Parallel Path Magnetic Technology for High Efficiency Power Generators and Motor Drives

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Parallel Path Magnetic Technology for High Efficiency Power Generators and Motor Drives

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Abstract. Parallel Path Magnetic Technology (PPMT) is an advanced magnetic force control technology that is applicable to motors, rotary actuators, linear actuators, and generators. PPMT uses permanent magnets controlled with a field coil in parallel magnetic circuits. PPMT is a simple but revolutionary concept that has been demonstrated in a wide variety of prototype devices. PPMT devices allow the control of a given amount of magnetic flux for less energy input compared to a conventional device. PPMT devices are smaller, lighter, run cooler, and are more energy efficient than their conventional counterparts.

Keywords: Motor, generator, actuator, magnetic latch, magnetic, permanent magnet, energy efficiency, Parallel Path Magnetic Technology, PPMT.
PACS: 41.20-q, 89.20.Bp, 89.30-g, 89.40-a.

PARALLEL PATH MAGNETIC TECHNOLOGY (PPMT) BACKGROUND

Parallel Path Magnetic Technology (PPMT) is an advanced magnetic force control technology that is applicable to motors, rotary actuators, linear actuators, and generators. PPMT is a revolutionary concept that has been demonstrated in a wide variety of prototype devices.

PPMT uses two or more permanent magnets placed in parallel. The basic magnetic circuit consists of a flux steering coil on each flux path as shown in figure 1. If there is no current in the coils the magnetic circuit then acts as if the coils do not exist.

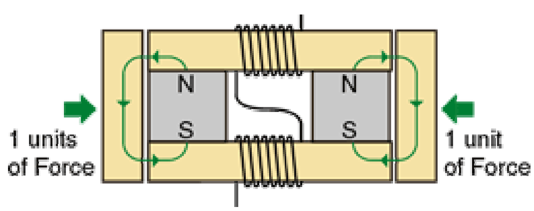

FIGURE 1. Basic PPMT Actuator (Flux Steering Coils Off).

However, if current flows in the flux steering coils to produce a magnetic polarity, as shown in figure 2, the flux produced by the coils couples with the permanent magnet's flux resulting in four units of force at the pole interface since $F \sim B^2A$.

Once the flux has switched and the actuation elements have moved to create an air gap on the zero force side, the steering coils can be turned off and the actuator or motor will remain in this new state at four units of permanent force with no power required. A momentary coil pulse with the opposite polarity, will switch the actuator in the opposite direction.

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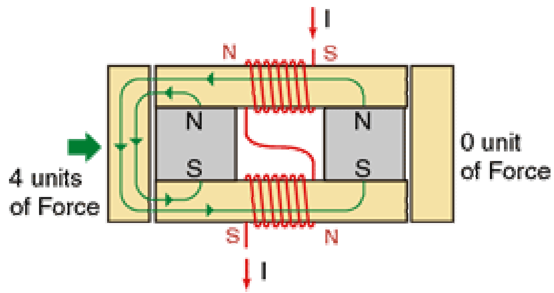


FIGURE 2. Basic PPMT Actuator Steering Coils Engaged to Switch All Magnetic Flux to One Actuator Pole.

In the actuation of the PPMT device, the steering coil only needs to have sufficient current to equal the flux of one permanent magnet. Thus, in PPMT devices a given amount of magnetic flux can be controlled with only half the field coil power required by conventional devices. Furthermore, the force generated by the PPMT device will continue, with no power required, as long as the geometric arrangement of the elements allow for it. This same basic magnification of the mechanical/magnetic/electric coupling relationship exists for generators and motors in a similar manner as it does for the actuator used in this simple example.

Compared to an equivalent conventional motor/generator, or actuator a PPMT device has: higher power density, higher power efficiency, lighter weight, smaller physical size, wider torque zone with high efficiency, wider power zone with high efficiency, and cooler operating temperatures.

