SEMA Technology Redundancy Advantages

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Purpose

The purpose of this document is to describe some of the advantages of Kinetic Art & Technology's (KAT's) Segmented ElectroMagnetic Array (SEMA) motor and generator technology over conventional permanent magnet motors in the area of redundancy and graceful degradation. SEMA machines have properties that allow independent control over individual motor/generator sections that, at best, are very difficult to achieve with conventional permanent magnet motors.

Note that there are proprietary innovations that have been demonstrated by KAT that are not being disclosed publicly. This paper, therefore, does not document all the redundancy advantages that have been developed by KAT, or are available with SEMA machines.

SEMA Technology Redundancy Advantages

SEMA machines lack the mutual inductance between motor phases that is common to conventional permanent magnet motors. Motor sections can be controlled independently with essentially no interaction between the sections. This allows for a great deal of flexibility in partitioning the control of the motor across multiple motor/generator controllers, providing a great deal of redundancy.

This section provides a description of various configurations that can be achieved and highlights some of the redundancy advantages of SEMA technology. For this discussion, motor applications are presented, though the same configurations support generator applications equally as well.

Logically Paralleled Slices

SEMA machines are sometimes referred to as an “axial gap” machine, in that the magnetic flux flows axially through the stator, as opposed to the more conventional “radial gap” design in which the magnetic flux flows radially. This creates a machine that is generally “flat”, and in industry is sometimes referred to as a “pancake” motor.

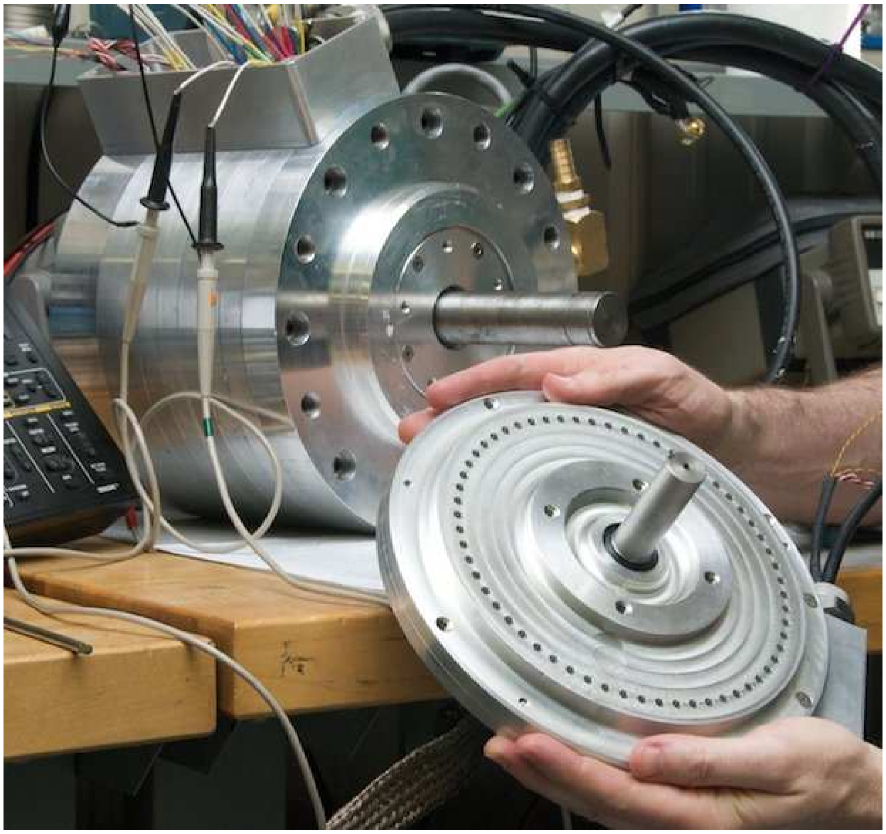

Figure 1. Single and Six-Slice 2s-158-6 Motors

In Figure 1, a “conventional” SEMA machine is shown in the foreground, and has the classic “pancake” shape of an axial gap machine. This is referred to as a “single-slice” motor. KAT has extended the SEMA technology in the axial direction using a “multi-slice” approach, in which multiple motor “slices” are integrated into a single motor. In the background in Figure 1 is a motor in the same 2s-158-6 motor family, but with the equivalent of six single-slice motors integrated into one motor. Note that the design is such that the six-slice motor weighs considerably less than six individual motors, due in large part to innovations developed by KAT.

