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MOTOR/GENERATOR AND ELECTRONIC CONTROL CONSIDERATIONS FOR ENERGY STORAGE FLYWHEELS

Frank Nola
NASA Marshall Space Flight Center
Huntsville, Alabama

REQUIREMENTS

Requirements of the system are to accelerate the momentum wheel to a fixed maximum speed when solar energy is available and to maintain a constant voltage on the spacecraft bus under varying loads when solar energy is not available.

- SOLAR POWER AVAILABLE

  ACCELERATE MOMENTUM WHEEL TO 35,000 RPM

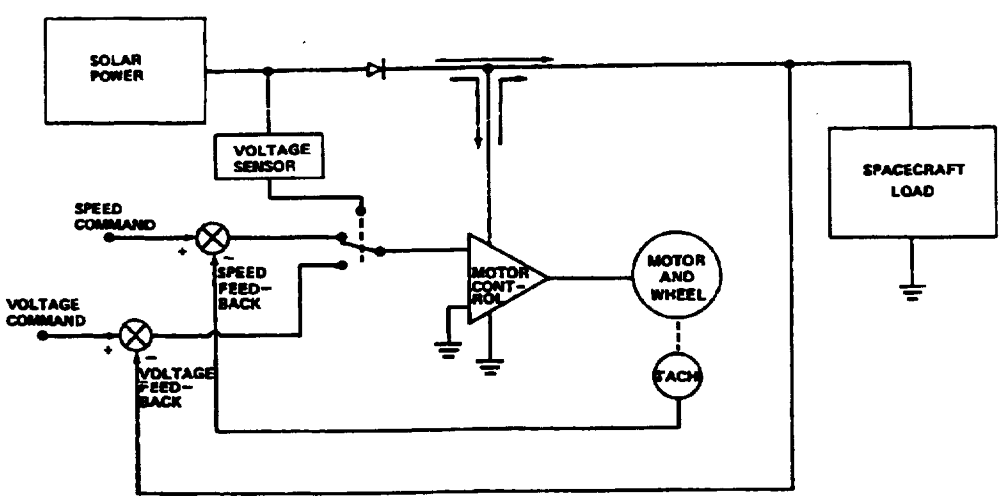
  MAINTAIN CONSTANT SPEED IF EXCESS ENERGY AVAILABLE

- NO SOLAR POWER

  DECELERATE WHEEL - PROVIDE ELECTRICAL ENERGY TO SPACECRAFT - MAINTAIN CONSTANT REGULATED SUPPLY VOLTAGE OVER VARIABLE POWER OUTPUT RANGE.

ENERGY FLOW CONTROL

This is a simplified energy flow control diagram. The motor controller senses the voltage level from the solar power source and compares it to a threshold. Voltage above the threshold indicates the availability of solar energy and the controller is switched to a speed control mode for accelerating the flywheel. Solar energy is being supplied to the IPACS and to the spacecraft in this mode. Voltage below the threshold indicates insufficient solar energy and switches the controller to a voltage control mode. In this mode, energy is being supplied to the spacecraft only by the IPACS and the voltage is held constant by the voltage feedback loop.



CANDIDATE MOTOR TYPES

Candidate motor types are discussed. Permanent magnet brushless DC motors and variable frequency AC induction motors are the only two considered for IPACS. The brushless DC motor is favored because of its high torque to weight ratio and high efficiency.

- SELF-SYNCHRONOUS PERMANENT MAGNET BRUSHLESS DC MOTOR
  - CONVENTIONAL STATOR
  - IRONLESS STATOR
- VARIABLE FREQUENCY AC INDUCTION MOTOR
  - BOTH ARE ESSENTIALLY AC MOTORS

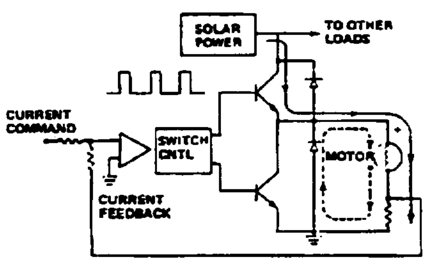
    DC LINE VOLTAGE CONVERTED TO AC FOR ACCELERATION
    AC MOTOR VOLTAGE CONVERTED TO DC FOR ENERGY RETURN
    COMMON CONTROLLER ACCOMPLISHES BOTH/CONTROLLER ALSO REGULATES LINE VOLTAGE IN GENERATOR MODE
  - AC INDUCTION MOTOR

    MOST RUGGED
    REQUIRES NO POSITION SENSORS
    REQUIRES SPEED SENSOR
  - BRUSHLESS DC MOTOR

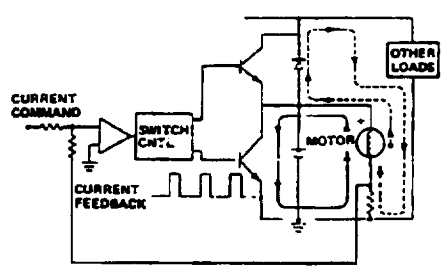
    HIGHEST TORQUE TO WEIGHT RATIO
    HIGHEST EFFICIENCY - PERMANENT MAGNET IS LOSS LESS
    BETTER REDUNDANCY POTENTIAL
    REQUIRES ROTOR POSITION SENSORS
    SAMARIUM COBALT MAGNETS INSURE RUGGEDNESS
    140 HP, 20,000 RPM MOTOR DEMONSTRATED (G.E.)

