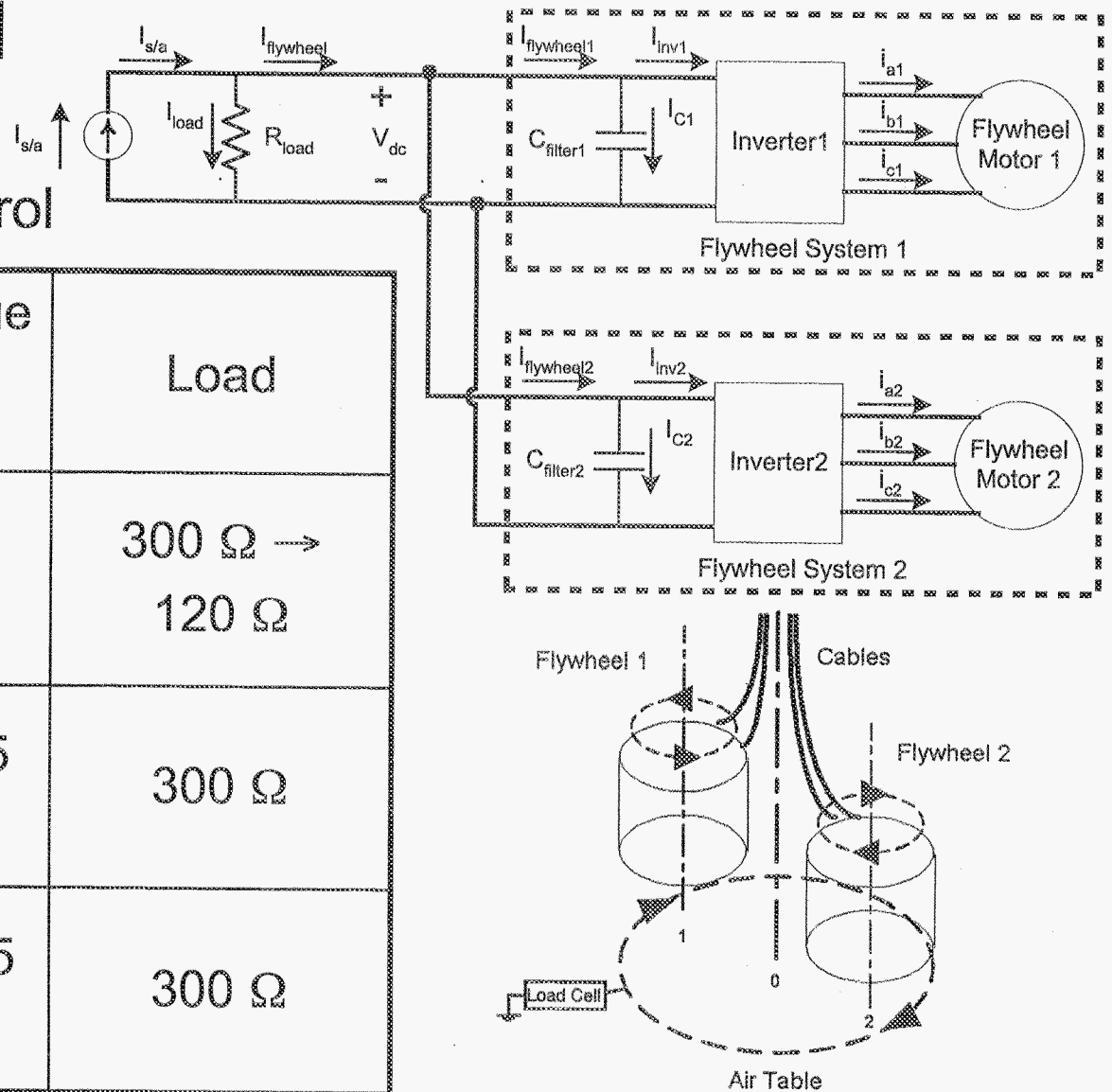
at Lewis Field



# IPAC Experimental Results

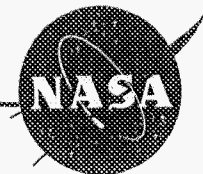
- Open loop torque control

Power Regulation Mode	Table Torque Command (N-m)	Load
Test 1: Charge → Discharge	$T^* = 0$	$300 \Omega \rightarrow 120 \Omega$
Test 2: Charge	$T^* = 0 \rightarrow -0.5 \rightarrow 0$	$300 \Omega$
Test 3: Discharge	$T^* = 0 \rightarrow +0.5 \rightarrow 0$	$300 \Omega$



