A 10-MJ ACTIVE ROTARY FLUX COMPRESSOR FOR DRIVING XENON FLASHLAMPS

C. A. Morgan, W. L. Bird, and W. F. Weldon
Center for Electromechanics
The University of Texas at Austin
Austin, TX 78712

Summary

An eight-pole, drum-type active rotary flux compressor (ARFC) has been designed to replace an 85 percent efficient 10-MJ (stored) capacitor bank for driving xenon flashlamps for solid-state lasers. The conceptual machine has a 1.1-m diameter rotor and will deliver 8.5 MJ at 18 kV from a speed of 2,680 rpm. Peak current is 750 kA with a 670 µs pulse width (FWHM).

Air-gap armature and compensating windings are bonded to fully laminated M-19 steel rotor and stator assemblies using a Fiberglas insulation system that is vacuum-pressure-impregnated with a high shear strength epoxy resin. This construction yields an inductance variation or flux compression ratio of 158:1.

The ARFC is a vertical-shaft generator and is driven by an 800-hp variable speed dc motor drive. An 800-kJ, 22-kV start-up capacitor bank is required to establish initial magnetic flux in the machine. The xenon flashlamps in series with the ARFC and start-up bank constitute the switching element to trigger the discharge.

Introduction

The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has been working since 1978 to develop the compensated pulsed alternator/rotary flux compressor class of rotating machinery.[1] These drivers have been proposed as potentially more compact, less expensive means of storing and converting energy for pulsed power applications, including driving xenon flashlamps for future solid-state laser systems. During the past five years, under sponsorship of Lawrence Livermore National Laboratory (LLNL) and the Naval Surface Weapons Center (NSWC), CEM-UT has developed an engineering basis for the design of larger machines that are capable of delivering up to 10 MJ at peak-power levels exceeding 10 GW. The effort to date has included:

- development of computer codes for generator design, impedance calculation, and nonlinear transient circuit simulation;
- compulsator proof-of-principle experiments at 130 MW;
- demonstration of inductance variation >40:1 for a small-scale active rotary flux compressor with fully laminated steel rotor and stator construction; and
- development of vacuum-pressure-impregnated (VPI) air-gap armature and compensating windings.

Recently, CEM-UT has completed the conceptual engineering design of a 10-MJ active rotary flux compressor (ARFC) flashlamp driver. This design has been presented to potential manufacturers to obtain budgetary cost estimates and to evaluate the feasibility of fabricating a system of 50 such units to drive flashlamps for a future solid-state laser.

The Active Rotary Flux Compressor

The machine design discussed is similar in construction to the 20-cm rotor diameter actively compensated rotary flux compressor described previously.[2] Air-gap armature and compensating windings are fabricated from multiple Litz wires wound in parallel. The conductors are bonded to the cylindrical laminated steel surfaces using a VPI high shear strength epoxy resin. A simplified cross-sectional view of an eight-pole machine is shown in Fig. 1. The generator is a four-terminal rotary inductor, shown schematically in Fig. 2. The compensating winding and armature winding are connected in series by means of a slip ring and copper-graphite brushes located at one end of the

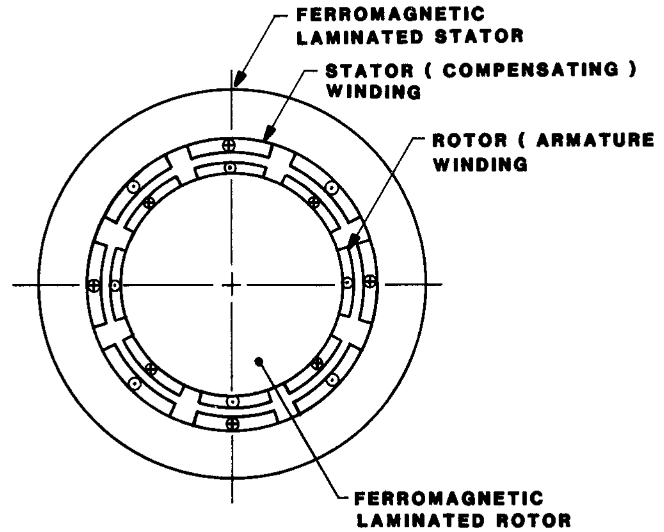

Fig. 1. ARFC with eight poles

assembly. At the opposite end, a similar slip ring and set of brushes connect the armature to the output terminal. As the rotor revolves, the mutual inductance changes sinusoidally, causing the net inductance to vary as

$$L_{gen} = L_{min} + \Delta L \left(1 - \cos \frac{N_p \Theta_m}{2}\right), \qquad (1)$$

where L_{min} = minimum inductance
N_p = number of poles
Θ_m = relative mechanical angle between rotor and stator windings.