PULSE WIDTH MODULATED CURRENT CONTROL

Simplified diagrams show the path of current flow in the pulse width modulated (PWM) controller for both the accelerating and decelerating mode. Diagrams show how both are accomplished in a common controller. Transistor switches are either full on, dissipating very low power; or full off, dissipating no power, resulting in high efficiency.



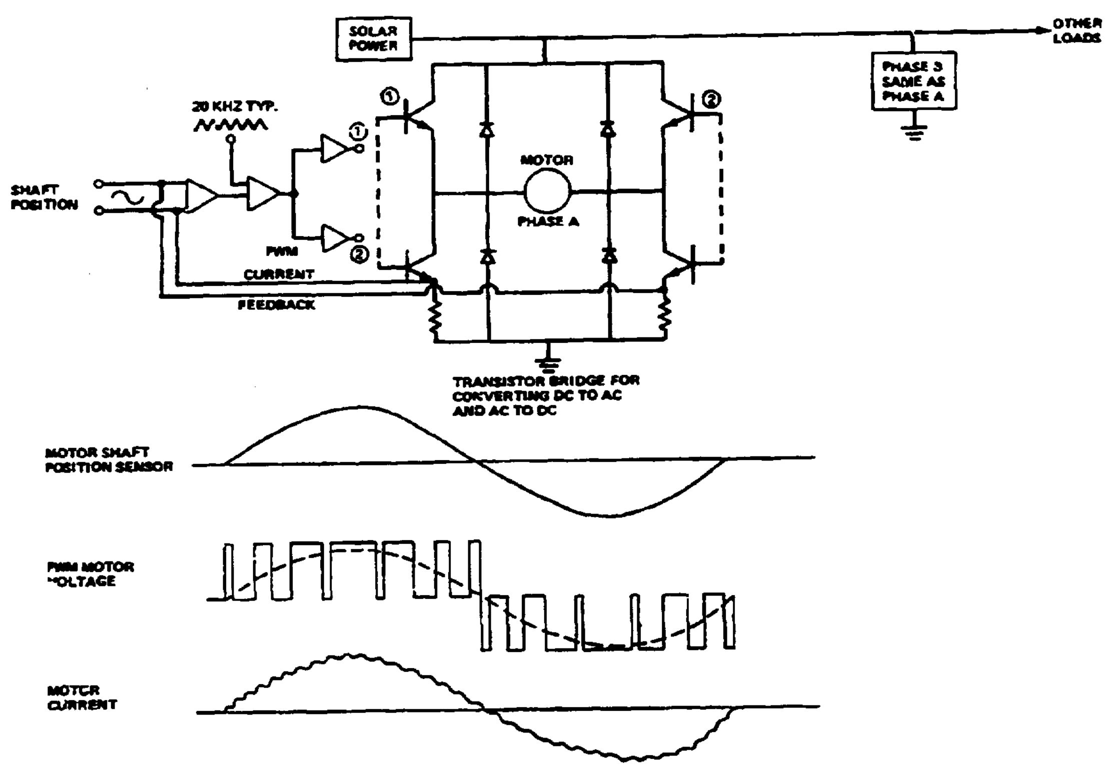
ACCELERATING
ENERGY STORAGE MODE



DECELERATING
ENERGY RETURN MODE

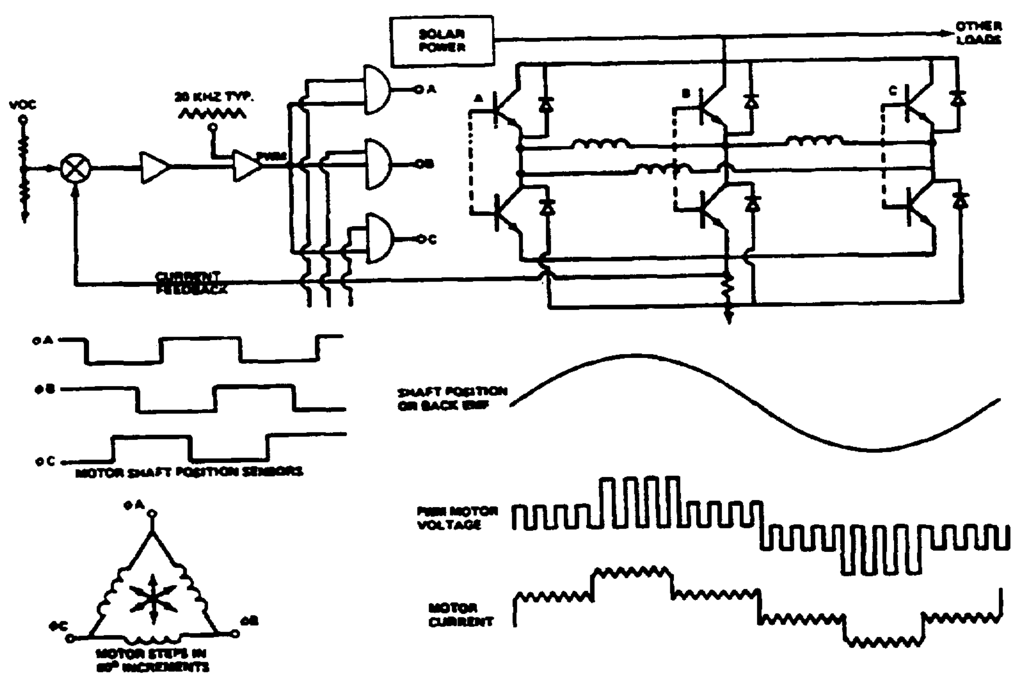
TWO-PHASE SINUSOIDAL PWM CONTROL - BRUSHLESS DC

A transistor bridge provides bi-directional current flow for converting DC to AC in the motor mode and AC to DC in the generator mode. In the two-phase system, sinusoidal outputs of the shaft position transducers are pulse width modulated as indicated to produce sinusoidal motor currents. Linear current feedback is used to control the amplitude of the current and to force it to be in phase with the position transducer. Maintaining sinusoidal motor currents essentially eliminates harmonic losses.



THREE-PHASE PWM CONTROL - BRUSHLESS DC

In the three-phase controller, the shaft position sensors are converted to square waves which, after conditioning, switch a square wave of current to the motor to essentially step the motor in 60 degree increments. In the accelerating mode, one top transistor is switched at the PWM frequency while one bottom transistor is switched on for a full 120 degrees to provide a path for "free wheeling" current. In the generating mode, one bottom transistor is switched at the PWM frequency to instantaneously short out the back EMF. The "free wheeling" current supplies power to the bus through one upper and one lower diode. Voltage appearing across the current sampling resistor is DC and is consistent with the DC current command voltages.