Basic Design of a PPMT Motor/Generator

A PPMT motor/generator is similar to conventional motor/generators in that a PPMT motor is also a generator if driven with a mechanical input. However, a PPMT motor/generator operates using different logic than any conventional motor/generator. In conventional motors, a field coil (on either the rotor or stator pole) directly attracts (or repels) another magnetic element in the motor (i.e. permanent magnet, field coil, iron core). However, in a PPMT motor the field coils do more, they provide both driving flux and provide flux control of the permanent magnets, which add their own flux to the driving force.

In a PPMT motor the rotor is similar to a conventional Variable Reluctance Motor (VRM). VRMs are often used for stepper motors. Like a VRM, the rotor of the PPMT motor is a high permeability iron laminate with no coils or magnets on the rotor. That is where the similarity to a VRM ends. Unlike a VRM, the stator portion of the PPMT motor includes permanent magnets. For each pair of magnets, two coils are wound onto the stator. In a conventional VRM, coils are wound around each stator pole and the flux generated by current flowing in these coils is used to generate torque. In the PPMT motor the permanent magnet flux plus the induced flux from the load current add to generate the shaft torque. Proper timing in the switching of the stator coils optimizes torque. The coils provide a flux steering service in directing the permanent magnet's flux to the proper poles at the proper times to produce torque. Because of the supplemental power due to the permanent magnet flux, the input power needed is substantially less than the power required by a conventional motor for each pound of torque generated. Thus, the PPMT motor is much more efficient. PPMT motors have exceptional performance in continuous duty applications. Compared to a conventional motor's continuous duty rating, a PPMT motor will be lighter, smaller, and higher efficiency than any conventional design.

In a PPMT motor the current in the stator field coil increases under load but at the same time provides an induced bucking flux to reduce the motors retard force. Unlike a conventional VRM the back emf (BEMF) is generated by the magnet flux switching back and forth through the field coil during rotation (BEMF = $\omega_m d\psi m/d\theta$). The result is a generator action internal to the motor that provides an additional energy source from the switching magnet flux to augment the energy coming from the power supply. Symptomatically the motor will display an over-voltage condition at the output of the power supply that will back bias the power supply rectification diodes and prevent power supply conduction during the over-voltage condition. Proper design allows one to thus improve motor efficiency compared to conventional motors by optimizing the operating point to make maximum use of the switched magnet flux. Essentially the motor uses the combined flux from the load-induced current added to the magnet flux to generate shaft torque. Similar benefits occur in applying the motor as a generator. In contrast a conventional VRM has its BEMF generated by the change in inductance with rotation angle as the rotor passes over the wound pole (BEMF = $\omega_m i dL/d\theta$) and does not have the same potential for increasing efficiency and torque.

The design and development of PPMT motors and generators is supported and optimized using Tera Analysis' Quickfield software magnetic modeling. Figure 3 shows a 6 magnet motor going through one control cycle as analyzed using Ansoft software. (Note: This sequence shows 1/15th of one rotor revolution. The tab on the rotor provides a reference for rotor location to help understand the change in rotor position.)

