DEMONSTRATION OF AN INDUCTOR MOTOR/ALTERNATOR/FLYWHEEL ENERGY STORAGE SYSTEM

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SUMMARY

This technical quarterly report covers the work on Tasks 2 and 3 of Contract E(11-1)-4010. Task 2 is the "Design and Fabrication of the Inductor Motor/Alternator/Flywheel." Task 3 covers the "Design and Fabrication of the Solid State Power Conditioner and Control Breadboard."

Vehicle propulsion concepts utilizing flywheel energy were described in the first quarterly progress report. The first quarterly report also included the design specifications for the hardware that is now being built.

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1.0 PROGRAM OBJECTIVE

The overall objective of the ERDA program is to demonstrate new technology associated with a novel concept for a high-speed flywheel energy storage system. The concept, consisting of a high-speed composite flywheel combined with an integral inductor-type motor/alternator, offers the possibility of a small, lightweight package with high energy storage capability. The basic technology demonstrated in this program will have application to a number of flywheel energy storage systems. The demonstration unit will have a nominal rating of 20 kVA.

2.0 INTRODUCTION AND BACKGROUND

The concept to be demonstrated consists of a high-speed composite flywheel combined with an integral inductor-type motor/alternator. The motor/alternator/flywheel will be a single package, hermetically sealed and will receive its power from a solid state inverter/rectifier unit designed to provide the necessary frequency control from a DC power source.

The energy storage package developed on this contract will be primarily aimed at a small transportation application, specifically a hybrid flywheel/battery electric van. However, the same technology and basic concept can be scaled up to meet stored energy requirements for other applications such as emergency standby power, energy storage from solar or wind power, a large hybrid propulsion system with a lead acid battery pack, or for large transportation or industrial applications. The basic technology to be demonstrated in this program should apply to a number of applications.

The basic concept of the inductor motor/alternator/flywheel package operating from a DC power source is shown in Figure 1. The main components are the inductor motor/alternator with its DC field control, and the composite flywheel which provides additional inertia over and above the rotational inertia of the inductor motor rotor. The motor/alternator/flywheel

Fig. 1 Basic concept of the inductor motor/alternator/flywheel package.

package will be coupled electrically to the inverter/rectifier which will be regenerative and can either put power into or take power from the DC power source. In this case, the DC source will be batteries although it could be solar cells, or power from a windmill.

2.1 The Specific Flywheel/Battery Vehicle Application

Analysis has shown that the range of an electric vehicle under urban multistop performance can be significantly increased by load leveling the battery and by recovering the braking energy when the vehicle stops.

This ERDA contract is aimed at developing an energy storage package of the type described which can ultimately be used in a hybrid configuration with a battery pack and will have the effect of reducing peak power loads on the battery and, in this way, increase the effective storage capacity of the battery package.

The limited operating range of a battery-powered electric vehicle is as severe a handicap to consumer acceptance today as it was 50 years ago. Batteries have improved over the years but are still the primary limitation on range. High-speed, advanced flywheels, either as a total energy source or in combination with a battery bank, offer the potential of improved energy storage capability. Flywheel energy storage has the advantage of being independent of drain rate, ambient temperature, and duty cycle.

For a battery-powered vehicle, range is dependent on many factors that fall into two major categories. The first is concerned with the battery itself, and includes such factors as initial charge condition, prior history of use, and temperature. The second is concerned with the vehicle and includes total vehicle weight including payload, vehicle speed, number of starts per driving cycle, acceleration, wind velocity, surface condition of the road, and the variation from a level route. In general, increased performance in these operational categories requires much higher currents and power from the battery. These high currents and high power drain rates are detrimental to a battery, resulting in less total energy being available than would be possible with lower current demand.

2.2 Flywheel Energy Storage Package for Regeneration and Load Leveling

The flywheel is an attractive alternative as a storage system for regenerative braking energy. Whereas a flywheel system may be somewhat heavier than a battery system for the same capacity (watthours/#), it has charge and discharge characteristics that make it desirable in combination with batteries.

A motor/generator/flywheel system can provide for positive control of current flow for vehicle operation. Short bursts of high power taken from

a flywheel during acceleration are limited only by the design of the flywheel drive motor and power conditioner. One important characteristic of a flywheel is the large number of charge and discharge cycles that can be designed into it (approximately 10^6 cycles vs 10^3 for a battery).