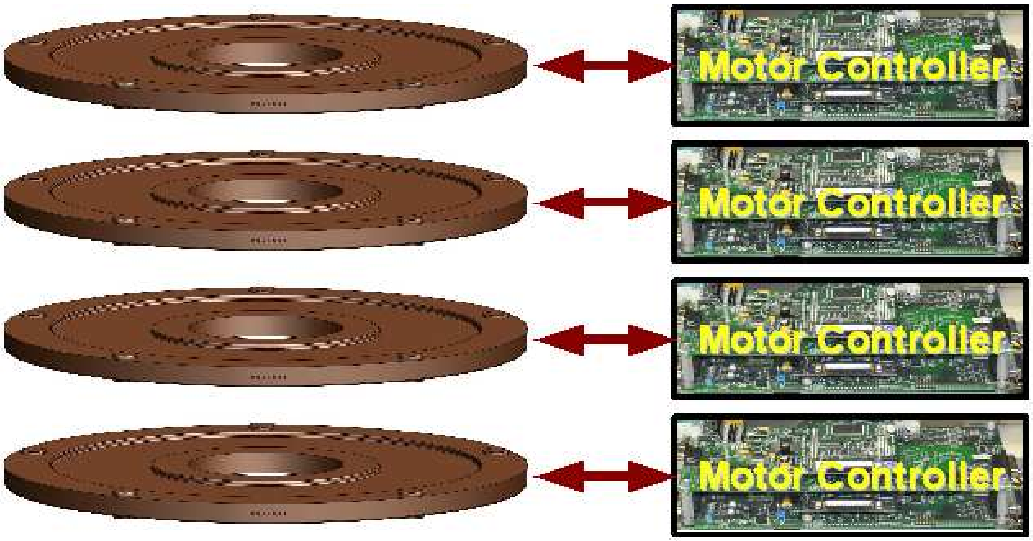

Figure 2. Four Motor Slices Controlled Independently

Despite the fact that the individual motor slices are integrated into a single motor, each slice can be driven independently. Figure 2 represents a four-slice motor in which each slice is driven by its own motor controller. If there is a failure in one of the slices or in one of the controllers, only one fourth of the available power is lost. Another factor also comes to play in a failure scenario, in that SEMA machines do not suffer from iron saturation and very high peak torques are possible. For limited periods, the three slices can provide as much power as four slices are capable of on a continuous basis.

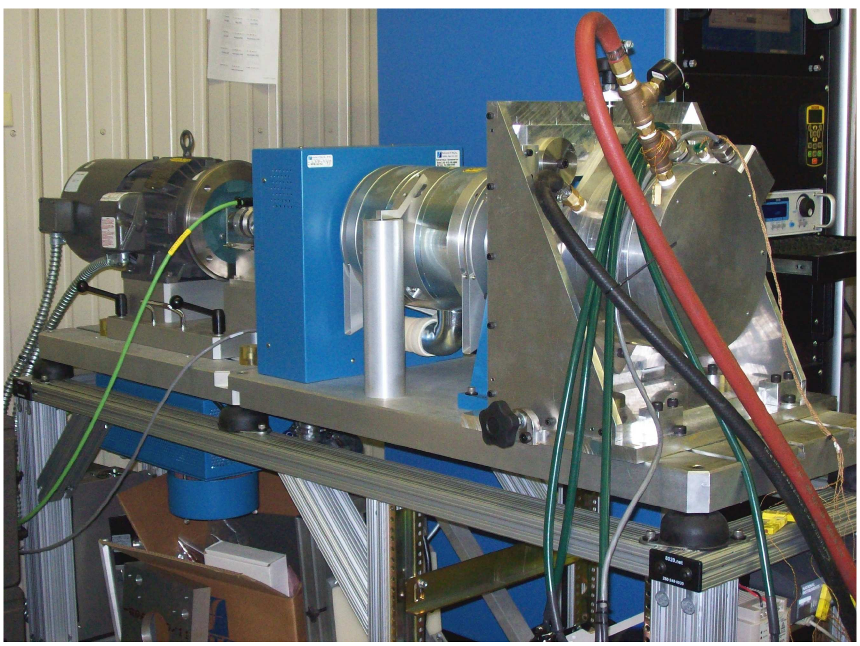
Figure 3. Four-Slice Motor on Dynamometer

