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

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SUMMARY

This quarterly report covers the work on Task 1, "Establish Specification for Inductor Motor/Alternator/Flywheel and Conduct Tradeoff Analyses", of Contract E(11-1)-4010.

Vehicle propulsion concepts utilizing flywheel energy are described. Analyses are presented for sizing an inductor motor/alternator/flywheel for application to a 3000 pound vehicle. Component tradeoffs are included for the inductor motor/alternator drive, the solid state inverter/rectifier, the control circuit, and a composite flywheel.

Design specifications for the machine are established and a test plan defined.

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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

Figure 1. Basic Concept of the Inductor Motor/Alternator/Flywheel Package

of the inductor motor rotor. The motor/alternator/ flywheel 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. Although new types of batteries are under development, the lead-acid battery will probably be the only type commercially available in this decade. Even a 2 to 1 energy storage improvement in lead-acid batteries designed specifically for electric vehicles will still result in a marginal supply of on-board energy.

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 which 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.

The approach normally used to improve vehicle performance is to increase the ratio of battery weight to total vehicle weight, taking advantage of

the "mass compounding effect" whereby the added structural weight of the vehicle increases by about 20% of the added battery weight. This has two effects on vehicle range. The first is that the battery capacity per unit weight has a net increase. The second is that the current and power density are reduced, thereby increasing the energy available from the battery. These factors have the effect of increasing vehicle range faster than the ratio of battery weight to gross weight as shown in Figure 2. For example, doubling the ratio of battery weight to gross vehicle weight from 25% to 50% can result in as much as a threefold increase in range. A significant part of this effect is due to the lower specific power peaks that result with the higher battery weight. However, there is a limit to the battery to vehicle weight ratio, with the desired ratio being much lower than 50%.

Figure 2. Effect of Battery Weight to Gross Vehicle Weight on Vehicle Range

One key to improving range is to avoid the peak current demands on the battery. To illustrate, Figure 3 shows schematically a typical plot of propulsion power required vs time for a 3000 lb electric vehicle. The upper curve shows the instantaneous power drawn from the energy storage device by the motor. Part of this power is lost as electrical losses. The portion available as power to the drive train is shown as the intermediate curve.

Part of this power is then lost as tire rolling resistance, friction and windage, bearing losses, transmission losses, etc. The lowest curve shows the power converted to kinetic energy. The area under the kinetic energy curve is proportional to the energy stored in the vehicle.

Figure 3. Electric Drive Power Profile During Acceleration and Braking (3000 Pound Vehicle)

Once the vehicle has reached its maximum speed, the power drain from the energy storage device (battery) is reduced to about a third of the peak value. At this point in the driving cycle, if vehicle velocity is held constant, the power required is that needed to overcome losses in the motor, aerodynamic drag of the body, rolling resistance of the tires, and the mechanical inefficiencies of the drive train.

It is the peak drains from a battery bank which occur during acceleration that reduce the available energy from the battery. It is important, therefore, that propulsion systems involving flywheels be developed which will accept these peak energy demands.

A second key to improving range is to recover vehicle kinetic energy when the vehicle stops. Normally, this energy is dissipated as heat in the

braking system. A portion of this available vehicle kinetic energy is lost due to the rolling resistance and vehicle drag as the vehicle comes to rest. If the traction motors are used as generators, a further portion is dissipated as electrical losses in the generator. What remains is that portion of the available kinetic energy indicated as "braking energy for potential recovery." Depending upon component efficiencies, this energy can amount to approximately 50% to 75% of the total vehicle kinetic energy.

Observation of the range of an electric vehicle in sustained driving without stops gives no measure of the range in normal traffic patterns. Each time a vehicle stops, the brakes thermalize the accumulated kinetic energy. This energy must again be accumulated in the moving vehicle as it accelerates to speed. In city traffic with perhaps four to six stops per mile, the range may be reduced to as much as one half of that which would be obtained in constant speed driving. Typical urban cycles in the United States for a subcompact include four stops per mile. Mail delivery trucks may have as many as twenty stops per mile. Delivery vans average between seven and ten stops per mile.

If braking energy is recovered through regeneration, the effect on range can be significant. Calculations show that with seven stops per mile, the range of a battery powered van can be approximately doubled for a given battery capacity by the use of regeneration, provided that an energy storage system is available to accept the energy at the rate matching vehicle braking conditions.

One energy storage approach which is frequently proposed is to regenerate to the main propulsion lead-acid battery. Unfortunately, the lead-acid battery cannot accept the required high rate of energy input unless the battery bank is in a low discharge condition. Typically, when the battery pack nears its full charge condition, battery charging currents must be limited to avoid excessive gas generation. Even then, the charging efficiency is only about 70%. With regeneration back into the battery, only a nominal improvement in range results due to the inefficiency of the fast charging rates on the lead-acid battery plus the inefficiency of energy conversion from mechanical to electrical.