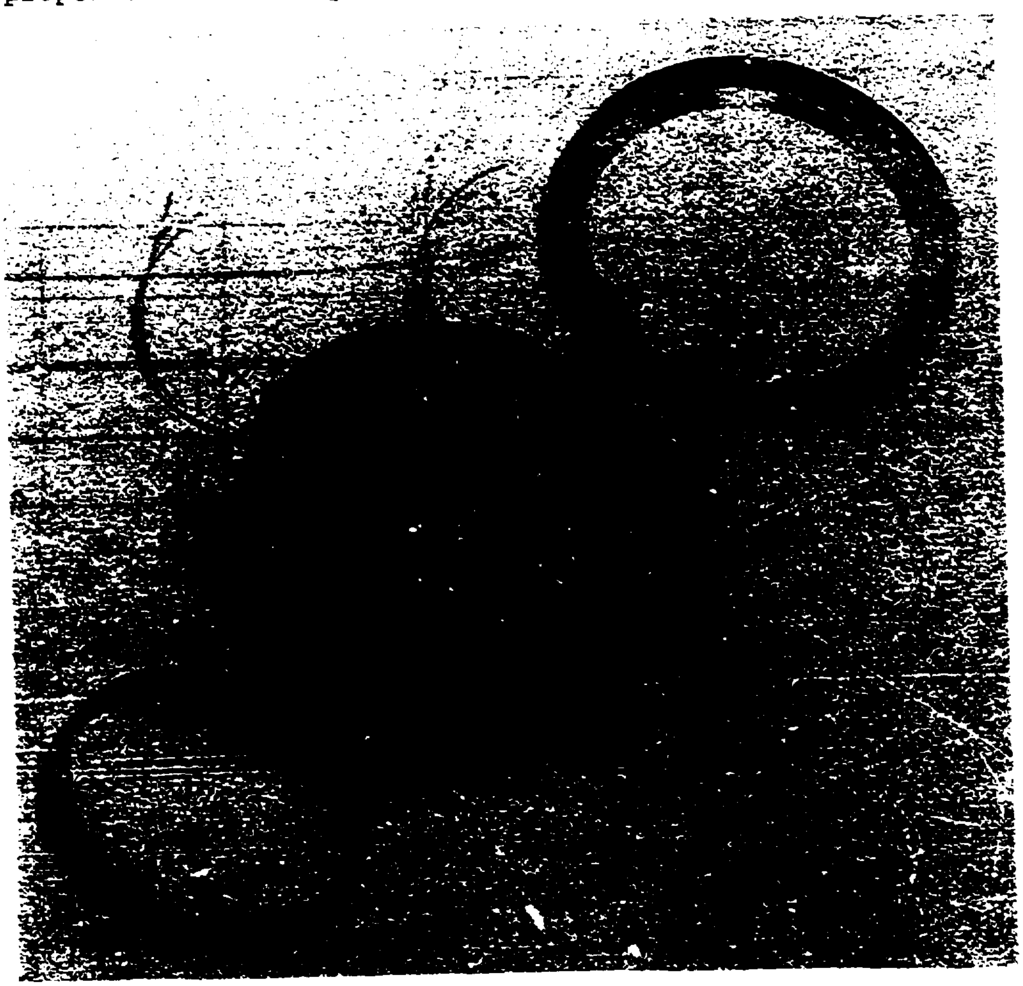
EFFICIENCY CONSIDERATIONS

Sources of power loss which affect the efficiency are listed. Included are the motor, the electronic controller, and bearings.

- SOURCES OF LOSS
  - MOTOR
  - ELECTRONIC CONTROLLER
  - BEARINGS - BALL OR MAGNETIC
- MOTOR EFFICIENCY OPTIMIZED BY INCREASING WEIGHT
  - REDUCES COPPER LOSS
  - LOWER FLUX DENSITY IN IRON REDUCES CORE LOSSES
  - IRONLESS STATOR ELIMINATES CORE LOSSES
- CONTROLLER EFFICIENCY OPTIMIZED BY OUTPUT POWER OF SYSTEM AND BY LINE VOLTAGE CONSISTENT WITH AVAILABLE TRANSISTORS
- EFFICIENCY DECREASES SIGNIFICANTLY WITH DEPTH OF DISCHARGE
  - CURRENT DOUBLES AT HALF SPEED
  - MOTOR I^2R LOSS INCREASES BY AT LEAST A FACTOR OF FOUR
  - CONTROLLER LOSS AT LEAST DOUBLES

BRUSHLESS DC MOTOR WITH IRONLESS STATOR

In the ironless stator motor below, the flux return path rotates with the permanent magnet rotor. Since there is no relative motion between the flux and the iron, core losses are eliminated. In high speed fly wheels, the return path may be the inner rotor and the magnets mounted in the outer structure to take advantage of the support provided by the wheel. The low inductance resulting from this type of structure may require external chokes for proper controller operation.



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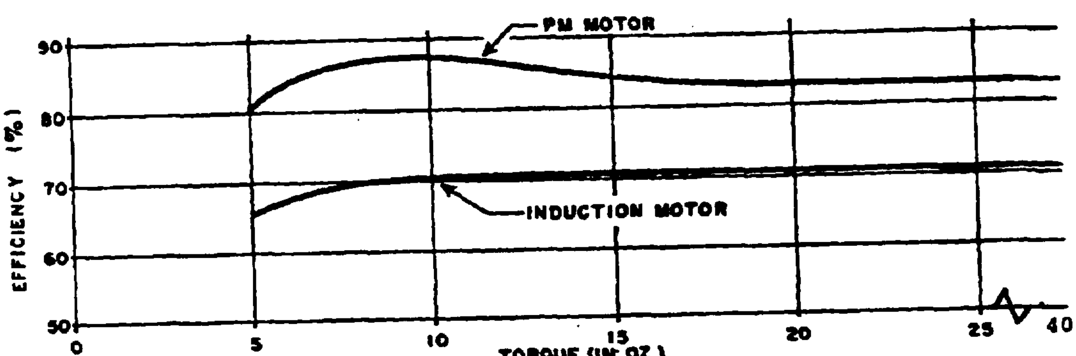
COMPARISON OF INDUCTION AND PERMANENT MAGNET (PM) MOTORS

A variable frequency AC induction motor and a brushless PM motor were designed to be interchangeable on the shaft of a control moment gyroscope. Both were tested with a common controller with only minor modifications to the input circuitry as required by each motor. The lower efficiency resulting from rotor excitation losses in the induction motor is clearly indicated. Also, the higher inductance of the induction motor forces a lower back EMF and torque constant than for an equivalent PM motor resulting in a higher current capacity controller.