Figure 2 describes a configuration demonstrated in partnership with Honeywell Aerospace. A four-slice motor is demonstrated in which each slice is individually controlled. In an aerospace pump application demonstration, each motor controller is configured such that it can be turned on or off from a control panel. The ability of this configuration to adjust readily to losing individual and multiple slices has been successfully demonstrated on both a dynamometer and a Honeywell Aerospace test cell. The motor described, operating on a KAT dynamometer, is shown in Figure 3. The heavy green cabling, visible in the photograph, are the phase leads for the four individual motors slices. For further details about this program, the reader is encouraged to contact KAT.

The configuration described, in which each motor slice is driven by its own controller, is referred to at KAT as being "logically paralleled." This refers to the fact that the motors are electrically separated, but mechanically work together in a parallel fashion. This is in contrast to a multi-slice motor that is "electrically paralleled." In that configuration, like phases across multiple slices are tied together and electrically paralleled. They are then driven by a single controller. This configuration is currently being demonstrated in a six-slice motor in which all six slices are in electrical parallel. For an example of the electrical effects of electrically paralleling motors, refer to Table 1 and the discussion proceeding it in a later section of this document.

Another example of logically paralleled slices is shown in Figure 4. An ElectroMechanical Actuator, or EMA, was designed by KAT to provide thrust vector control of elements of NASA's Constellation Program. The work was done under a NASA SBIR. It included proprietary innovations in redundancy not described here due to their sensitive nature. The design included a proprietary controller in which some of the proprietary redundancy innovations were demonstrated. The EMA incorporates a three-slice motor, very similar to the three-slice linear brake actuator described in following section. This EMA was designed to demonstrate logically paralleled controls, in that each slice can be controlled independently.