This ERDA program will develop a flywheel energy storage system sized for a 3000 lb battery electric van. The balance of this report discusses the design and fabrication of the energy storage package.

3.0 DESIGN AND FABRICATION OF THE INDUCTOR MOTOR/ALTERNATOR/FLYWHEEL UNIT

This section describes the work relating to Task 2 of the contract.

3.1 Design Specifications

The first Quarterly Report listed the design specifications for the machine and the flywheel as follows:

Inductor Motor/Alternator

Input power: 52 V, 3 phase AC
Input frequency: 500 to 1000 Hz
Rotor speed: 7500 to 15,000 rpm (min. to max.)
Number of poles: 8
Power rating: 20 kVA
Rotor diameter: 7.45 inches
Active stator stack length: 3.5 inches
Rotor inertia: 0.4 lb inch sec.²
Rotor stored energy: (15,000 to 7500 rpm) 0.0116 kWh
Rotor weight: 60 lb plus 132 lb of composite flywheel
Calculated machine efficiency: 82%
Oil lubricated bearings

Flywheel

Diameter: 30 inches
Energy storage capacity: 1 kWh (15,000 to 7500 rpm)
Weight: 132 lb
Maximum rpm: 15,000
Construction: GE Alpha-5 "cross ply"
Material: E-glass polyester composite
Thickness: 3 inches

These specifications have been the basis for the electromagnetic and mechanical design of machine and flywheel during the second quarter. The design resulting from that work is discussed below.

3.2 Electromagnetic Design of the Inductor Motor/Alternator

As has been pointed out in the First Quarterly Report, a very important design parameter is the so-called commutating reactance of the machine since it determines the reactive power rating of the machine.

A GE computer program, which includes a conservative calculation for the commutating reactance for inductor alternators, has been utilized for the design trade-offs. The machine as specified before would have to have a commutating inductance of $56\mu\text{H}$. This as well as the magnetic and thermal capability of the desired machine was used as selection criteria. The design selected is described in the following Table I:

TABLE I

Machine Design

General Data:

Rated Power	20 kVA
Rated Speed	7500 rpm
No. of Poles	8
Frequency	500 Hz
Rated Voltage	52.5 V L-N
Rated Current	127 A

AC Stator Data:

Total Stack Length	3.5 in.	No. of Slots	96
Lamination OD	9.5 in.	Slot Width	0.132/0.155 inch
ID	7.632 in.	Slot Depth	0.410 inch
Thickness	0.007 in.		

AC Winding Data:

Turns/Phase	16	No. of Strands	12
No. of Phases	3	No. of Circuits	2
Resistance/Phase	$0.0347\Omega @ 150^\circ\text{C}$		
Current Density	6660 A/in^2		

Field Coil Data:

No. of Turns	456	Rated Field Current	8.8A
Inside Diam	8.45 in.	Winding Resistance	$8.3\Omega @ 160^\circ\text{C}$
Outside Diam	9.48 in.	Current Density	5500 A/in^2
Width of Coil	1.98 in.		

TABLE I (Continued)

DC Frame Data:

Outside Diam	10.5 in.	Length 5.5 in.
Inside Diam	9.5 in.	(Magnetic Steel)

Rotor Data:

Outside Diam	7.452 in.	(Magnetic Steel 4340)
Pole Length (axial)	1.750 in.	
Pole Width	2.113 in.	
Pole Height	1.800 in.	
Axial Spacing of Poles	2.000 in.	

Electrical Data:

$X_d = 0.2561 \Omega$	} @ 500 Hz
$X_g = 0.1562 \Omega$	
$X_c = 0.1757 \Omega$	

AC winding losses @ rated current

$P_w = 0.71 \text{ kW @ } 150^\circ\text{C winding temperature}$

Field winding losses @ rated field current

$P_F = 0.64 \text{ kW @ } 160^\circ\text{C field coil temperature}$

Stator Core Iron Losses

$P_c = 0.56 \text{ kW}$

Rotor Pole Face Losses

$P_{RE} = 0.32 \text{ kW}$

The calculated no-load, full-load, and short-circuit performance curves are shown in Figure 2.

Fig. 2 Predicted performance curves.