EFFICIENCY AT 8000 RPM VS. TORQUE
CONTROLLER LOSSES INCLUDED

PM MOTOR

28 VOLTS
5.7 LB
.17 OHM/PHASE
.6 MILLIHENRY/PHASE

INDUCTION MOTOR

28 VOLTS
7.2 LB
.26 OHM/PHASE
1.2 MILLIHENRY/PHASE

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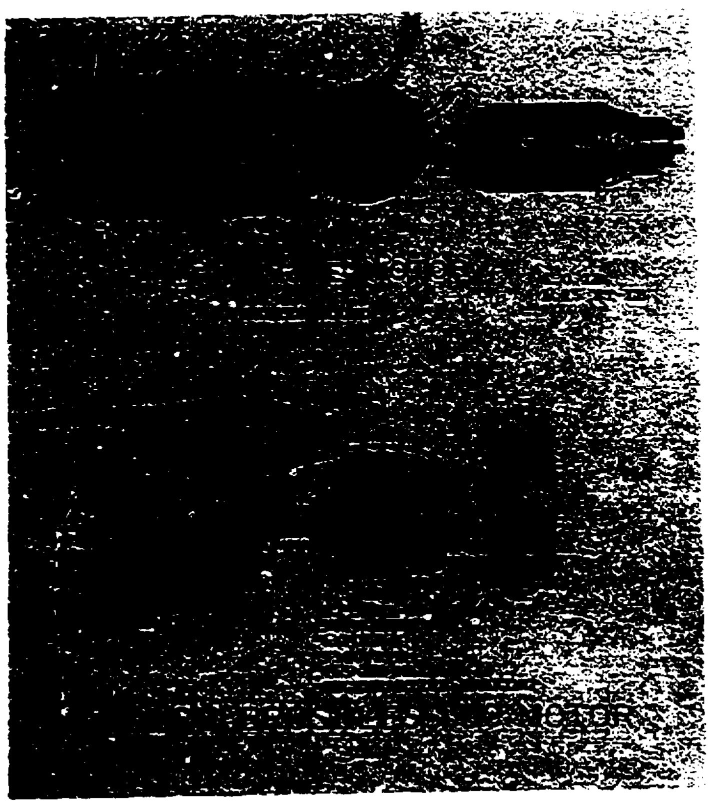
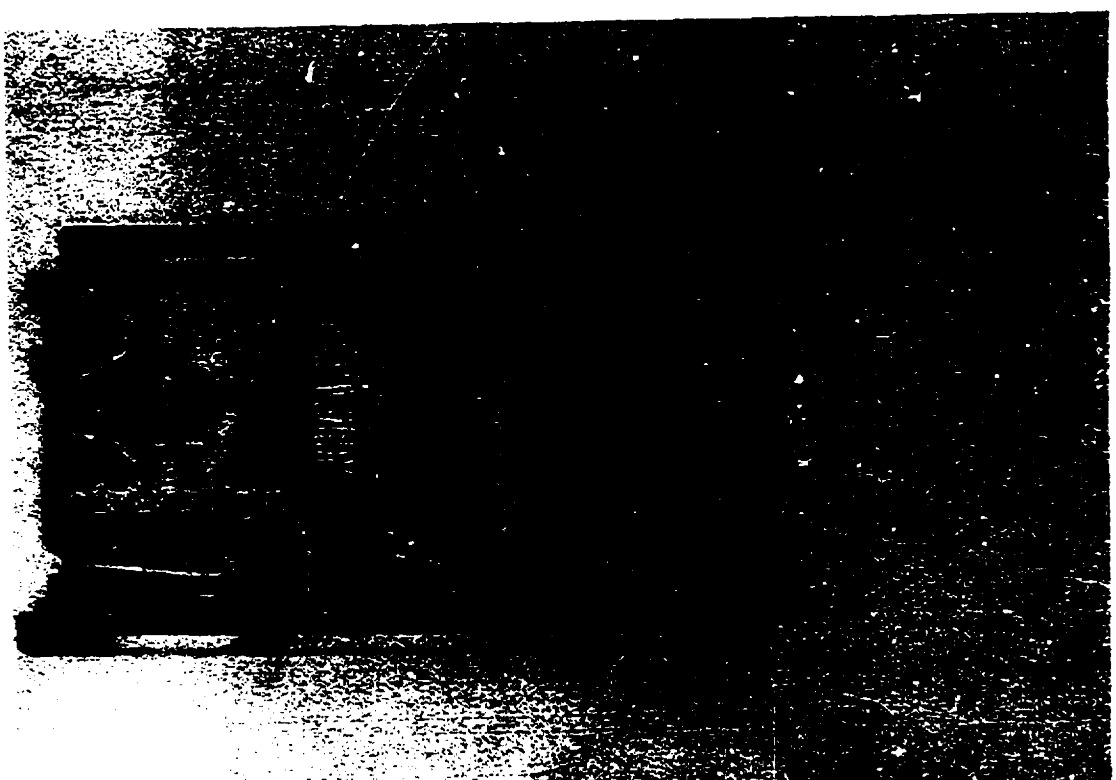
LUNAR ROVING VEHICLE (LRV) MOTORS

Both a series wound motor and a brushless permanent magnet (PM) motor were developed for the Lunar Roving Vehicle. The series motor completed qualification first and was incorporated in the flight system. The PM motor was used in other off-road vehicle programs. The regenerative braking feature and 465 hertz excitation frequency (equivalent to 27,900 RPM, 2-pole motor) of the PM motor are similar to the requirements for a high speed energy storage flywheel application. Because of its low inductance, small external chokes were used (as opposed to raising the PWM frequency) for smoothing the PWM current.