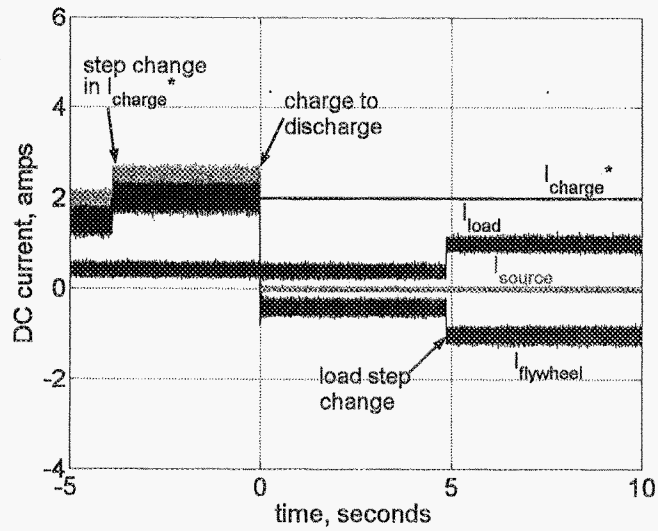
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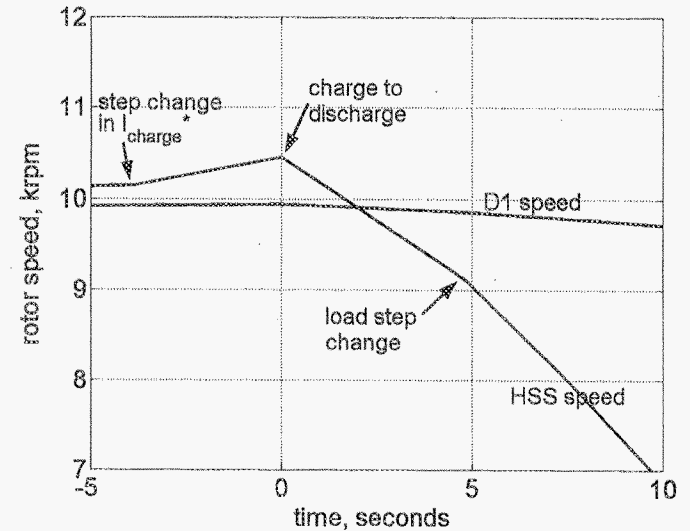