It is of interest to compare these curves to the test curves of an inductor alternator of similar electrical rating and characteristics but of different mechanical design, which has been fabricated on a General Electric funded program. The test curves show no-load and short-circuit performance in Figure 3. Note that the no-load voltage measured is larger than the computed value at low excitation levels, while it is lower for high excitation levels with a limit of 74 volts. This limit is not predicted by the calculations. A flux distribution analysis of the test machine revealed a significant amount of leakage flux from the magnetic shaft extensions into the DC yoke of the stator. This additional leakage flux saturates the iron and results in the voltage limit. This additional leakage flux is not accounted for in the computations. The machine to be built under the ERDA contract will have nonmagnetic shaft extensions and a thicker yoke, and thus should not show the voltage limit within the thermally allowable field current range.

The short-circuit current which is not influenced by the saturation effect shows very good agreement between test and prediction. The predicted

Fig. 3 Comparison of predicted and tested performance.

negative commutating reactance (= negative sequence reactance) of $56\mu\text{H}$ is slightly higher than the one measured for the test machine, which is expected as a result of the conservative computation method. Synchronous reactance in the direct axis and negative sequence reactance as measured for the test machine are shown in Figure 4.

Of interest is the voltage waveform of the GE test machine -- the machine to be built for ERDA will have a similar waveform shape -- as shown in Figure 5. Of significance is the flat top, which is more suited to rectifier/inverter operation than a sine wave.

The test data and computed data are all given for 500 Hz. The inductances and the short-circuit current are independent of frequency, while the voltage will increase linearly with frequency as long as the excitation current is kept constant.

Fig. 4 Inductances vs field current.

Fig. 5 No-load voltage waveform.

3.3 Mechanical Design Layout of the Energy Storage Package

An assembly view of the inductor-alternator and flywheel that are being manufactured for this ERDA contract is shown in Figure 6. The assembly consists of the alternator mounted directly over the flywheel. There are bearings at each end of the rotor shaft. The machine housing must maintain the relative position of these bearings in the presence of atmospheric and acceleration forces.

Fig. 6 Overall alternator/flywheel assembly.

3.4 Motor/Alternator Drive

The alternator shown in Fig. 6 is the inductor-alternator described in the First Quarterly Report, page 14, and in Fig. 11 of that report.

The toroidal field coil between the two stacks of stator laminations is epoxy impregnated and insulated with Kapton sheets.

The two stacks of laminations consist of 7-mil-thick laminations welded together at the outside under pressure and shrunk into the soft iron frame. The slots are insulated with Kapton insulation sheets. The multi-stranded conductors are inserted into the slot, Kapton phase separators separate the two coil sides in the slot. The wound stator assembly is vacuum impregnated with epoxy to achieve mechanical stiffness of the windings and improve the heat transfer within the slot. The stator for the ERDA machine has been completed except for the final epoxy impregnation.

The rotor of the alternator consists of two sets of four poles which are offset by 45° circumferentially and the rotor body of which the poles are an integral part. The rotor body also serves as part of the shaft. Nonmagnetic shaft extensions are welded to that rotor. The rotor cross section in

one of the pole planes is shown in Figure 7. Also shown in this figure are the mechanical stress levels at the most critical points as predicted at 16,000 rpm overspeed. All stresses are well within the fatigue limit of 26,000 psi for 10^6 cycles of the selected rotor material, No. 4340 steel.

Fig. 7 Rotor cross section and stress levels.

The heat developed in the rotor as a result of windage losses and electrical pole surface losses will be transferred by convection to the ambient gas and into the stator. The stator in the ERDA demonstration machine will be cooled by fluid in a spiral passage around the outside. This cooling passage will also receive the heat from the internal windage losses. The liquid cooling on this machine will allow the use of simple calorimetry during the machine testing phase. Depending upon the vehicle design, it is anticipated that this cooling system will later be replaced with air cooled fins.

In order to obtain a reasonable level of windage loss, it is planned to operate the machine in a reduced pressure helium or hydrogen gas environment as explained later.

3.5 Composite Flywheel

The development, reduction to practice and patent application for this concept of composite flywheel construction, was done during 1975 and 1976

by General Electric Company, with Company funds. The results of this development work will be applied in fabricating the flywheels for this contract.