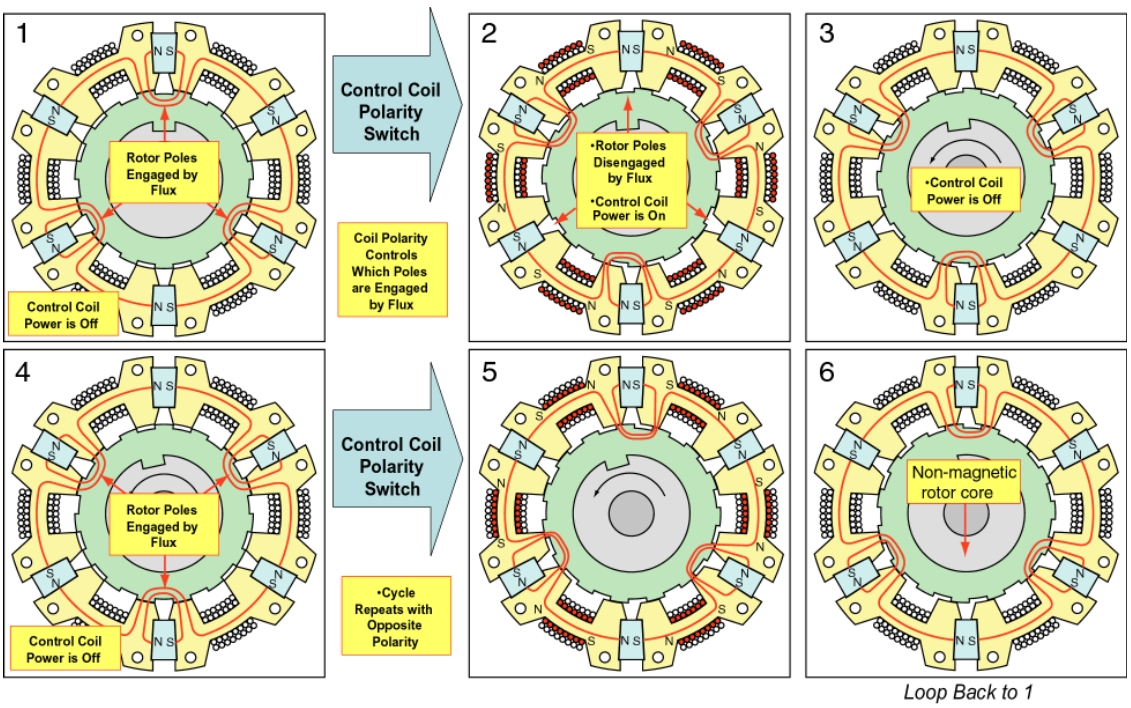


FIGURE 3. Six Magnet Motor Flux Sequence (Rotor Turning Counterclockwise).

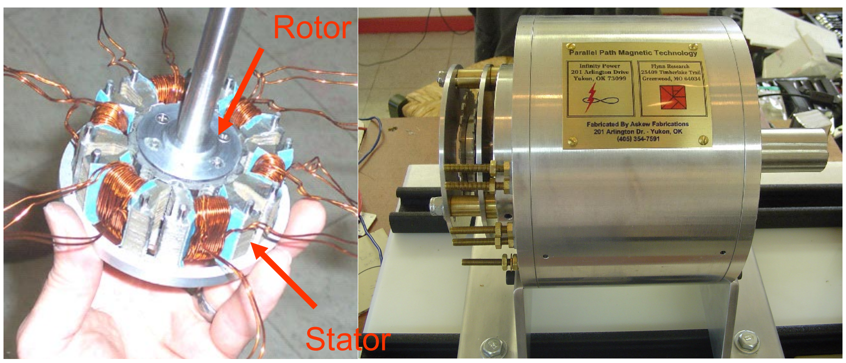
Mechanically turning the motor/generator shaft and connecting an electrical load across the stator coils can turn a PPMT motor into a PPMT generator. As the rotor turns, the flux line paths passing through the steering coils change with time. As with any conventional generator, this generates electricity in proportion to the magnetic flux strength and the rate of change.

A PPMT generator has extraordinary performance in continuous duty applications because it places less load on the mechanical prime mover than a conventional generator for the same amount of power generated. This is due to a combination of events that occur as the rotor of the generator is turned by the mechanical prime mover. The steering coils now act as the generator windings and these windings are placed in series with the external load. As the rotor turns, flux from the permanent magnets is commutated through the core region of the windings by the rotor. The sensor that senses the rotor position and switches on and off the control coils when operated as a motor now determines which winding will supply electrical power to the load. Because of the unique magnet and coil relationship in a PPMT generator/motor, the current induced into the windings forms a magnetic polarity in the windings and field-poles that supports rather than opposes the direction the rotor is turning. This is commonly referred to as the 'motor effect' in a generator, but with conventional generators this effect normally opposes the direction of rotation, reducing the efficiency of the generator and creating "drag" on the prime mover. With a PPMT generator this drag is reduced.