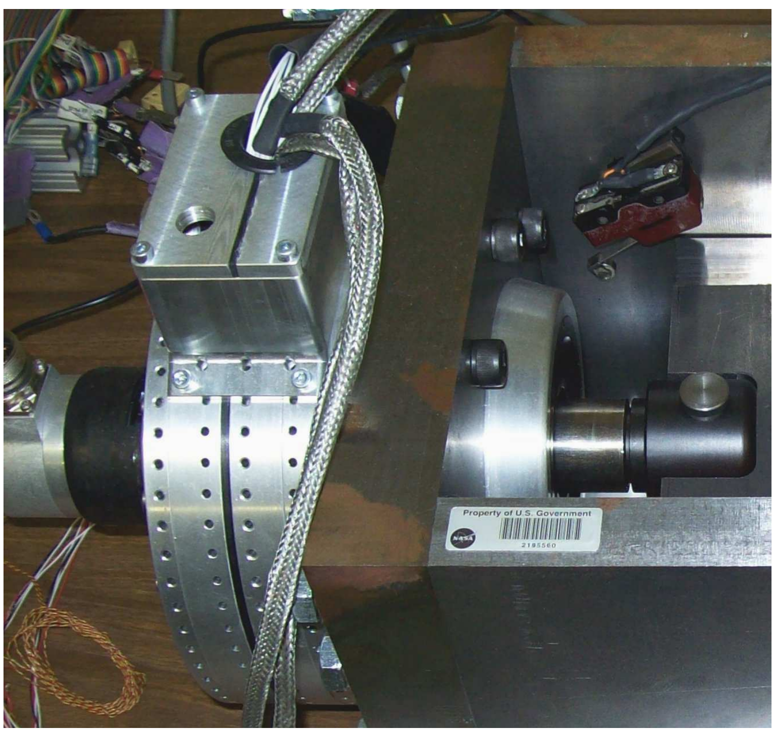

Figure 4. Three-Slice EMA Designed For NASA SBIR

Series Slices

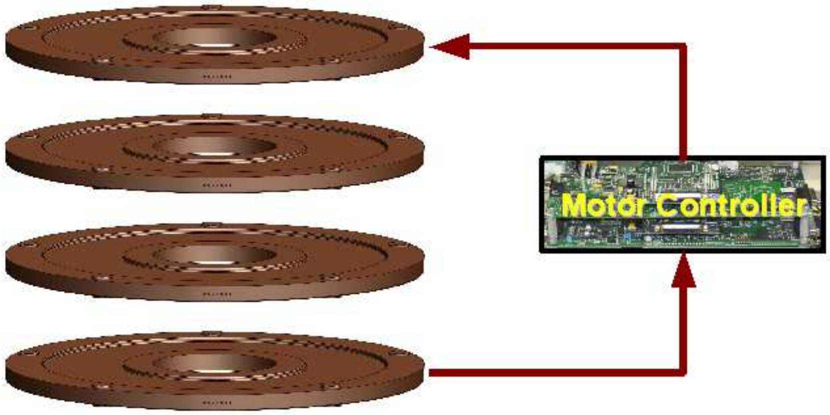

Figure 5. Four Motor Slices Driven by a Single Controller

Not only can the individual motor slices be driven in a parallel configuration, they can be driven in a series configuration. In such a configuration, the phases of each slice are placed in series with one another. In the example in Figure 5, four motor slices are driven by a single controller. While there is no redundancy advantage to this configuration, it does demonstrate some of the flexibility possible with SEMA machines.

Figure 6. Serially Connected Three-Slice Linear Actuators

An example of placing multiple motor slices in series is shown in Figure 6. Shown are four linear brake actuators developed for a demonstration for Honeywell Aerospace. Integrated into the linear actuator is a three-slice SEMA motor. The phases for each slice are placed in series and driven by a single controller. The four actuators shown successfully completed testing at a Honeywell Aerospace test cell.

Series & Parallel Slices

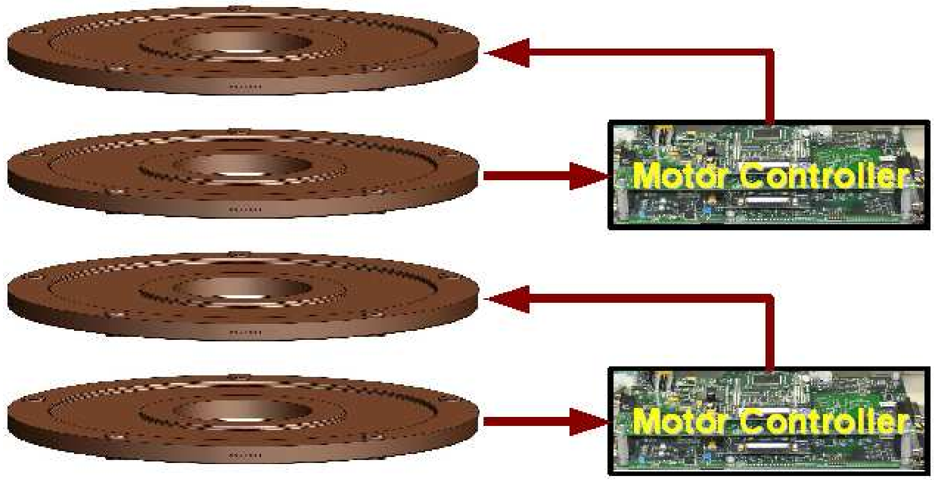

Figure 7. Four Motor Slices Driven by 2 Motor Controllers

The flexibility of SEMA multi-slice machines becomes even more apparent when the ability to combine series and paralleled motor slices is demonstrated. Figure 7 presents a four-slice SEMA machine that is driven by two motor controllers.