The flywheel shown in Fig. 6 will consist of three 1-inch-thick disks, supported between two 9-inch-diameter flanges. At present, it is expected that each disk will be balanced individually and then the rotor assembly balanced after the flywheel is installed. The flywheel disks are centered by a 1/2-inch pilot shaft, and the shaft axial stiffness carried through the disks by six 1/2-inch-diameter bolts on an 8-inch-diameter circle.

Each flywheel disk will be a composite assembly. Out to a diameter of 29 inches, it will be made of laminated sheets of glass fibers and epoxy resin. The material chosen is manufactured by the 3M Co., as Scotch ply type 1003. Between 29 and 30 inches in diameter, the wheel will be made of a circumferential wrap of Kevlar and epoxy tape. This material is also supplied by the 3M Co., as Scotch ply type 326. The reason for the outer wrap is to contain those fibers in the laminated sheets that are parallel to and at the circumference of the laminated sheet. These fibers, held in only by the epoxy glue, are the weakest part of the laminated wheel. The usual speed limitation on this design wheel occurs when these fibers release because of centrifugal force.

A sample 1-inch-thick composite disk was manufactured from material available within the General Electric Company. Because of the material width, this sample was limited in diameter to 9 3/8 inches. It was spun to 1450 ft/min tip velocity. This was short of the 1970 ft/min design tip velocity corresponding to the 30-inch flywheel at 15000 rpm. The 1450 ft/min tip velocity was limited by problems in the spin pit. The disk dropped into the pit while rotating at 35,000 rpm. Superficial scratches on the disk surface appeared to be the only damage. The sample disk was made 1 inch thick. This is a reasonable design limit to the thickness. The constraints on thickness are exotherm in the resin during curing and pressure variations near the edge of the disk during compaction. A thick disk would have damaged resin as a result of overheating in the center, and misplaced fibers near the periphery resulting from material yielding to radial forces during compaction before cure.

3.6 Flywheel Hub Design

The following factors have been considered in the design of the flywheel hub:

- Composite flywheel modulus of elasticity
- Composite flywheel molding accuracy

- Completed shaft stiffness
- Machine alignment.

Since the epoxy-glass laminates have moduli about one-tenth that of steel, they have to be considered as soft and yielding when put into an assembly. The radial extension of the flywheel will be greater than that of the steel hub when the rotor is brought up to speed. This relative motion must be allowed for in the hub design.

The parallelism of the molded disks must be accepted as that which can be obtained from the large press used in the curing process. It is important that the pressure be uniform during the cure, so that trying to space the press platens by using spacer blocks will result in a poor composite. It is necessary to be very careful in the lay-up of the material, and use as accurate a press as is available. The sample piece made for us indicates that a TIR of 0.015 inch is the tolerance on thickness that is attainable. Machining after molding is unacceptable, since it cuts the glass fibers.

The alternator rotor shaft has a moment of inertia of 20 in^4 . Six half-inch bolts on a 8.25-inch bolt circle will have the same moment of inertia. Thus, the use of these bolts will carry the shaft stiffness through the flywheel.

Since we cannot depend on the flywheel material for hub spacing, the through bolts will have shoulders to space the two hubs. The three disks of the flywheel will be held between the hub flanges by a resilient material such as leather. The individual disks will be balanced for both eccentricity and couple before assembly to minimize the stress on this resilient material.

The disks will be aligned by a closely fitting pin on the rotor axis. There will be clearance holes, approximately $9/16$ inch in diameter, in the disks to accommodate the through bolts, and allow the relative radial motion to take place. The complete rotor will be balanced after assembly.

3.7 Critical Rotor Speed

A major concern in the design of the alternator rotor-fly wheel assembly is the critical speed of the complete rotor. The most significant variables under our control are the shaft and bearing stiffnesses. A series of computer runs were made to investigate these problems and showed that the feasible flywheel hub designs all had adequate stiffness, and that the controlling factor in determining the shaft critical speed is the bearing stiffness. The bearings chosen, on the basis of life, have stiffnesses that yield a shaft critical speed just above the upper speed limit of the machine. It becomes apparent from these studies that the design of the flywheel hub has to be one that maintains mechanical alignment through the flywheel, and that if this is done, the shaft stiffness will be adequate.

3.8 Flywheel Housing

The flywheel housing shown in Figure 6 is composed of two shallow cones with a short cylindrical section at the joint between the two. The design of this housing must consider:

- Atmospheric forces
- Alternator weight
- Bearing alignment
- Flywheel containment
- Flywheel viscous torque.