2.2 Flywheel Energy Storage Package for Regeneration and Loadleveling

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 (watt hours/#), it has charge and discharge characteristics that make it desirable in combination with lead-acid 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.

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 considerations made in selecting the preliminary specifications for the energy storage package.

3.0 VEHICLE PROPULSION SYSTEM CONCEPTS UTILIZING FLYWHEEL ENERGY

The basic concept of the battery/flywheel propulsion system for a vehicle is shown schematically in Figure 4. The main components are the battery, the traction motor/alternator, the energy storage package (the motor/alternator/flywheel) and a regenerative control system. The battery will supply the main energy for propulsion. The flywheel set needs to store only enough energy to accelerate the vehicle. For the ERDA design, additional flywheel storage capacity will be available in a composite flywheel. This will provide additional energy for hill climbing. When the vehicle slows, the traction motor operates as a generator and transfers a portion of the kinetic energy back into the flywheel. System losses will be made up by the main battery storage system. The short bursts of high power required for vehicle acceleration will be supplied by the flywheel motor/alternator. The battery need not supply the peak current demands of the system.

Figure 4. Basic Concept of Battery/Flywheel Propulsion System

3.1 DC System

There are several ways to implement a flywheel regenerative system in a vehicle. One way would be to use a classical Ward Leonard D. C. system as shown in Figure 5 in which a DC separately-excited motor is connected to a flywheel which supplies the acceleration power and accepts the regenerative power during braking. Tests have shown that energy consumption can be reduced as much as 30% with regeneration. Peak power drains from the battery power source are also reduced. The advantage of the Ward Leonard D. C. system is that no electronic components are in line with the main power flow. The disadvantage is that the DC components are heavy since the DC drive motor for the flywheel is speed limited. In order to achieve a high flywheel speed, it is necessary to use a speed increasing gear. In order to keep flywheel friction and windage at a minimum, the flywheel must be hermetically encased in a vacuum or low pressure gas. With a DC drive this means that a shaft seal is required since the DC motor must be located outside of the hermetic chamber.

ADVANTAGES

- Fully Regenerative
- Low Battery Drain Rate
- Power Electronics Rated for Field Power
- Simple DC Components

DISADVANTAGES

- Gear for Flywheel
- Heavy (Low Speed DC)
- High Mechanical Losses Gears, Seals, Brushes

Figure 5. Battery/Flywheel Hybrid - Regenerative Ward Leonard System

3.2 AC System

The alternative to the DC system is an AC flywheel drive of the type which will be developed on this contract. This system has many advantages

over a DC system. Higher rotational speeds can be obtained which will reduce the weight of the machine and allow a more optimum length/diameter ratio of the flywheel to be utilized. Brush drag is eliminated. Also the flywheel and motor will be combined into a single unit hermetically sealing the rotating assembly. By this means, rotating seals are eliminated and losses will be further reduced. A disadvantage is that power conversion equipment is now required to transfer the power between the AC system and the DC battery and the DC propulsion system generally used. The AC system has been selected for this ERDA program.

As a result of evaluation of a number of AC flywheel drive motors and systems, including synchronous, induction, and inductor, the solid-rotor synchronous machine (inductor-type) appears to offer the best match for a flywheel drive system. It has a number of advantages over an induction motor. The inductor machine has a simple solid rotor whereas the induction motor rotor is constructed of laminations and rotor bars. The inductor machine, therefore, has the highest rotor speed capability, and allows the direct coupling of a high speed electrical machine with the flywheel. The solid rotor exhibits a rotor tip velocity capability which is limited only by the mechanical properties of the magnetic rotor material. Thus, the machine is ideal for high speed applications. Since the inductor-type is a synchronous machine, power losses in the rotor are due solely to eddy current losses. In general, this results in lower rotor losses as compared to a wound rotor or squirrel cage machine, either synchronous or induction. The machine efficiency is therefore somewhat higher. It is also easier to cool an inductor rotor than an induction rotor. Further, the inductor machine has a DC field which permits control of output voltage.

The inductor/motor/alternator/flywheel concept is shown in Figure 6. The main components are the inductor motor/alternator with its DC field

Figure 6. Regenerative AC System with Flywheel Storage

control and the solid state inverter/rectifier. The motor/alternator/flywheel package is coupled electrically to the bidirectional inverter/rectifier so that power can flow either in or out of the flywheel package. A secondary storage package of this type has the desired effects of reducing the peak loads on the battery and recovering a portion of the braking energy, thus increasing the effective storage capacity of the battery bank. Additional energy storage capacity will be obtained by adding a composite flywheel mass.