It follows, that with a greater electrical load, a larger amount of current flows through the windings resulting in a 'counter torque load'. In the case of conventional generators this results in increasing prime mover "drag" and decreasing efficiency. In the case of a PPMT generator with increasing electrical load, the current generates a canceling flux to reduce the "drag" seen by the prime mover thus maintaining very high efficiency even as the electrical load changes. This allows for greater electric power output at reduced input torque from the prime mover and easier high-speed operation. This unique characteristic has been verified through empirical tests.

Since the flux in a PPMT generator does not traverse through the center of the rotor, as in a conventional generator, the rotor can be a thin ring mounted on a material that is much less dense than silicon steel, allowing for a substantial weight reduction. Also due to the unique design of the PPMT generator the stator does not require 'back iron' which also allows for another substantial weight reduction. The net result is that a PPMT generator produces greater power output for a given input torque, with cooler operation at a higher power density in a smaller footprint than any known conventional generator. This effect is fully scalable from tiny generators producing a few watts of power to large generators producing many kilowatts.

A wide variety of PPMT motors have been built demonstrating the basic physics and performance of PPMT designs. One key characteristic of PPMT motors is the minimal heat generation at full power over long periods of time. A typical PPMT motor will not exceed 25 degrees F above ambient temperature, even in an uncooled housing during continuous and extended operation. Figure 4 shows a 3.5-inch diameter (approximately 1hp), 6 magnet PPMT motor/generator being assembled on the left, and a 6 inch diameter (approximately 10Kw) motor/generator developed for Boeing's Phantom Works division on the right.

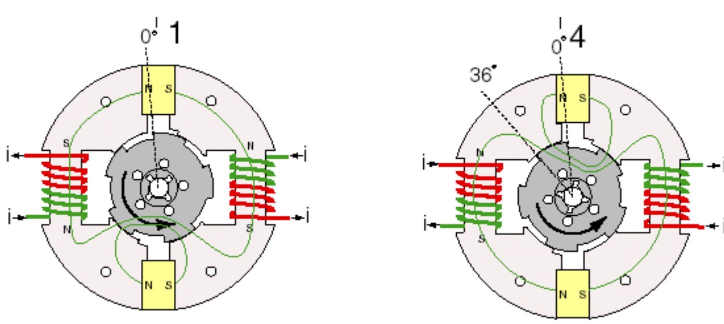


(a) 3.5" Motor. **(b)** 10Kw Motor.

FIGURE 4. Examples of a 3.5" PPMT Motor with End Cap Removed and a 6" Diameter 10Kw PPMT Motor/Generator.

EXPERIMENTAL DATA & ANALYSIS

A significant effort has been aimed at completing a model that could be used to predict the motors behavior to allow designing for different operating loads. While we had hoped to show some load data and efficiencies from the original prototype motor we were unable to complete that testing. However, the following wave shapes taken from the no-load operation of the motor will help to explain its operation. The motor used for this purpose was the original prototype "A-type" shown below in figure 5.



(a) 2 Pole Motor in Position 1. **(b)** 2 Pole Motor in Position 2.

FIGURE 5. Two Pole PPMT Motor (A-type Pole Configuration).

No-load voltage and operating current data were taken over a pole period for the above motor starting at 2 volts supply voltage ranging up to 18 volts. Figure 6 shows the wave shapes for the 18volt supply setting compared to the modeled results.