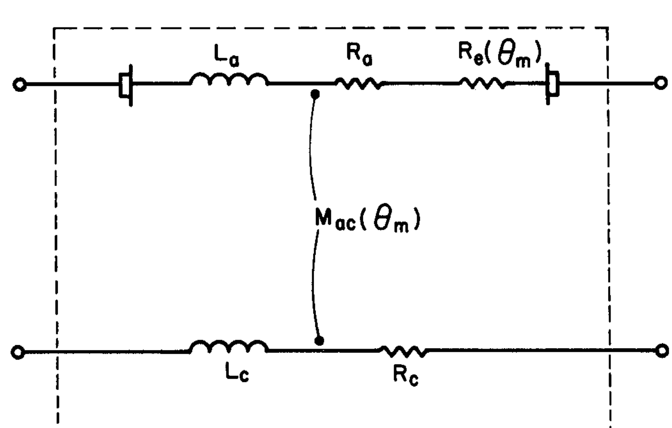

Fig. 2. Schematic diagram of ARFC

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Flashlamp Load and Generator Circuit

The full-scale ARFC was designed to replace a 10-MJ capacitor bank driving xenon flashlamps. It provides 8.5 MJ of energy to the flashlamp load in a sub-millisecond pulse at 18 kV, and is therefore equivalent to the 85 percent efficient capacitor bank discharge. The circuit used to deliver the pulse is shown in Fig. 3. In operation, the ARFC is motored to 2,680 rpm by an 800-hp variable speed dc motor-driver. The start-up capacitor bank is charged to 22 kV using a high voltage power supply (HVPS). Just prior to reaching a maximum inductance position, a 1.5- to 3-kV trigger pulse to the lamp reflector initiates a small arc-streamer in the bore of the flashlamp. The capacitor bank is

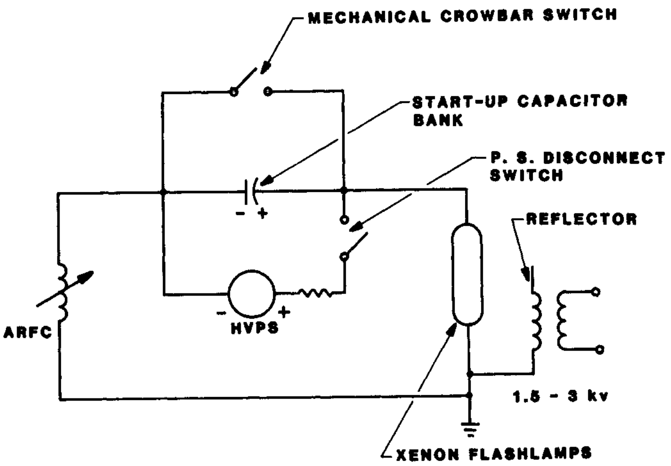

Fig. 3. Flashlamp driver circuit

discharged through the generator circuit, in a time period which is short compared to the time for the rotor to rotate one pole pitch.

Magnetic flux is established by an initial current at the maximum inductance position. Current is increased as the rotor approaches the minimum inductance position, since the circuit tends to maintain constant flux linkages during discharge. Inertial energy is then converted to magnetic energy in the air gap and electrical energy in the load.

Electrical Design

An interactive computer code was developed and used to calculate electromagnetic parameters, physical characteristics, and machine performance. The program requires machine and material constraints such as

- maximum allowable rotor tip speed;
- insulation dielectric, shear, and compressive strengths;
- banding tensile strength;
- Litz wire filament diameter and construction; and
- lamination core loss coefficients and permeability factors.

Design variables used by the code include

- number of poles;
- number of conductors per pole;
- radial conductor thickness;
- rotor diameter;
- rotor length-to-diameter ratio (ℓ/D); and
- start-up capacitor bank voltage.

The design code then computes

- generator impedance;
- rotor inertia;
- winding heat capacity;
- rotor and stator dimensions;
- flux compression ratio;
- short-circuit energy gain; and
- ideal short-circuit pulse width.

A circuit simulation code computes

- delivered energy;
- current pulse width;
- maximum torque;
- peak current;
- energy discharge efficiency; and
- other performance characteristics.