LRV BRUSHLESS MOTOR ELECTRONICS

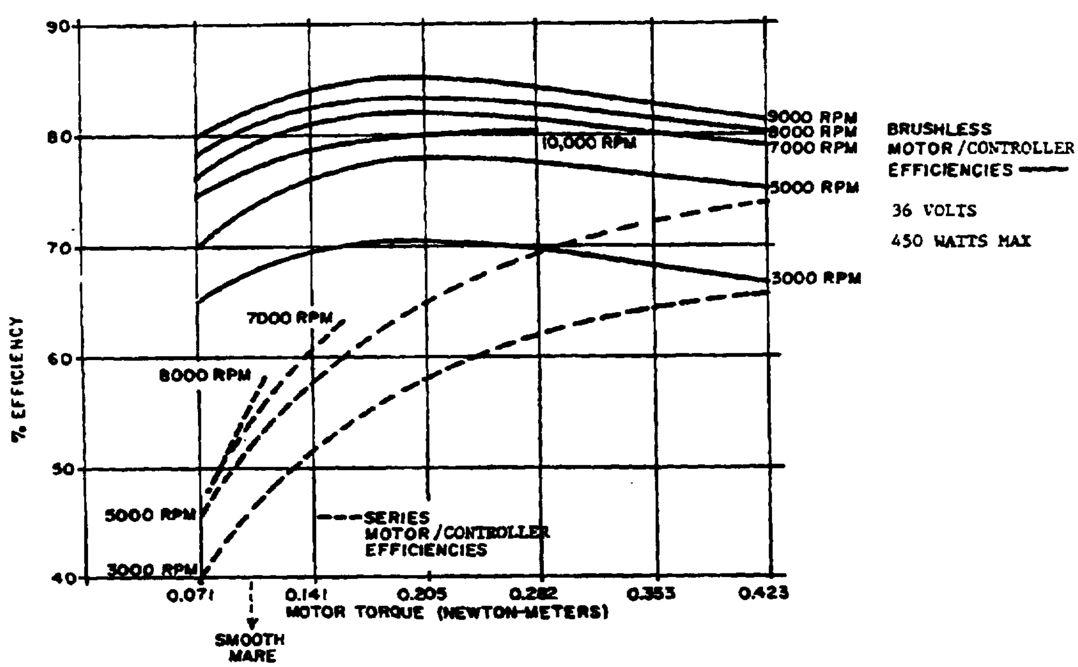
The electronic controller developed by Marshall Space Flight Center for the LRV included regenerative braking similar to that required for energy storage flywheels as well as electronic gearings. The motor winding was tapped at one-fourth of its turns. The vehicle started with the full winding applied to the controller for high accelerating or climbing torque. At one-fourth maximum speed, the controller automatically switched to the one-quarter turns tap for high speed, low torque operation. This reduced the current handling requirement of the controller by 75 percent.



LRV BRUSHLESS MOTOR ELECTRONICS

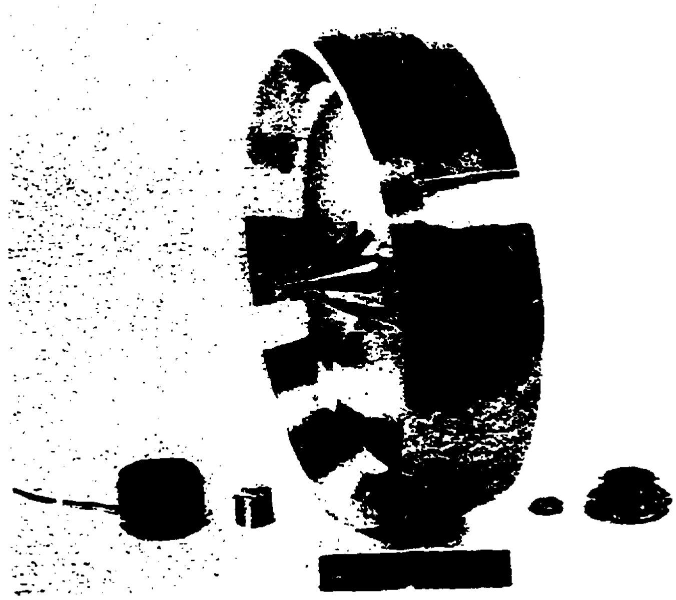
EFFICIENCY VS TORQUE OF LRV MOTORS

Peak motoring efficiencies of 85 percent were obtained for the LRV motor and electronic controller. Efficiencies shown are for a 36-volt system. The motor was weight critical and was not optimized for efficiency. Increased motor weight and higher line voltage would result in a significant increase in efficiency.



BRUSHLESS DC MOTOR AND FLYWHEEL

The brushless DC motor and flywheel shown below were fabricated early in the SKYLAB program (1967) to investigate control concepts for high speed brushless motors driving momentum storage wheels. The 162-pound wheel has an angular momentum of 2000 ft-lb-sec at 8000 RPM and stores 315 watt-hours of energy. While the motor exhibits efficiencies in excess of 95 percent, it operates from a 28-volt source resulting in an overall efficiency of slightly greater than 80 percent when controller losses are included. Bearing losses are also appreciable. Although the system is not optimized for efficiency, it is presently in use at MSFC for developing motor/generator concepts related to integrated flywheel systems.