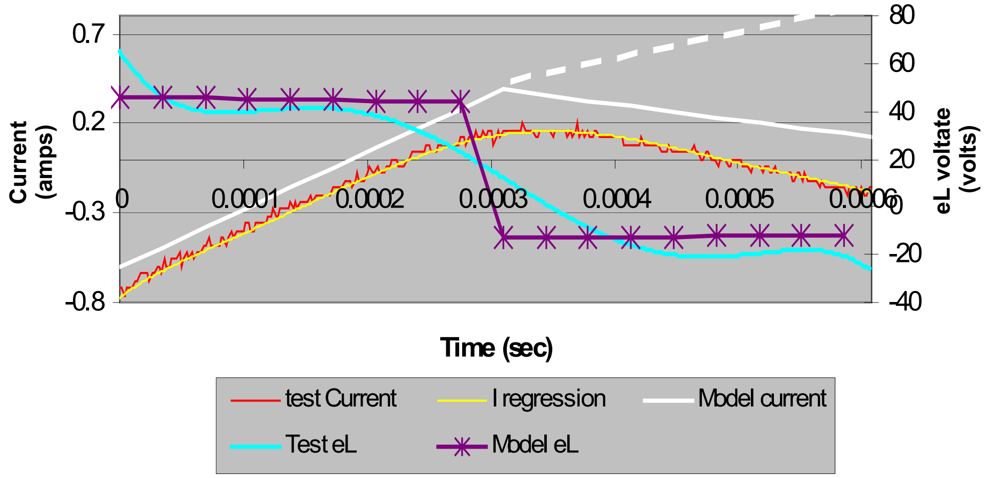


FIGURE 6. Test Data Wave Forms for one Pole Switching Event in an A-type Motor, Showing Current and Voltage Profiles at 18 Volts/9,868 RPM.

The red and yellow traces are the test current and regression line respectively to permit taking the current derivative in calculating the induced voltage in the coil; e = Ldi/dt. As can be seen the induced voltage is significantly greater (~42V) than the 18-volt supply setting. The solid white trace is the modeled current. While there is some offset the results are reasonably close. The lack of rounding at the peak is believed due to the saturation effects of the edge-to-edge condition of the pole at the time of commutation.

Specific attention should be paid to the amount of current above and below the zero axis; Positive values indicate flow from the power supply or its output capacitor into the motor; Negative current indicates flow from the collapsing field in the coil during electronic commutation. This action generates a voltage greater than the supply setting and charges the output capacitor thus back biasing the rectification diodes and preventing conduction. One can easily see that the efficiency under these conditions would be extremely high.

As the motor is put under torque load the current trace during the second half will start approaching the path of the white dotted trace. Proper selection of the number of turns can optimize the motor to favor heavy or light loads. Under light load the generator action from the permanent magnet flux will provide a greater portion of the energy since the higher rpm will result in a higher BEMF. Under heavy loads the flux from the load current will dominate.

Figure 7 shows a speed torque curve that was modeled with the same constants used in correlating the model to the no-load conditions. The white trace shows rpm that correlates to the output power (red trace) and input power (black trace) respectively. Efficiency is shown by the brown trace. We had hoped to be able to show experimental data for load conditions that correlated to the above graph but were not able to complete testing before the submittal deadline. The modeled results suggest that the motor would provide a relatively constant power out (40-58 watts range) between ~20 ozin and ~ 280 ozin. Efficiency starts close to 100% at very light loads and shows a linear drop to about 35% at about 280ozin. Our plan is to complete correlation of the model to experimental results to gain the needed insights to allow designing the motor for specific applications.