4.0 SIZING THE INDUCTOR MOTOR/ALTERNATOR/FLYWHEEL DRIVE SYSTEM

In general, the sizing of the motor/alternator/flywheel system is dependent upon the required energy transfer rates during braking and acceleration of the vehicle and thus is tied to the specific velocity-time profile for the vehicle.

The machine to be built under this ERDA contract is for a 3000 lb utility van. A typical velocity time profile for such a utility vehicle is shown in Figure 7. This profile requires 3 mph/sec acceleration up to about 50% of maximum speed ($Vel_{max} = 25$ mph) and acceleration on the natural constant voltage series motor characteristic up to full speed.

Figure 7. QT Vehicle Performance; 3600 lb, 84 Volts

The mode of flywheel operation and to some extent the energy storage capacity required depends on the system configuration. Figure 8 shows two alternate configurations in which the energy storage package can be used. The first alternate consists of a series propulsion motor. The second alternate uses the same propulsion motor with a separately excited field.

Figure 8. System Configurations

In both cases, traction motor armature voltage control is supplied by the flywheel motor/alternator field exciter until the traction motor back emf (controlled by vehicle speed) is equal to the battery voltage, at which time the battery contactor (B) is closed. The current flow to the traction motor then depends on speed in the series motor case and speed and the excitation level determined by the field chopper in the separately excited motor case. When a combination battery-flywheel system is used, the flywheel speed would then be allowed to decrease along a predetermined profile of vehicle speed by supplying some of the traction motor current. This action is necessary so that the flywheel is able to accept the vehicle braking energy (proportional to vehicle speed squared).

Two major differences exist between the series and separately excited traction motor systems. The series motor requires field reversing for braking (probably with contactors) and the minimum flywheel energy storage requirement may be greater with the series motor.

In the separately excited motor, the motor field current can be maintained at a higher value even though a low vehicle acceleration is required. Thus, the motor back emf can be high enough so that the battery contactor can be closed at a low vehicle speed. Figure 9 summarizes the operating conditions for the motoring mode of operation. A separately excited motor is assumed. Thus, a constant power acceleration at higher speed is shown. Figure 10 shows the operation of the system in braking when the battery contactor is open, the traction motor acts as a generator, and the flywheel motor/alternator operates as a motor. All control of deceleration rate is done with flywheel motor/alternator field control.

Figure 9. Motoring Operation of Flywheel System

Figure 10. Braking with Flywheel

4.1 System Rating

The rating of the flywheel motor/alternator and the inverter/rectifier which is to be built as part of this ERDA contract depends on both the motoring and braking conditions. The worst case motoring condition occurs at 12.5 mph. At that time, the flywheel is at a speed higher than minimum since energy taken will only be about 1/3 of the braking energy. Thus, the flywheel motor/generator will not, in general, be voltage limited. The rectifier part of the power converter and the flywheel machine must accept a short time DC current of 310 A.

The traction motor loss may cause the output power to the flywheel to be less during braking than expected thus causing the energy storage efficiency to be less than desired. Improvement of the traction motor efficiency to the level of the flywheel motor/generator will greatly improve the system efficiency. The actual numbers for efficiency will only be known after test.

The voltage on the AC side of the inverter/rectifier is determined from the equation

$$V_{AC} = (84 + 2 \times V_b) / 2.34 = 37.4 \text{ V}$$

2.34 is for a Bridge (3 phase) Rectifier

Similarly, the AC current per phase is obtained as

$$I_{ACF} = .78 \times I_{DC} \text{ (fundamental)} = 181 \text{ A}$$

$$I_{ACRMS} = .816 \times I_{DC} \text{ (heating)} = 189 \text{ A}$$

The actual power supplied by the AC alternator is

$$P = 3 \times I_{ACF} \times V_{AC} = 20.3 \text{ kW}$$

The peak power during the braking cycle occurs at the top speed. Because of the power needed to overcome rolling resistance (3.3 kW), the power (P_w) which reaches the shaft of the drive motor will be less than the peak power.