It is imperative that the bearings be kept as close together as possible. Therefore, the axial length available for making the housing stiff is very small. With this constraint, the stiffest shape is a cone. In addition, the viscous drag effect of the flywheel is minimized by making the inside of the housing smooth, and toroidal.*

The conical section shown is calculated to have an axial deflection of 0.040 inch when the interior pressure is reduced to 0.1 atm. The atmospheric forces are much larger than the weight of the alternator -- at 0.1 atm gas pressure the atmospheric force is 11000 lb vs 200 lb alternator weight -- so that the design for atmospheric forces is more than adequate to handle all expected alternator acceleration forces.

This housing also serves as a containment for the flywheel in case of mechanical failure. While preliminary experimental operation has verified that the cross-ply composite wheel is very strong, and will probably fail by shedding small fibers, there are other modes of failure possible. To keep the wheel inside the housing in the event of a shaft or hub failure is one necessity. To this end, the housing as shown with a 1-inch minimum thickness of aluminum is an adequate design. The peripheral wall thickness has been designed at 1 3/8 inches to allow more material in the region of greatest exposure should wheel failure occur.

3.9 Windage Losses

The windage loss of the flywheel in its housing is readily calculated. The problem of a disk in a close-fitting housing has been well treated by

*The bulk of the gas in the flywheel housing rotates as a unit at slightly less than half shaft speed. Any reduction of drag, on this bulk, at the housing surface is also a reduction in flywheel torque.

Daily and Nece. ⁽¹⁾ They show the torque M on the sides of a disk rotating in a housing as given by:

$$M = C_m \cdot \frac{\rho \omega^2 a^5}{2}$$

where

M = Torque

ρ = Fluid mass density

ω = Shaft speed

a = Disk radius

C_m = Dimensionless coefficient

C_m is a slowly varying function of both Reynolds number and the disk-to-housing clearance. Typical values of C_m are shown in Table II, for three gases at both atmospheric and one-tenth atmospheric pressure.

In addition to the side torque, there is also a rim torque caused by the finite width of the flywheel. This is calculated by:

$$C_{ma} = C_m + C_m'$$

where $C_m' = \frac{f \pi b}{8a}$ for completely turbulent flow. In this equation, b is the flywheel width, and f is the Moody friction factor, which is dependent upon the surface smoothness of the flywheel. A reasonable value of this factor is 0.01, which leads to $C_m' = 0.00078$ for this design. Note that as long as the flow is completely turbulent, this factor is independent of the gas density and pressure.

TABLE II

Disk Drag Coefficients -- 30-inch Wheel, 15,000 RPM

Gas	Pressure (atm)	Re ($\times 10^6$)	C_m
Air	1	14.7	0.0029
	0.1	1.47	.0025
Helium	1	1.98	.00342
	0.1	0.198	.00297
Hydrogen	1	2.15	.00336
	0.1	0.215	.00293

1. J.W. Daily and R. E. Nece, "Chamber Dimension Effects on Induced Flow and Frictional Resistance of Enclosed Rotating Disks," Trans ASME Paper No. 59-Hyd-9, 1959.

The variation of wall spacing with radius introduces a small error in the above values of C_m . The change from using the mean spacing to using either the minimum or maximum in our design is approximately 5%. This change will be neglected.

The predicted windage loss for the ERDA machine is tabulated in Table III.

TABLE III
Windage Losses -- 30-inch Wheel, 15,000 RPM

<u>Gas</u>	<u>Pressure (atm)</u>	<u>C_m ($\times 10^{-3}$)</u>	<u>ρ (lb/ft³)</u>	<u>Loss kW</u>
Air	1	3.68	0.07	63.6
	0.1	3.28	.007	5.7
Helium	1	4.20	.0112	11.6
	0.1	3.75	.0012	1.1
Hydrogen	1	4.14	.0056	5.7
	0.1	3.71	.00056	0.5

The loss column of Table III shows that we should use as low a pressure of either helium or hydrogen as is feasible, considering the requirement of cooling the motor rotor. For comparison, the windage losses measured for the GE test machine, which does not contain a flywheel, are shown in Figure 8.