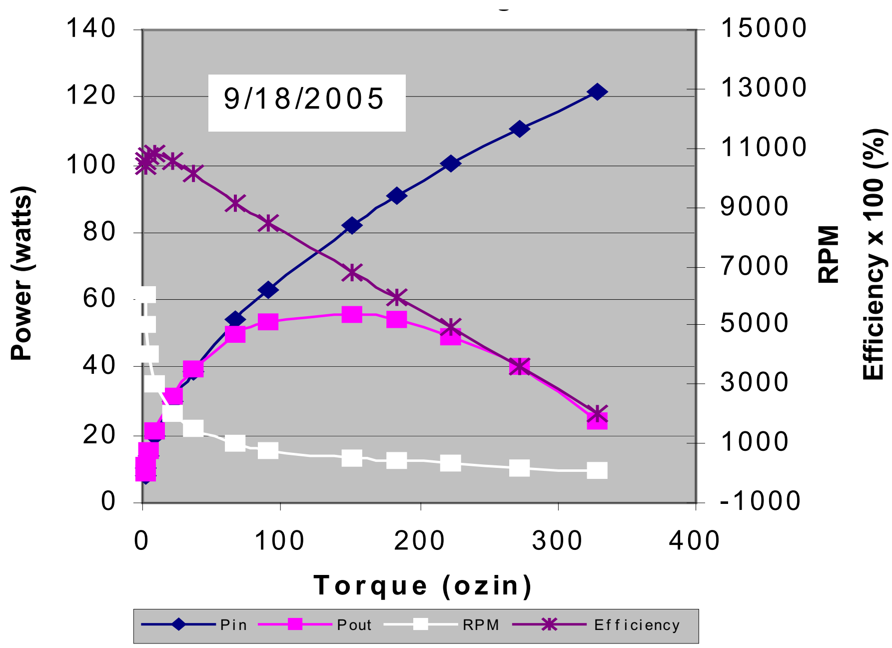


FIGURE 7. Example PPMT Motor Speed /Torque Curve with 18 Volt Input.

Flynn PPMT Motor Theory

The "Conventional Reluctance Motor" would have the following equations:

$v(t) = iR + Ldi/dt + \omega_m idL/d\theta$ where the last term is the back-emf (BEMF).

Instantaneous Power (p) = $vi(t) = i^2R + Lidi/dt + \omega_m\, i^2dL/d\theta$

The mechanical power conversion $p = \omega_m Te$ where Te is the instantaneous electromagnetic torque and is what remains after subtracting out the i^2R loss and the rate of change of the magnetic stored energy from the input power (vi).

$(p)/\omega_m = T_e = 1/2\ i^2\ dL/d\theta$ (Miller, 2001)

The conventional reluctance motor gets its torque from the exchange of electromagnetic field to mechanical energy as the reluctance of the gap changes causing a change in inductance with rotation. In this case coils are wrapped around each pole.

Flynn PPMT Motor Equation:

The power supply voltage feeding the motor input is derived as follows:

$v(t) = iR + d\psi(i,L)/dt \pm d(\psi_{pm,})/dt$

$v(t) = iR + \omega_m d(L,i)/d\theta \pm \omega_m d(\psi_{pm})/d\theta$ The $dL/d\theta$ term drops out since L is constant

$v(t) = iR + Ldi/dt \pm \omega_m d(\psi_{pm})/d\theta$ Where the last term is the back-emf (BEMF)

$p = vi(t) = i^2R + iLdi/dt +/- i\omega_m d(\psi_{pm})/d\theta$ Where the last two terms show that the output power is a function of both the changing magnet flux and the induced flux superimposed in the coil from the load current.

Because the magnets placed in the stator separate it into multiple segments, the gap dimensions imposed by the magnets determine the reluctance around the stator. The result is a reduction in the core-loss terms, eddy currents, hysterisis loss etc. because the magnetic path is no longer contiguous in a magnetically soft material. What was a very small BH area in the soft material virtually disappears into a straight line. The net result is a very small core loss and hence small temperature rise.

The +/- term for the BEMF is because the current switching starts when the stator/rotor poles are at a 50/50% overlap whereas the flux commutation from the magnets reverses direction every time the alternate poles go through full alignment. In the Flynn motor the coil is wrapped on the back iron of the stator and has flux alternately switching direction through it as the rotor passes an aligned position. Experimentally it has been shown that for the 2-magnet prototype motor the inductance stays constant within 10% when rotated past one pole. Unlike a conventional VR motor, the BEMF can exceed the supply voltage since it is not dependent on power supply current but only on the magnet flux, rpm, and the number of turns. This suggests that under lighter loads (higher rpm) the combination of the current through the coil times the integrated flux area (as the poles alternate between alignment and non-alignment) provides energy to the system that significantly improves efficiency. As the rpm diminishes under load, the BEMF reduces and delivers less and less power contribution compared to the induced flux from the increasing load current and efficiency will tend to drop approaching normal VR efficiencies. But performance will still be better than a conventional VR motor since, although reduced, there is still a contribution from the generator action of the BEMF. Proper design can take advantage in optimizing the switching magnet flux contribution in supporting a target load. Conversely, the $\omega_m idL/d\theta$ BEMF term that appeared in the conventional VR motor equation disappears because "L" is constant

In the Flynn motor, torque is also delivered from the iLdi/dt term since the current, unlike the conventional Reluctance motor, varies between a triangle shape at light load to an L/R exponential ramp at higher loads. In contrast, with the conventional Reluctance motor, current pulses tend to approach square waves and the Ldi/dt voltage effect cancels out of the torque equation because the positive and negative going edges both occur within the pole period.