$$P_w = 22.4 - 3.3 = 19.1 \text{ kW}$$

This shaft power is converted to electrical power within the DC machine. The resultant electrical output power is:

$$P_{DCOUT} = .85 \times 19.1 = 16.2 \text{ kW.}$$

The field excitation current for the DC machine is at the same level as it was during peak acceleration resulting in a terminal voltage of

$$V_{DCG} = 115 \text{ V}$$

with a DC current of

$$I_{DCG} = 195 \text{ A}$$

The corresponding voltage and current levels at the motoring AC machine terminals are:

$$V_{AC} = 49.1 \text{ V}$$

$$V_{ACF} = 152 \text{ A (Fundamental)}$$

$$I_{ACH} = 159 \text{ A (Heating)}$$

The fictitious AC voltage due to the load commutation of the inverter is found to be

$$V_{AC}^i = 62.3 \text{ V}$$

Since V_{AC}^i defines the flux and excitation level within the AC machine, it is also used for the rating of the AC machine.

$$P_{AC} = 29.7 \text{ kVA}$$

The current loading is below the rating while the voltage level is 20% above rated voltage. The different voltage and current levels for acceleration and deceleration illustrate that the actual rating of the AC machine has to take the highest voltage and highest current level of each of the peak power conditions and combine those into the actual machine rating.

The key to successful operation, especially during the braking cycle, depends upon the commutation capability. Thus, a low commutating reactance is of prime importance. Since the inductor alternator is much more saturation limited than a wound rotor synchronous machine, the rated voltage has been selected as 52.5 V, close to the peak voltage required during braking. The rated current of 125 A is relatively high for a traction machine when compared to the maximum required current of 151%. However, this seems to be reasonable for rectifier operation since commutation is also important in this case. The power factor depends upon the commutation reactance and is based upon previous experience with this type of solid rotor machine. For this machine, a power factor of .78 lead was selected as practical. Thus, an AC voltage of 52.5 V, combined with an AC current of 125 A at a power factor of .78 lead, results in a machine rating of:

$$P_R = 20.0 \text{ kVA}$$

This analysis establishes the rating for the inductor motor/alternator and inverter/rectifier for this ERDA demonstration program.

5.0 COMPONENT TRADEOFFS

This section discusses the three major components comprising the energy storage system. They include:

- inductor motor/alternator
- inverter/rectifier
- composite flywheel

The various tradeoffs made in establishing the specifications for each component are discussed.

5.1 Inductor Motor/Alternator Drive

The basic function of an inductor machine can best be explained by means of Figures 11 and 12. Figure 11 shows a DC field coil between two stacks of

Figure 11. Cross Section of an Inductor/Alternator

Figure 12. End View of an Inductor/Alternator

stator laminations. A DC current in the field coil drives a magnetic flux, as indicated, through one stack of laminations into the rotor through the rotor center axially, radially out of the rotor through the second stack of laminations and the frame to close the loop. Large magnetic slots (Figure 12) in the rotor interrupt the flux at the air-gap and cause the flux through the AC winding to pulsate. This in turn generates an AC voltage in these windings. The windings are located in slots in the laminated stator stacks close to the air-gap. In order to make the induced voltage in both stator stacks add properly, the magnetic rotor slots in both rotor halves are offset by one-half pole pitch.

Inductor Motor/Alternator RPM and Frequency Selection

A rotor speed of 15,000 rpm was set primarily by bearing limitations. This maximum rotor speed was determined by both mechanical and electrical considerations. To minimize system size and weight, the rotor speed should be as high as practical. Rotor speed is limited by the maximum allowable rotor stress which is the fatigue limit of the material for a specified number of cycles. A second restriction on the maximum rotor speed is the bearing life which is a function of rotor weight (including any flywheel), speed, and operating temperature. The selected preliminary design specifications set bearing life at 3,000 hours.

A next step in the speed consideration was to estimate the minimum operating speed for the flywheel machine. The extractable or useful energy of a flywheel is given as:

$$\Delta E = I/2 (n_{\max}^2 - n_{\min}^2)$$

$$\Delta E = \text{useful energy}$$

$$I = \text{rotor inertia}$$

$$n_{\max} = \text{maximum operating speed}$$

$$n_{\min} = \text{minimum operating speed}$$

Figure 13 shows this relation as a function of the speed ratio. At 50% of maximum speed, 75% of the flywheel energy at maximum speed will be extracted for external use. Since a specified amount of energy is to be stored in the flywheel, a new function could be established with the required inertia as a function of the speed ratio. Furthermore, assuming a fixed maximum diameter for the flywheel results in a weight vs speed relationship as shown in Figure 14. For 50% speed ratio, the weight of the flywheel is 32% larger than what it would have to be if all of the energy in the flywheel were extracted.