# Test 1: Charge to discharge mode with a constant torque command

DC Currents



Flywheel speeds



DC bus voltage

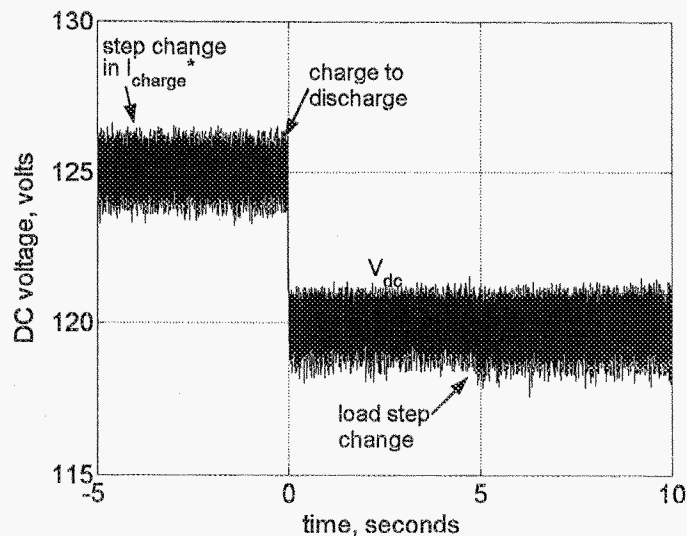
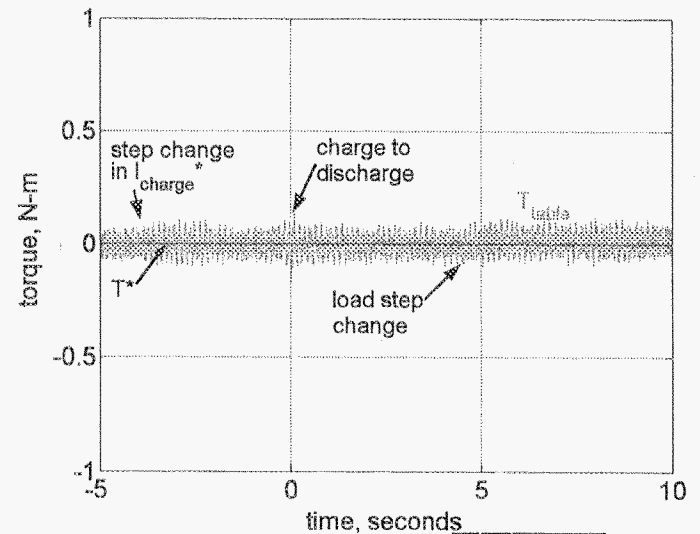


Table torque



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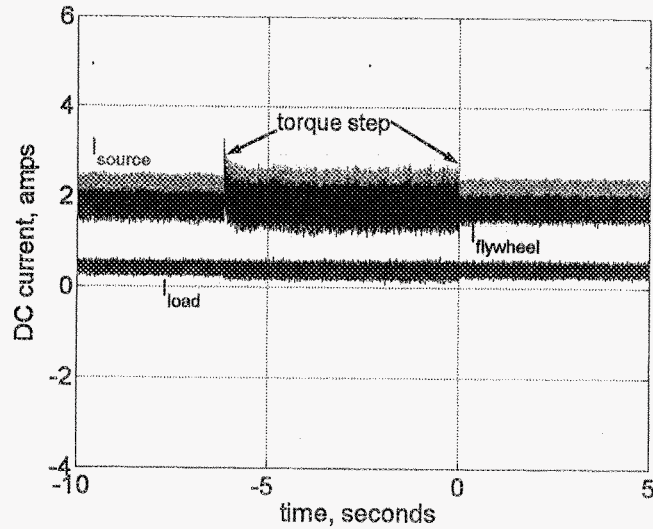
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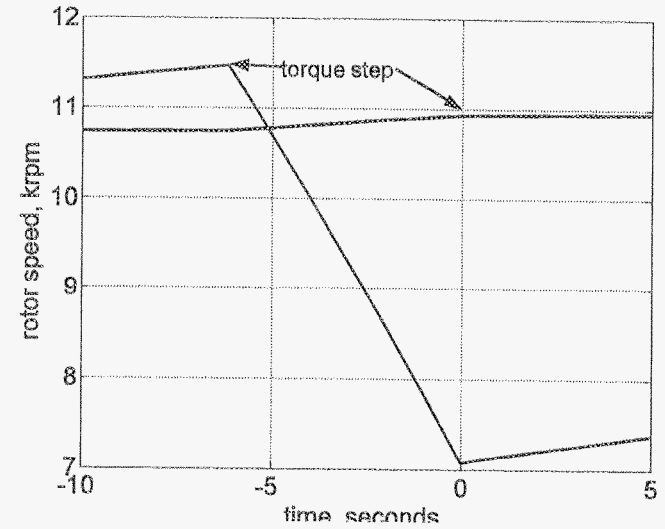