The upper curve is the friction and windage loss for air at 1 atm, and the lower solid curve the same losses for helium at atmospheric pressure. The dotted line shows the estimated portion of either loss resulting from friction. This friction is not just the bearings of the rotor, but is the load varying component of all the drive system losses. Note that the rotor windage loss with helium, at 15,000 rpm and atmospheric pressure is 0.7 kW. This is 12% of the flywheel windage in the same environment. Because the rotor windage is intimately associated with the rotor cooling, we will not shroud the rotor to reduce its losses, but will reduce the pressure in the machine to the value needed for rotor cooling. This will give the minimum total windage loss for rotor plus flywheel. The exact pressure will be determined when the machine is tested.

Fig. 8 20 kVA inductor alternator windage and friction losses.

4.0 DESIGN AND FABRICATION OF THE SOLID STATE POWER CONDITIONING AND CONTROL EQUIPMENT

As described in the First Quarterly Report, General Electric has a related program to develop advanced controls and power conditioners for synchronous motor drive systems. The effort during this quarter relied heavily on this related program for the purpose of feeding information into the engineering design and fabrication of the breadboard power conditioner and control equipment for this ERDA contract. This report describes the work performed and the results obtained on the contract and the related program during the Second Quarter.

The work effort during this second quarter has been concentrated in three major areas:

1. The operation of the power conditioner in the forced commutation mode to determine the validity of the design equations previously presented.
2. The development of a control strategy on the hybrid computer simulation.
3. The operation of the inductor generator with a rectifier load in order to determine its power capability.

4.1 Power and Commutation Circuit

The power and commutation circuit is the fourteen SCR circuit shown on Figure 15 of the First Quarterly Report. A revised circuit diagram is shown as Figure 9, which shows greater detail of the main and auxiliary SCR di/dt reactors, snubbers, etc. These components have been specified based on the results of the breadboard testing with a static R-L load.

Figure 10 shows the major power semiconductor waveforms when operating as a DC-AC inverter in the forced commutation mode with a static R-L load. The source voltage was 84 volts, which is the rated battery voltage for this system. The frequency of operation for the waveforms shown on Figure 10 was 166 Hz. This frequency corresponds to one-third of base motor speed and it is anticipated that the transfer from forced commutation to machine commutation can be completed prior to attaining this speed.

Figure 10(a) shows the main SCR voltage and current; the 120 degree conduction interval is indicated. The increase in current in the middle of a conduction period is caused by the commutation circuit. The voltage steps from half magnitude to full magnitude is from the wye connected resistors reflecting a voltage divider action during the nonconduction interval. The auxiliary SCR voltage indicates its operation at the third harmonic of the output frequency and the fact that the commutating capacitor overcharges the DC voltage magnitude.

Fig. 9 Power circuit schematic diagram.

Figure 10(b) shows a detail of the SCR turn-on interval. The pulse train firing logic produces jitter in the initial start of conduction. At this load condition the main SCR di/dt is less than $1 \text{ A}/\mu\text{s}$. Figure 10(c) shows the main SCR turn-off interval at a current level of 18 A. The SCR turn-off time is $125 \mu\text{s}$ and the reapplied dv/dt is less than 1 V per microsecond. At higher current levels, the SCR turn-off time will be reduced and the reapplied forward voltage rate will increase.

Figures 10(d) and 10(e) show the operation of the auxiliary SCR in greater detail. The conduction interval is $380 \mu\text{s}$. The peak current is 24 A with an initial di/dt of 2 A per microsecond. The reapplied forward voltage rate is limited by the reactor connected between the two auxiliary SCR's to 40 V per microsecond.

Based on the design equations given in the First Quarterly Report, together with the test data previously obtained, the major components as shown on the parts list in Figure 11 were ordered.

$i_{\text{main SCR}}$

-0

$e_{\text{main SCR}}$

-0

$e_{\text{aux SCR}}$

-0

10(a)

Main and auxiliary SCR voltage; main SCR current whole cycle.

$i_{\text{SCR}} = 20 \text{ A/div.}$

$i_{\text{main SCR}}$

-0

$e_{\text{main SCR}}$

-0

$e_{\text{aux SCR}}$

-0

10(b)

Detail of main SCR turn-on.

$i_{\text{main SCR}}$

-0

$e_{\text{main SCR}}$

-0

$e_{\text{aux SCR}}$

-0

10(c)

Detail of main SCR turn-off.