The solution to the above equation yields a fairly simple result i.e. a current exponential rise to a target dictated by the algebraic sum of the power supply voltage (Vs) and the motor BEMF divided by the motor resistance. Properly combining the instantaneous currents and the involved flux areas delivers shaft power that is a function of both the load current and the switching magnet flux. Modeling results show relatively good correlation for at least light loaded systems. Further testing is needed to qualify the modeling under load conditions.

PMMT SPACE APPLICATIONS

PPMT has the potential to provide both a high performance power generation system and reduce the power consumption for spacecraft and planetary exploration vehicles. The wide variety of PPMT applications for space vehicles includes generators, motors, rotary actuators (PPMT motors are essentially high performance stepper motors), linier actuators (PPMT has been built into linier stepper motors), and latches. Some of the advantages of PPMT generators, motors, and actuators over legacy systems include:

- High specific force per unit volume/weight. PPMT devices are typically smaller and lighter than equivalent high performance conventional systems designed for continuous duty.

- Low power consumption per unit of force/torque. PPMT devices generate twice the magnetic flux strength and four times the force of an equivalent direct field coil system for the same electrical input.

- No power consumption for latches, linier actuators, or rotary actuators to hold force. Since PPMT devices derive their primary motive force from permanent magnets they hold with full force during power-off conditions.

- Rapid actuation of liner actuators, rotary actuators, and latches. PPMT device actuation and motor speeds are limited only by flux path speed and inertial constraints.

- High reliability – PPMT designs require no commutation or other active elements in moving components. The moving components are typically simple iron laminates on a lightweight carrier structure.

- Operate cooler - PPMT generators, motors, and actuators operate at very cool temperatures due to their extreme efficiency. PPMT devices typically operate at no more than 25° F above ambient, even at maximum continuous duty. This in turn reduces spacecraft thermal management loads. The cool operating temperatures also allow for lightweight construction, where components that would normally require metallic construction can now be made of plastic, graphite composites, or other high performance materials.

Applications of PPMT devices to spacecraft and planetary exploration vehicles are many and varied. Potential applications for latches and linier actuators include: door latches, solenoid replacement, relay replacement, safety releases, robotic manipulators, etc. Applications for motors and rotary actuators include: rover drive motors, robotic manipulators, fan motors, control surface actuation motors, flywheel motors, and electric air vehicle primary drives (planetary exploration and long duration near-space air vehicles). Applications for space power generators include: power generation using solar collector/sterling-cycle as primary mover (or any other closed rotary system) and high performance wind power for planetary exploration of planets with atmospheres.

CONCLUSIONS

PPMT devices can save weight and improve performance of spacecraft and planetary exploration vehicles. Compared to an equivalent conventional motor/generator, or actuator a PPMT device or motor/generator has: Higher power density, Higher power efficiency, Lighter weight, Smaller physical size, Wider torque zone with high efficiency, Wider power zone with high efficiency, Cooler operating temperatures.

NOMENCLATURE

ψ_i = Total flux due to current (Webers)
ψ_{pm} = Total magnet flux (Webers)
θ = Rotor position (radians)
ω_m = Angular velocity (radians/sec) = $d\theta/dt$
$Nd\psi_i$ = Ldi
L = Inductance (Henries)
N = Turns
i = Current (amps)
v = Voltage
t = time
R = Resistance

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Professor Jack Judy (retired) University of Minnesota made contributions to our understanding of magnetic physics.

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