# Test 2: Charge mode with a step change in torque command

DC Currents



Flywheel speeds



DC bus voltage

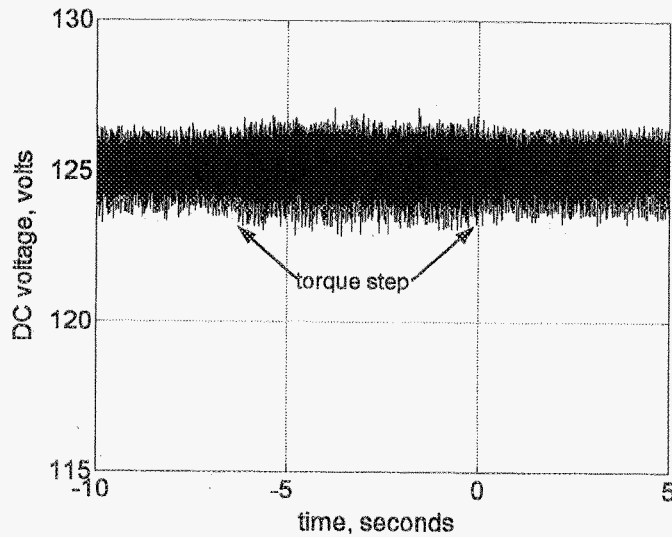
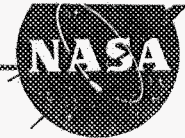
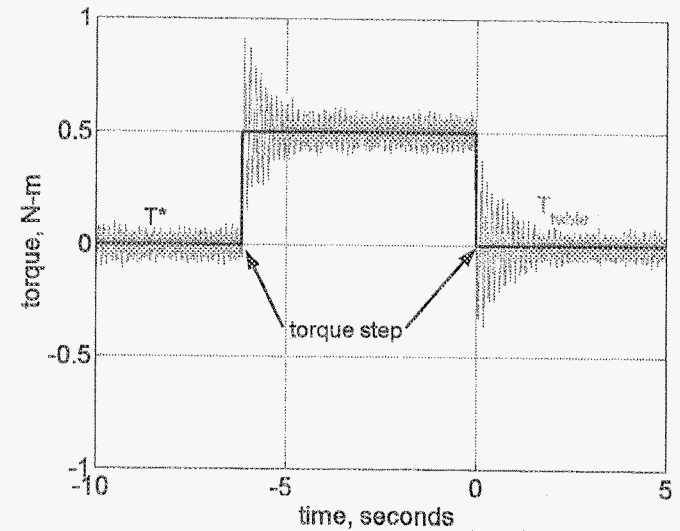
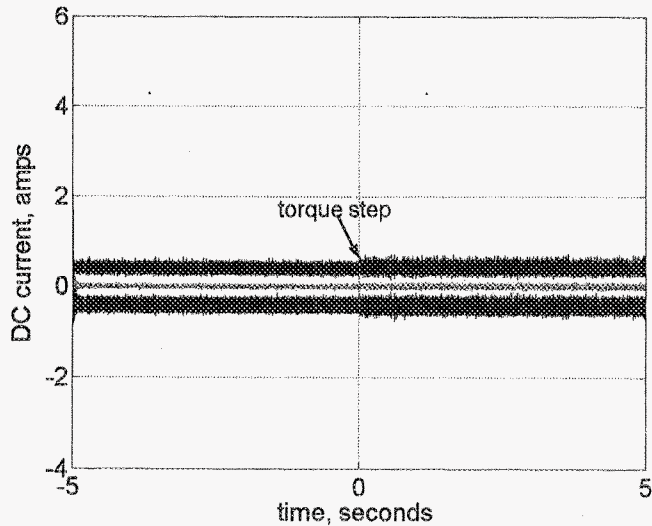