The purpose of this document is not to detail the trade-offs between various series and parallel slice configurations. However, it is useful to look at an example of the differences in the electrical parameters. While the power of a motor always increases linearly with the number of motor slices, other electrical motor parameters change very differently depending on whether the slices are driven serially or in electrical parallel. Note that for logically paralleled slices, the electric parameters for each slice are exactly the same as a single slice motor. Refer to Table 1 as an example of the electrical differences between driving slices in electrical parallel or in electrical series.

2s-158-6-56.3 Multi-Slice Parameters													
Parameter	*Symbol*												
Number of Slices		**1**		**2**		**3**		**4**		**5**		**6**	
General[1] *40°C 0.5 gpm/slice*													
Continuous stall torque	T_C	10.55 N·m	7.78 lbf·ft	21.1 N·m	15.56 lbf·ft	31.65 N·m	23.34 lbf·ft	42.2 N·m	31.12 lbf·ft	52.75 N·m	38.9 lbf·ft	63.3 N·m	46.68 lbf·ft
Peak torque (<1 sec.)[2]	T_{pk}	52.75 N·m	38.9 lbf·ft	105.5 N·m	77.8 lbf·ft	158.3 N·m	116.7 lbf·ft	211 N·m	155.6 lbf·ft	263.8 N·m	194.5 lbf·ft	316.5 N·m	233.4 lbf·ft
Rated Speed	S	4,651 RPM		4,651 RPM		4,651 RPM		4,651 RPM		4,651 RPM		4,651 RPM	
Rated Power	P_{out}	5.14 KW	6.89 hp	10.28 KW	13.78 hp	15.42 KW	20.67 hp	20.56 KW	27.56 hp	25.7 KW	34.45 hp	30.84 KW	41.34 hp
Peak Power (<1 sec.)[2]	P_{out}	25.7 KW	34.45 hp	51.4 KW	68.9 hp	77.1 KW	103.4 hp	102.8 KW	137.8 hp	128.5 KW	172.3 hp	154.2 KW	206.7 hp
Electrical ~20℃													
Stators in Electrical Series													
Torque Constant	K_T	0.932 N·m/A	0.687 lbf·ft/A	1.864 N·m/A	1.375 lbf·ft/A	2.796 N·m/A	2.062 lbf·ft/A	3.728 N·m/A	2.75 lbf·ft/A	4.66 N·m/A	3.437 lbf·ft/A	5.592 N·m/A	4.124 lbf·ft/A
Voltage constant (phase-phase)	K_E	56.3 V_{rms}/krpm		112.6 V_{rms}/krpm		168.9 V_{rms}/krpm		225.2 V_{rms}/krpm		281.5 V_{rms}/krpm		337.8 V_{rms}/krpm	
Continuous stall current	I_c	12.87 A_{rms}		12.87 A_{rms}		12.87 A_{rms}		12.87 A_{rms}		12.87 A_{rms}		12.87 A_{rms}	
Resistance (phase-phase)	R	1.0 Ω		2.0 Ω		3.0 Ω		4.0 Ω		5.0 Ω		6.0 Ω	
Inductance (phase-phase)	l	148 μH		296 μH		444 μH		592 μH		740 μH		888 μH	
Stators in Electrical Parallel[3]													
Torque Constant	K_T	0.932 N·m/A	0.687 lbf·ft/A	0.932 N·m/A	0.687 lbf·ft/A	0.932 N·m/A	0.687 lbf·ft/A	0.932 N·m/A	0.687 lbf·ft/A	0.932 N·m/A	0.687 lbf·ft/A	0.932 N·m/A	0.687 lbf·ft/A
Voltage constant (phase-phase)	K_E	56.3 V_{rms}/krpm		56.3 V_{rms}/krpm		56.3 V_{rms}/krpm		56.3 V_{rms}/krpm		56.3 V_{rms}/krpm		56.3 V_{rms}/krpm	
Continuous stall current	I_c	12.87 A_{rms}		25.74 A_{rms}		38.61 A_{rms}		51.48 A_{rms}		64.35 A_{rms}		77.22 A_{rms}	
Resistance (phase-phase)	R	1.0 Ω		0.5 Ω		0.3 Ω		0.25 Ω		0.20 Ω		0.17 Ω	
Inductance (phase-phase)	l	148 μH		74 μH		49 μH		37 μH		30 μH		25 μH	