Iterative design computations were repeated while optimizing a performance merit function. Machine specifications resulting from the interactive design process are summarized in Tables 1 through 3.

Table 1. Load and Circuit Parameters

Load parameters		
Lamp impedance constant $(K_o)_{eff}$ = 19.9 Ω-A$^{1/2}$		
Delivered energy	8.5	MJ
Peak current	750	kA
Pulse width (FWHM)	670	μs
Circuit parameters		
Start-up bank capacitance	3.33	mF
Start-up bank voltage	22	kV
Start-up bank energy	805	kJ
Initial generator firing angle	-1.1	rad
Rotor angle at bank crowbar	-0.36	rad
Current at bank crowbar	105	kA
Time at bank crowbar	2.63	ms
Time to peak torque	3.6	ms
Time to peak current	3.84	ms
Rotor angle at peak current	-0.03	rad
Half current points	3.36,4.04	ms
Energy gain	10.6:1	
Current gain	7.16:1	

Table 2. Impedance Parameters and Motoring Requirements

Impedance parameters		
Maximum inductance	1.27	mH
Maximum saturated inductance	112	μH
Minimum inductance	8.07	μH
Compression ratio	158:1	
Armature winding resistance*	2.97	mΩ
Compensating winding resistance*	2.98	mΩ
Maximum core loss resistance	15.2	mΩ
Maximum conductor eddy current loss resistance	6.22	mΩ
Axial fringing field eddy current loss resistance	1.88	mΩ
Total maximum stray loss resistance at 670 μs pulse width	23.3	mΩ
Motoring requirements		
Maximum torque	2,130	N-m
Maximum power @ 2,680 rpm	800	hp
Mechanical losses @ 2,680 rpm	<258	hp
Windage	37	hp
Thrust bearing	85	hp
Guide bearings, maximum	<136	hp

* dc resistance @ 20°C

Figure 4 shows the expected discharge current waveform computed using the design code.

Mechanical Design

A cross-sectional view of the ARFC is shown in Fig. 5. Mechanical dimensions and calculated mass of the rotor and stator components are listed in Table 4.

Table 3. Performance Parameters Under Load

Peak current	754	kA
Peak terminal voltage	17.8	kV
Peak output power	13.4	GW
Peak torque	61.9	MN-m
Peak mechanical power	16.6	GW
Initial speed	2,680	rpm
Final speed	2,500	rpm
Polar moment of inertia	2,120	kg-m^2
Inertial energy stored	84	MJ
Discharge efficiency, η *	76	%
Peak armature mmf	2.26	MA-t/pole
peak air gap flux density	8.5	T
Maximum magnetic pressure	28.7	MPa
	(4,170)	(psi)
Armature temperature rise	14	°C
Effective mechanical shear area	4.6	m^2
Maximum average shear stress	25.1	MPa
	(3,640)	(psi)

$$* \ \eta = \frac{\text{Delivered Energy to Load}}{\text{Change in Inertial Energy Stored}}$$

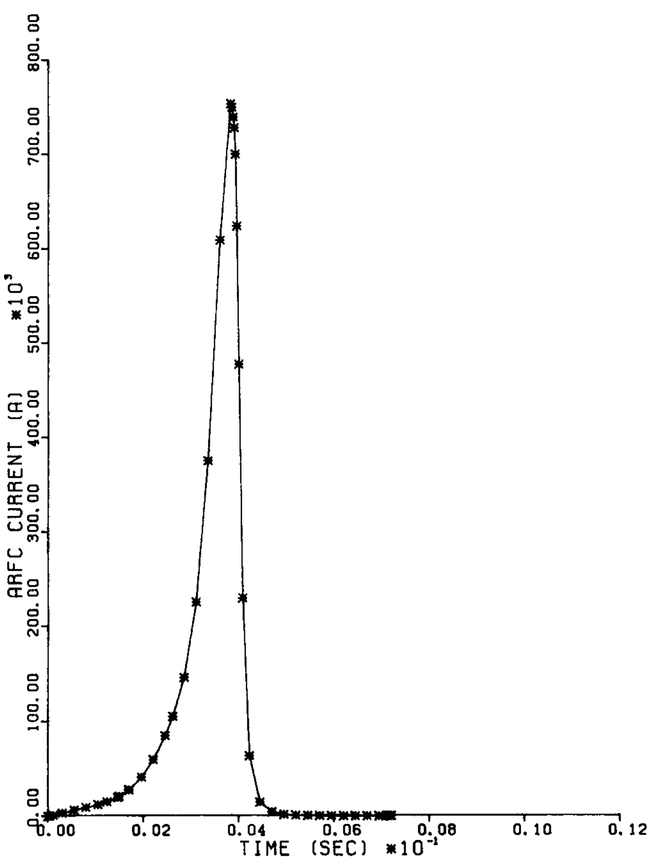

Fig. 4. Computed discharge current waveform

The stator laminations are segmented because of the unavailability of M-19 sheet steel in widths greater