Fig. 10 Operation of inverter with static load.

$e_{\text{main SCR}}$

$i_{\text{comm. cap.}}$

$e_{\text{aux SCR}}$

10(d)

Main SCR voltage
auxiliary SCR volt-
age and current.
Whole cycle.

$i_{\text{comm. cap.}}$

= 20 A/div

$e_{\text{main SCR}}$

$i_{\text{aux SCR}}$

$e_{\text{aux SCR}}$

10(e)

Detail of auxiliary
SCR turn-on.

Fig. 10 (Cont'd) Operation of inverter with static load.

COMPONENT LIST

Rectifier/Inverter and Field Current Controller

Main SCR	V = 300 V I = 77 A avg. f = 1000 Hz max.	GE C364 M 600 V 300 A 30 μ s
Auxiliary SCR	V = 300 V i _{peak} = 300 A f = 500 Hz max operating period = 5 min.	GE C144M30M 600 V 30 μ s
Inductor	L = 300 μ H I _{DC} = 200 A	Signal Transformer Company, N.Y., N.Y. C H 200, 300 μ H R _{DC} 0.001 Ω
Fuse	I _{DC} = 300 A	Bussmann KAA 300, 130V, 300A
DC Current Sensor	I _{DC} = $\pm$ 300 A	American Aerospace Model 910 $\pm$ 300A, 10 μ s
DC Field Current Control	E _{DC} = 84 V I _{DC} = 10 A	GE CR&D Design
Snubber	R = 10 Ω , 25W N.I. C = 0.22 μ fd, 600V	Dale NH-25, 10 Ω , 3% Sprague 196P22406S13
Main SCR Interphase Reactor	6 μ H with permalloy ring	CR&D Design
Auxiliary SCR Interphase Reactor	6 μ H with permalloy ring	CR&D Design
Dual Gate Driver		GE 36C762856AB Dual Gate Driver Card and Components

Fig. 11

4.2 SCR Firing and Gating Logic

The power conditioner fabricated on the parallel program required the fabrication of two control cards for firing the main and auxiliary SCR's operating in the inverter mode. Figures 12 and 13 show these hand-wired control cards. The control cards to be fabricated for this ERDA contract will use CMOS logic rather than TTL because of its greater noise immunity, easier interfacing with analog circuitry and reduced power consumption. The cards to be fabricated on the contract will be hand-wired.

The SCR gate pulse generator's function is to increase the power level of the SCR gate signal command and provide sufficient isolation from the logic levels to the SCR gate-to-cathode. A gate pulse amplifier previously developed by a GE product department and in production has been selected as suitable for this project. There are two independent amplifiers on the printed circuit card shown on Figure 14. Figure 15 shows the pulse train of SCR gate current into a main SCR. This circuit board was selected in order to reduce the engineering design time to design, debug, and fabricate a new SCR gate pulse generator.

Fig. 12 Main and auxiliary SCR firing logic card.

Fig. 13 Commutating Capacitor and DC Current Feedback control card.

Fig. 14 Dual isolated
SCR gate
pulse gener-
ator.

Fig. 15 SCR gate current
for main SCR..
 $i = 1 \text{ A/div}$
 $t = 20 \mu\text{sec/div}$

4.3 Power Conditioner Control Strategy

The development of the power conditioner control strategy continued utilizing the hybrid computer as described in the first quarterly review meeting. The objective of this program is to develop a stable control technique to regulate the SCR turn-off time in the inverting mode without the need for shaft position sensor signals. Terminal voltages and current signals can be processed to provide the proper inner control loops. An overall outer loop using DC link current feedback will control the overall system. It is planned to use the hybrid computer to control the complete system during the later phases of the project.

4.4 Rectifier Tests with Inductor Generator

The inductor motor fabricated on the GE program has been connected to a high current, three-phase, full-wave rectifier and subjected to various tests that will be representative of its operation as an inductor generator with a diode rectifier. Figure 16 shows the test setup circuit diagram.

Fig. 16 Inductor generator test setup.