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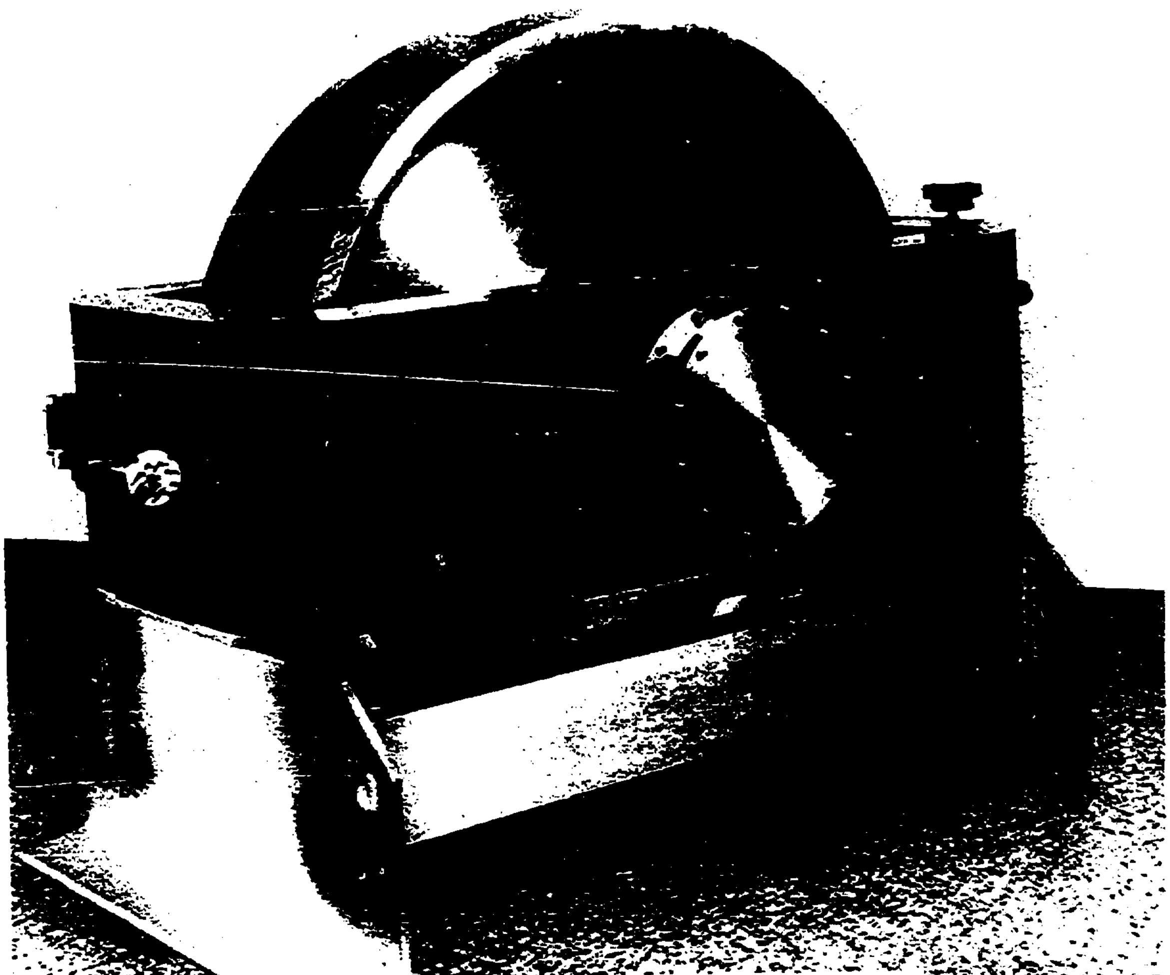