Table 4. Physical Parameters

Physical Parameters		
Number of poles	8	
Number of conductors per pole	3	
Rotor speed	2,680	rpm
Laminated rotor diameter	1.067	m
Lamination tip speed	150	m/s
Laminated rotor ℓ/D ratio	1.64	
Overall ℓ/D ratio	2.25	
Shaft length	3.0	m
Shaft diameter	0.52	m
Outer winding diameter	1.090	m
Mechanical clearance	0.32	cm
Rotor inertia	2,120	kg-m^2
Total rotor mass	15,650	kg
Inner stator diameter	1.096	m
Outer stator lamination diameter	1.532	m
Stator stack length	1.750	m
Stator mass (laminations & winding)	11,800	kg
Maximum stator diameter	2.10	m
Total stator length	2.58	m
Total stator mass with housing	20,500	kg
Total mass	36,000	kg

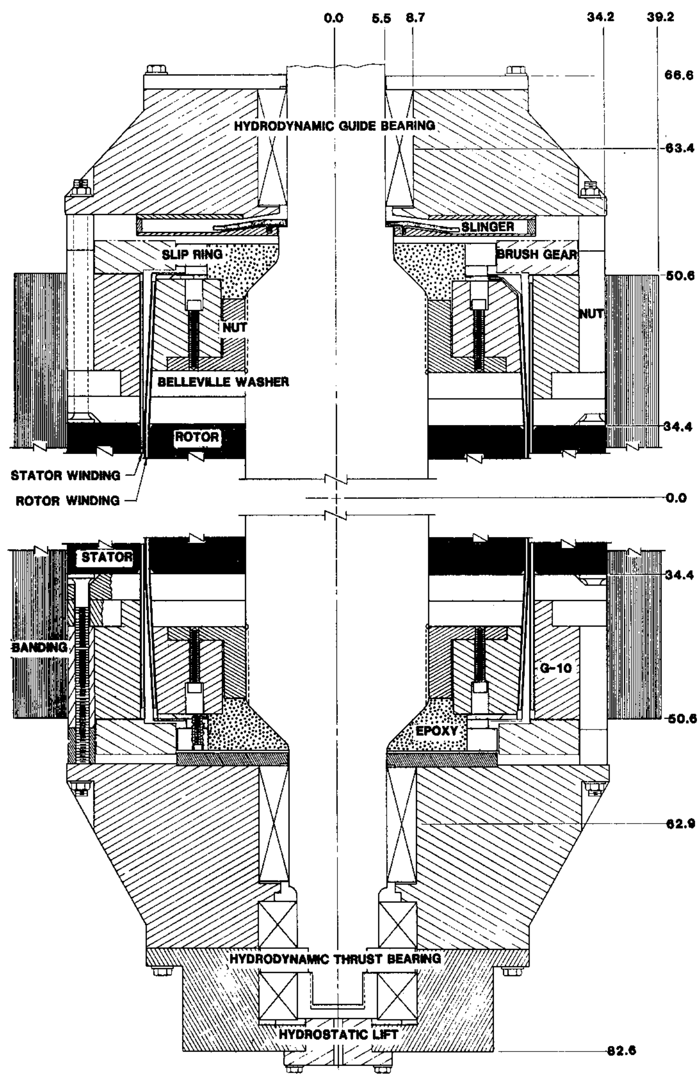

Fig. 5. 10-MJ ARFC cross-section

than 42 in. To increase stator strength, the segmented stator laminations are bonded, clamped between washers and nuts on threaded connecting rods, and banded with high tensile strength Fiberglas tape. These features are required to withstand a winding shear stress of 25.1 MPa (3,640 psi) due to deceleration torque and hoopstress due to a magnetic pressure of 28.7 MPa (4,170 psi).

Figure 6 shows the ARFC in its pit and installed in a reinforced concrete torque frame. An angular contact turntable bearing transmits vertical loads through the pedestal support to the foundation. A second (radial) turntable bearing allows the stator to rotate slightly into Belleville springs mounted in the torque frame, absorbing shock and reducing discharge stresses.