Table torque

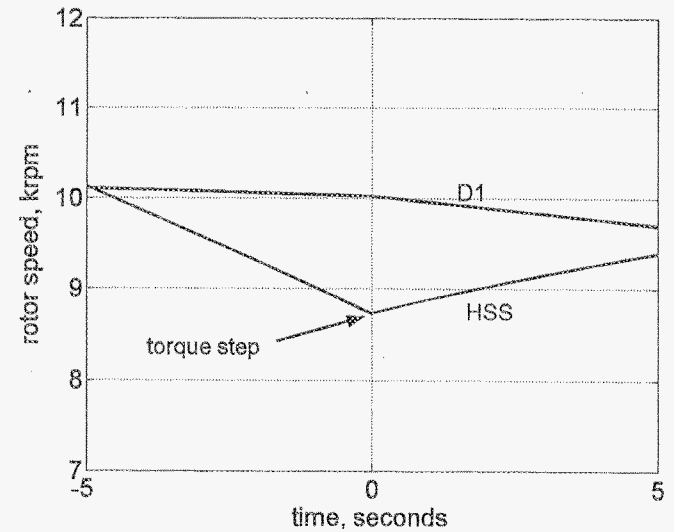


# Test 3: Discharge mode with a step change in torque command

DC Currents



Flywheel speeds



DC bus voltage

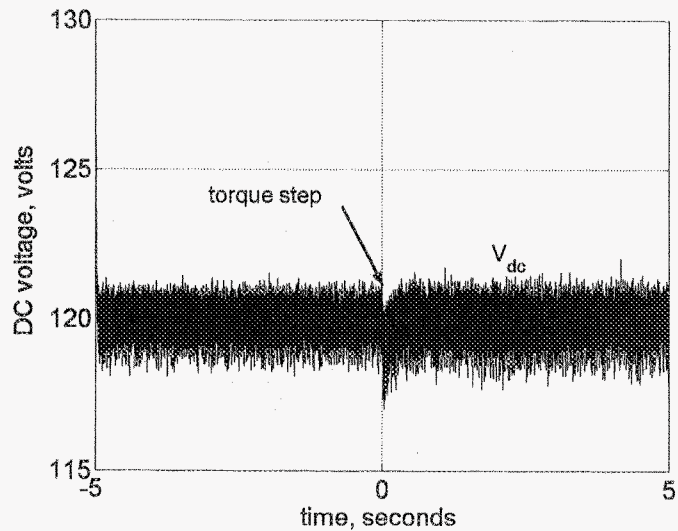
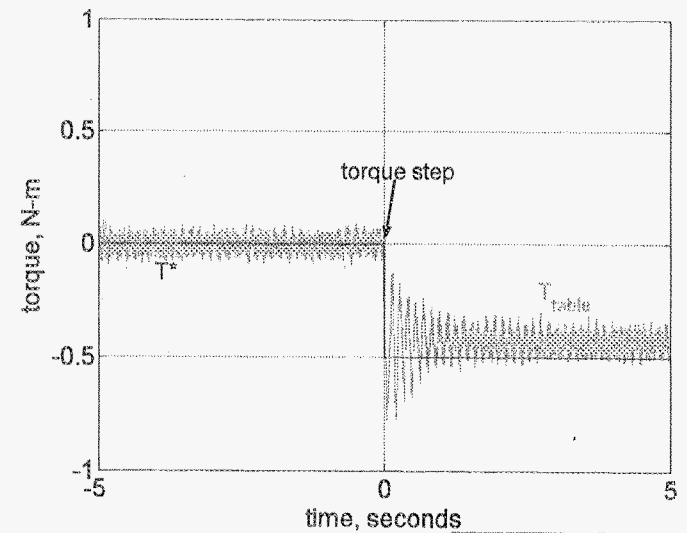


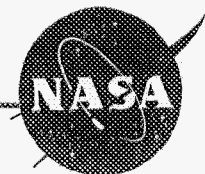
Table torque





# Conclusions

- PM machine with field orientation control and sensorless position and speed estimation enables high performance flywheel outer loop control.
- NASA GRC has demonstrated single axis combined attitude control and bus regulation (IPAC) using two flywheels.
  - Single axis torque and DC power can be independently controlled and regulated.
  - DC bus voltage is accurately regulated by flywheels during discharge during load and/or torque steps.



# Future Work

- NASA GRC and Lockheed Martin are building a two axis, three flywheel combined attitude control and bus regulation system (COMET).
  - Testing this summer at GRC
- NASA GRC will replace the high speed shaft with G-2 flywheel for full speed demonstration of single axis combined attitude control and bus regulation .
  - Testing this summer at GRC
- Working to move motor control and magnetic bearing algorithms to FPGAs.