The first set of tests consisted of measuring the open circuit DC voltage vs DC field current for a fixed speed. The data are plotted in Figure 17 for two fixed generator speeds (7,500 and 15,000 rpm). This curve is a replica of the conventional AC open circuit test but presented in terms that are directly related to its operation into a rectifier and DC load. The oscilloscope waveforms of line-to-neutral and line-to-line output during this open-circuit test are shown on Figure 18. Figure 18 (a) shows the line-to-neutral voltage at 500 Hz for the five values of field current. Figure 18 (b) presents the line-to-line voltages for the same speed and field currents. Figure 18 (c) and 18 (d) show similar waveforms for operation at 1000 Hz.

Fig. 17 DC voltage vs field current open circuit.

Data for a DC short circuit on the output of the rectifier were obtained for operation at 500 Hz and field currents of 2, 4, 6 and 8 A. Since the reactance to limit the current is in the AC generator, rather than in the DC loop, the generator line current has a sinusoidal waveform. The values of DC current are plotted on the abscissa of Figure 19. These two points (for the same field current) determine the open-circuit DC voltage/short-circuit DC current intersections. Other points are shown on Figure 19 for values of load resistance (other than infinity and zero) to determine the shape of the machine power capability curve. The two dotted curves on Figure 19 show the 5000 and 10,000 W power parabola. Data points to the left and below the 5000 W curve indicate that the power level (E_{DC} times I_{DC}) is less than 5000 W. The power limitation on the data is from the maximum current rating of the power supply driving the DC motor that is supplying mechanical power to the inductor generator. The 6 A field current line is assumed to be "rated" field current, therefore the maximum power in the generator mode is approximately 13.5 kW (90 V at 150 A). Operation at an equivalent impedance level as a motor will be reduced because of the necessity for providing turn-off time for the controlled rectifiers. This means that the commutating angle must be decreased from 180 degrees, which is equivalent to a rectifier operating at 0 degree phase retard.

Fig. 18(a) Open circuit, line-to-neutral, generator voltage, 500 Hz, 50 V/div.

Fig. 18(b) Open circuit, line-to-line, generator voltage, 500 Hz, 50 V/div.

Fig. 18(c) Open circuit, line-to-neutral, generator voltage, 1000 Hz, 50 V/div.

Fig. 18(d) Open circuit line-to-line, generator voltage, 1000 Hz, 100 V/div.

Fig. 19 DC voltage vs DC current -- for constant field current with rectifier load. Frequency = 500 Hz; Speed = 7500 rpm.

Figure 20 shows the same data as Figure 19 except that the generator speed has been doubled to maximum speed. The open-circuit voltage increases by approximately a factor of two while the short-circuit current does not increase. This is because the back EMF has increased by a factor of two, and the frequency has increased by a factor of two. Since the machine impedance is primarily reactance, the impedance is doubled resulting in the same value of short circuit current. The machine rating is doubled; however, the rating at minimum speed is the important parameter. Several data points are given in Figure 20 for finite values of DC load resistance. Increased power could be provided from the DC power supply for the DC motor because the voltage could be increased while the power supply current was at its limit value. The output power was equivalent to 7.5 kW DC.

Figures 21 and 22 show the motor AC terminal voltages and line current for the data points indicated on Figure 20 for finite load resistances. The waveform of current clearly shows the long commutation times associated with the machine. The reverse recovery current of the rectifiers can also be seen as an approximately 10 A pulse of current flowing in the "reverse" direction. The line-to-line and line-to-neutral terminal voltages are severely distorted because of the effects of the machine reactance. These waveforms depart from the textbook waveforms which assume no AC reactance and an infinite DC reactance. The reverse is true on this system as there is a large AC reactance and no DC reactance for the test photos. These waveforms do agree with the waveforms generated by the hybrid computer.

Fig. 20 DC Voltage vs DC current -- for constant field current with rectifier load. Frequency = 1000 Hz; Speed = 15,000 rpm.

Fig. 21(a) Line current and line-to-neutral voltage; 1000 Hz, 1,500 W.
i = 20 A/div.

Fig. 21(b) Line current and line-to-neutral voltage; 1000 Hz, 2770 W.
 $i = 20 \text{ A/div.}$

Fig. 22 (a) Line current and line-to-line voltage; 1000 Hz, 1,500 W.
 $i = 20 \text{ A/div.}$

Fig. 22(b) Line current and line-to-line voltage; 1000 Hz, 2770 W.
 $i = 20 \text{ A/div.}$

Fig. 22(c) Line current and line-to-line voltage; 1000 Hz, 7800 W.
 $i = 20 \text{ A/div.}$