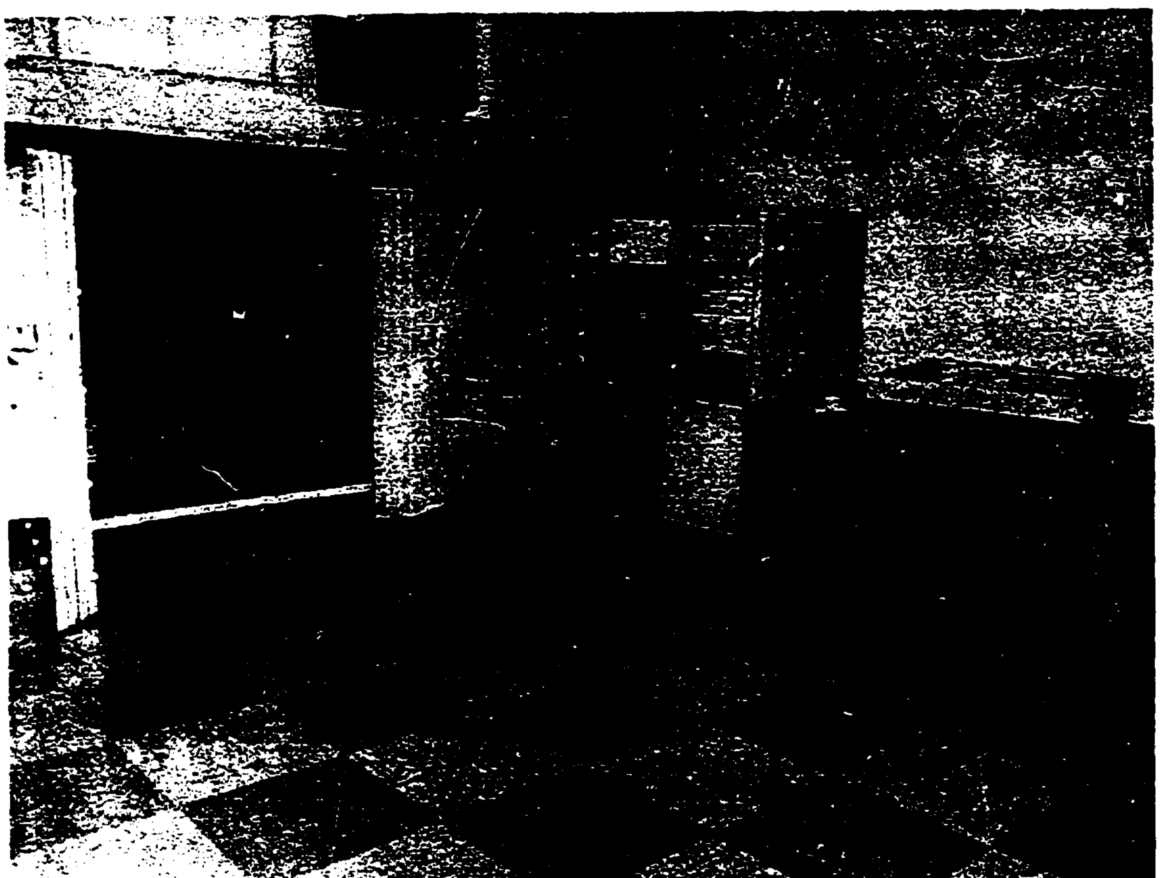
FLYWHEEL MOUNTED IN GIMBAL