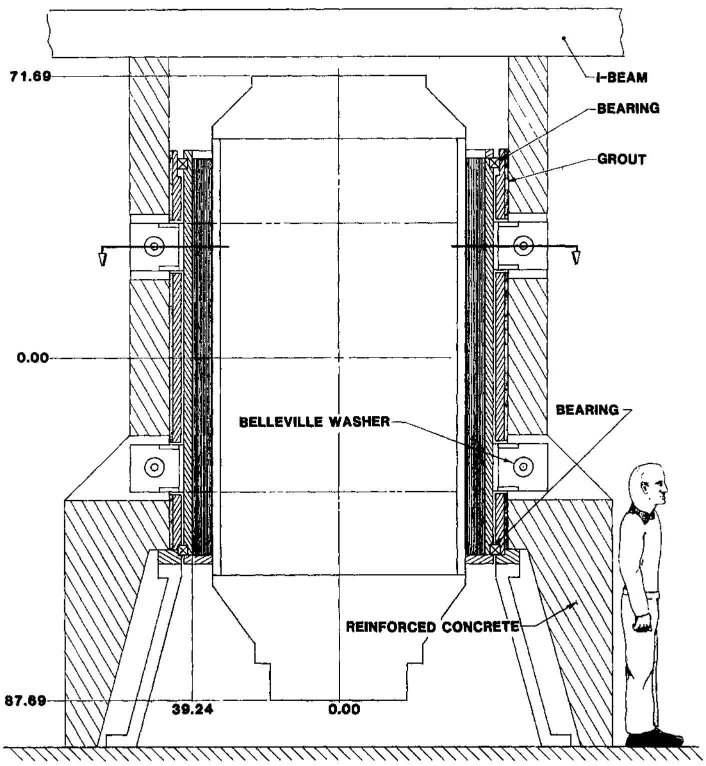

Fig. 6. 10-MJ ARFC flashlamp driver in torque frame

Cost Comparison with Capacitor Banks

Based on budgetary price estimates obtained from potential manufacturers, projected specific costs for a 500-MJ, 1-TW, single-shot power conditioning system to drive laser flashlamps were compared with present modular capacitor banks and a future monolithic capacitor bank. These estimates were prepared by Carder at LLNL and are listed in Table 5.[3]

These figures show the ARFC to be potentially a factor of two less expensive than existing modular capacitor banks and to cost six percent less than the projected costs of a large monolithic bank.

Conclusions

CEM-UT has completed the conceptual design of an active rotary flux compressor to replace a 10-MJ capacitor bank for driving xenon flashlamps. The design has been presented to manufacturers of rotating electrical machinery to obtain an independent technical assessment of the RFC technology and to develop a basis for cost comparisons with capacitor banks.

In discussions with potential manufacturers, the air-gap winding was found to be the most significant fabrication problem when compared to more conventional methods of winding coils. The design of the segmented stator core, rated to withstand a 28-MPa magnetic pressure during discharge would require development. For this reason, the fabrication by industry of a 0.81-m rotor diameter ARFC design was recommended, since the stator laminations could be punched from continuous sheet and provide hoop strength without external support.

Table 5. Projected Costs for 500-MJ, 1-TW Power Conditioning Hardware to Drive Laser Flashlamps

Specific Cost, Cents per Joule

	Capacitor Banks: Present Modular		Capacitor Banks: Future Monolithic		Rotary Flux Compressor
Energy		10.0		5.5	5.0
Capacitors	4.3		3.0		
Circuit Equipment	2.5		1.0		
Switches	1.6		0.7		
Power Supplies	1.6		0.8		
Load		3.4		1.0	1.0
Flashlamps	2.7		0.7		
Cables/J-Boxes	0.7		0.3		
Installation		0.8		0.5	0.5
Fixed Costs		1.0		1.0	1.0
Total		15.2		8.0	7.5

Projected costs for single-shot systems indicate that the rotary flux compressor can provide significant cost savings compared to existing capacitor technology and is competitive with the projected cost of large monolithic capacitor banks. However, the potential cost savings compared to future capacitor banks is not considered sufficient to warrant additional development effort for single-shot systems. The ARFC does appear to have the best potential of any device for short burst (50 to 100 Hz) or continuous pulsed power (1 to 10 Hz) applications. It is likely, therefore, that development of the compulsator/rotary flux compressor class of machine will continue when a multiple-pulse laser system or other rep-rated applications are identified.

Acknowledgement

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