[1] 40C 0.5 gpm liquid cooled operating point is an example. Other operating points are possible under different conditions.
[2] Peak values highly time dependent. 5X rated values shown - 10x is typical.
[3] For slices driven independantly (logical parallel), electrical parameters for each slice are the same as a 1 slice motor

Table 1. Comparison of Series Vs. Parallel Slices for 2s-158-6-56.3 motor family

Partitioned Slices

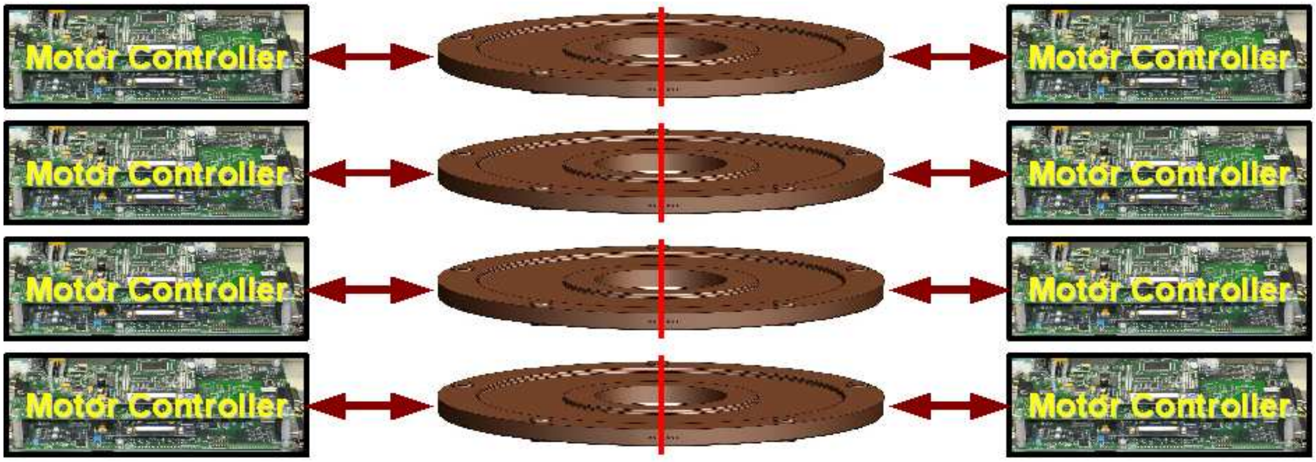

Figure 8. Four Motor Slices Driven by 8 Motor Controllers

Not only can each slice of a multi-slice motor be driven independently, but due to the proprietary construction of SEMA stators, a motor slice can be partitioned into sections that can be controlled independently. Note that no changes to the rotor are required. Generally, the independently controlled sections are divided equally across the coils so that each section has the same number of coils, though that is not a necessity. The number of coils is determined by the number of pole-pairs. Thus, a high level of redundancy can be accomplished with even a single-slice SEMA machine.

Figure 8 demonstrates a system in which a high level of redundancy is of extreme importance. Not only is each motor slice driven independently, but each motor slice is driven by two controllers, for a total of eight independently controlled motor sections. If one section fails, 87.5% of the total continuous motor power is available, and full power is available for extended periods of time.

Proprietary Redundancy Innovations

Kinetic Art & Technology has additional innovations in the field of SEMA motors and generators, as well as in proprietary motor controls. Some innovations take advantage of properties of SEMA machines, while others have potential application with other electric machines. Due to the proprietary nature of these innovations, they are not discussed in this paper. If the reader has interest in further enhancements in motor and generator redundancy beyond those already described, the reader is encouraged to contact KAT.

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