The flywheel is shown mounted in its gimbal support and vacuum enclosure assembly.


2000 FT-LB-SEC WHEEL IN GIMBAL

HIGH ENERGY FLYWHEEL TEST VAULT

Control concepts for storing energy in flywheels and for converting stored energy to supply a constant bus voltage under varying load and wheel speed conditions are being tested in the vault shown below.



TECHNOLOGY ASSESSMENT

An assessment of the technology related to motors/generators and electronic controls for high speed flywheels is presented in the comments below.

- PRESENT MOTOR TECHNOLOGY ADEQUATE - TRADE-OFFS MAY BE REQUIRED TO ACHIEVE ULTIMATE IN EFFICIENCY
- PWM TECHNIQUES FOR CONTROLLING POWER IN BOTH THE MOTOR AND GENERATOR HAVE BEEN WELL DEVELOPED AND DEMONSTRATED
- HIGH EFFICIENCY (> 95%) ELECTRONIC CONTROLLERS IN THE 1/2 TO 1 kW RANGE HAVE BEEN DEMONSTRATED
- DESIGN AND TRADE-OFF STUDIES FOR HIGHER POWER SYSTEMS WILL BE REQUIRED TO MAINTAIN HIGH EFFICIENCY. SWITCHING LOSSES IN HIGHER POWER BIPOLAR TRANSISTORS BECOME APPRECIATIVE AT PWM FREQUENCIES REQUIRED FOR HIGH WHEEL SPEED OPERATION
  - POSSIBILITIES INCLUDE:
    - USE OF NEW MOSFET POWER TRANSISTORS
    - MOTORS WITH MULTIPLE PARALLEL WINDINGS AND MULTIPLE TRANSISTOR BRIDGES FOR CURRENT SHARING
- REDUNDANCY MANAGEMENT TECHNIQUES FOR MULTIPLE WHEEL OPERATION NEED TO BE DEVELOPED
  - FOR MOST EFFICIENT OPERATION ALL WHEELS SHOULD SWITCH FROM MOTOR TO GENERATOR MODE AND VICE VERSA SIMULTANEOUSLY
  - ALL WHEELS SHOULD SHARE A COMMON ERROR VOLTAGE TO INSURE THEY SHARE EQUALLY IN SUPPLYING THE SPACECRAFT LOAD
  - NEAR EQUAL WHEEL SPEEDS MAY SIMPLIFY MOMENTUM MANAGEMENT CONTROL LAWS