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

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.

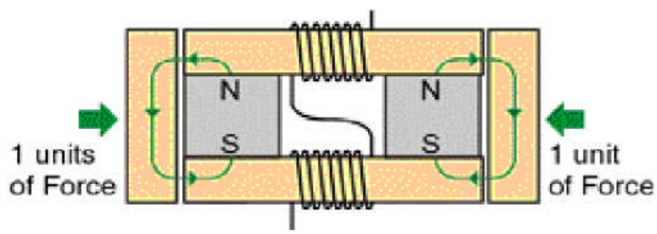

Figure 1. Basic PPMT actuator (flux steering coils off)

However if current flows in the flux steering coils to produce a magnetic polarity, as shown in figure 2, the magnetic flux produced by the coils couples with the permanent magnet's flux and the result is four units of force at one pole of the device (four units, not two, is due to the squared force law of the combined permanent magnet flux). 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.

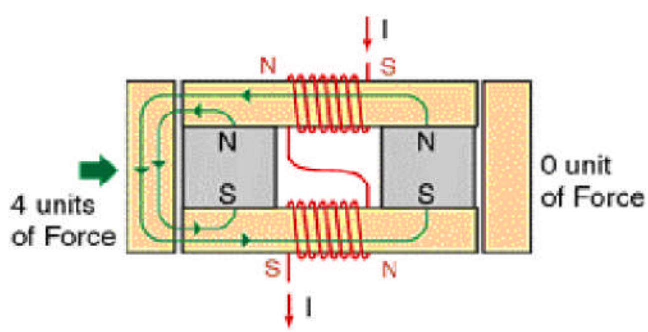

Figure 2. Basic PPMT actuator steering coils engaged to switch all magnetic flux to one actuator pole

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. Torque is optimized by proper timing in the switching of the stator coils.** 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. 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. A PPMT 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. In other words, even when being driven as a motor, a PPMT device is also simultaneously acting as a generator for part of each switching cycle. 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 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 FEA software for magnetic modeling. Figure 3 shows a 6 magnet motor going through one control cycle. (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.)

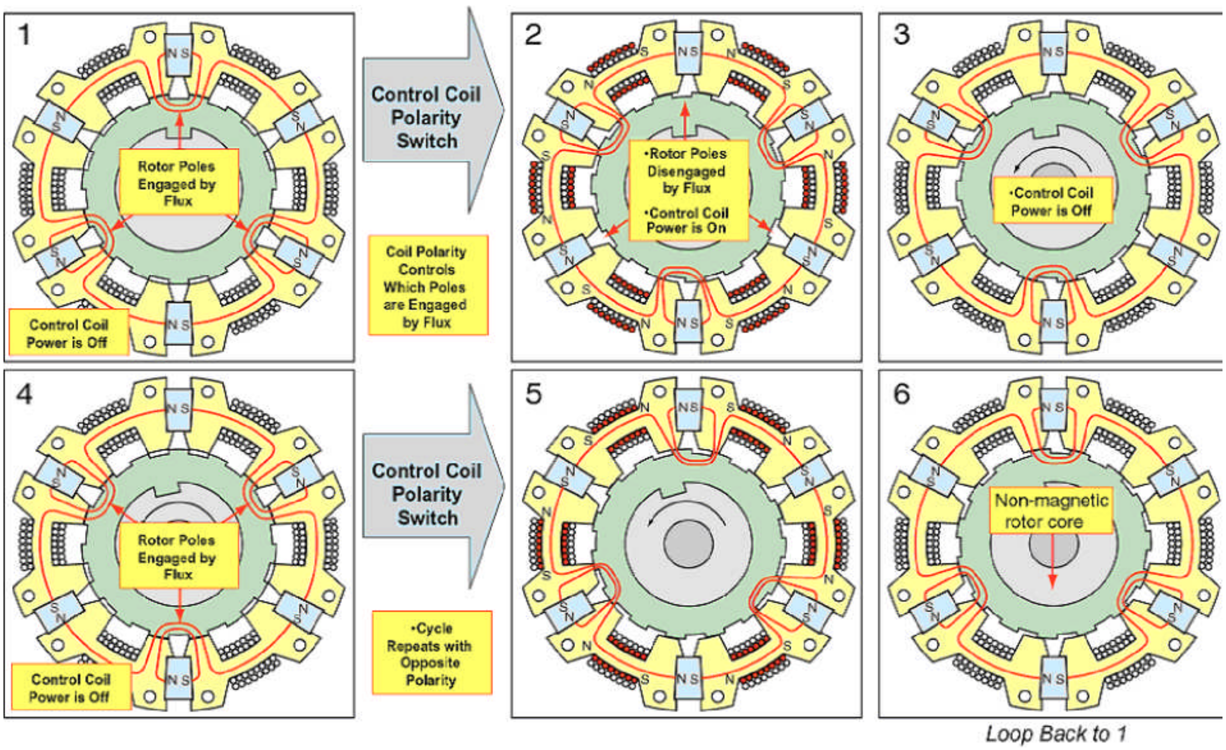

Figure 3. Six Magnet Motor Flux Sequence (Rotor Turning Counterclockwise)

PPMT Generator

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 the motor 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 greater ‘motor effect’. In the case of conventional generators this results in increasing prime mover “drag” and decreasing efficiency. In the case of a PPMT generator the greater the electrical load, the greater the direction of rotation is supported, thus reducing prime mover “drag” and 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 and our customers are welcome to review any and all data.

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 and generators 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.

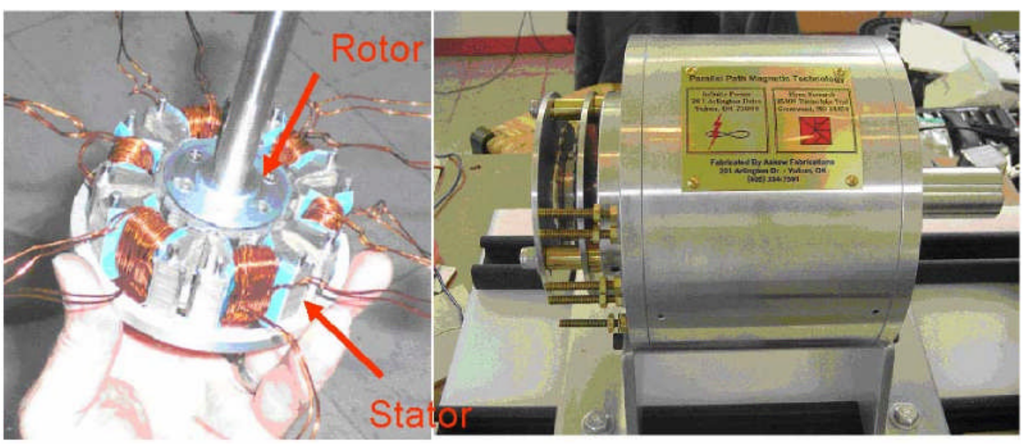

Figure 4. Examples of a 3.5” PPMT motor with end cap removed and a 6” diameter 10KW PPMT motor/generator

PMMT APPLICATIONS AND ADVANTAGES

The applications of PPMT are limitless. PPMT can provide high performance, linear actuators, power generation systems and motors. It has applications in transportation systems, industrial systems, local power generation, and power generation for the grid. The advantages of PPMT lend themselves to almost any electro-mechanical situation:

- **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, linear 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.

Parallel Path Magnetic Technology the possibilities are limitless.