In the same general terms, the effect of the speed ratio upon the sizing of the electrical machine can be established. It has been found that based upon experience with high speed machines built for aircraft application, the following relationship between the electrical machine weight, rated power and rated speed is valid

$$(P_R/n_R)^{.75} \sim W$$

where W = weight

P_R = rated power (kVA)

n_R = rated speed, rpm

Note that rated power and rated speed are defined at the lowest operating speed of the machine. A plot of weight ratio as a function of speed ratio is shown in Figure 14. Thus, depending upon the weight contributions from the flywheel and the generator, an optimum speed ratio can be established for a

Figure 13. Flywheel Speed Ratio vs Energy Ratio

Figure 14. Flywheel Speed Ratio vs Weight Ratio

given ratio of stored energy and power rating. For the case of equal weight contribution, the optimum appears at 52.5% speed ratio. Since the actual weight contribution depends upon various factors which can only be determined through a very detailed design study, a reasonable judgmental approach has been to initially select a 50% speed ratio for the operation of the flywheel storage system. Based on the preliminary design specification of an upper speed of 15,000 rpm and a 50% speed ratio, a minimum speed of 7,500 rpm results.

The frequency selected for a machine for a given speed range depends upon the following considerations:

- impact on machine size
- maximum frequency limitations in the inverter/rectifier
- interface requirements for successful inverter-motor operation

The impact on the machine size is evident in two major areas. One is the endturn length with all the dependent implications. The second is the height of the AC yoke (stator). Both follow the same pattern. For a given machine rating and speed, the endturn length and the yoke height decrease with increasing frequency. This effect is counter-balanced by the fact that for higher frequencies, where the pole pitch in the machine becomes very small, the coupling between the armature winding and the magnetic field, produced by the excitation winding, worsens with increasing frequency.

From past experience, it has been established that conventional machines are at an optimum size and weight for eight to twelve poles. Inductor alternator type machines tend to be optimally designed for a larger number of poles. However, the gain due to an increase in frequency is overshadowed by the two other limitations mentioned and by the iron losses which tend to increase severely with frequency.

The inverter does not impose a frequency limitation in this low voltage case since this type of inverter is operable up to 4 to 5 kHz.

The most severe limitation is determined by the fact that the machine has to commute the inverter, e.g. the machine rating reflects this in terms of a leading power factor requirement. The commuting reactance of the machine is directly responsible for this additional power requirement. The commuting reactance which for all practical purposes can be equated with the negative sequence reactance of the machine, can be expressed as follows:

$$X_C = X_S + X_E + C_1 \cdot X_{ad} = \text{commutating reactance}$$

$$X_{ad} = \text{synchronous reactance in direct axis}$$

$$X_S = \text{slot leakage reactance}$$

$$X_E = \text{endturn leakage reactance}$$

The factor C_1 accounts for the influence of the different quadrature axis reactance, of the field leakage reactance, and of the amortisseur leakage reactance. For simplicity, it is assumed independent of the frequency. It can be shown that X_{ad} is inversely proportional to the frequency - provided rotor diameter and velocity are kept constant. The slot leakage reactance is directly proportional to the frequency. Thus, we obtain a relationship for X_C vs frequency as follows:

$$X_C = C_S \cdot f + C_E/f + C_{qd}/f$$

Depending upon the values of the various constants C , there is a point beyond which X_C is directly proportional to the frequency. In general, the commutation process becomes more difficult with increasing frequency.

Thus, weighing all these factors: size impact, iron losses, inverter requirements and commutating reactance, the number of poles in the machine has been fixed as eight poles which, in combination with the 7,500 to 15,000 rpm speed range, results in a frequency range of 500 to 1,000 Hz.

5.1.1 Sizing Considerations for the Inductor Machine. Speed range, number of poles, and power rating having been established, the remaining task is to select the proper flux and ampere-turn combination which will determine the actual machine dimensions. Again, the consideration of commutation reactance plays a significant role. The important point for an inductor alternator in contrast to a conventional wound rotor synchronous machine is that the inductor alternator has a significantly higher subtransient reactance (and negative sequence reactance) because the damping effect of the solid rotor surface is poorer, especially at high frequencies, than a well-designed amortisseur circuit. Since the reactance level is a function of the number of turns per phase squared and grows only linearly with the air gap area, a low reactance level is generally achieved by decreasing the number of turns and increasing the total air-gap area. The total magnetic flux in an inductor machine has to be carried axially through the center of the rotor. Thus, the necessary rotor cross-section area of the center portion is directly determined by the airgap flux and the maximum material flux density. The diameter of the center portion also determines the rotor diameter because of the minimum saliency requirements for this type of machine. Initial design calculations have established that a rotor diameter of 7.45 inches and an active stack length of 3.5 inches result in a machine which exhibits a reasonable commutating reactance level.

The analysis of the rotor indicates that a slotted rotor (which is the natural way) has an inertia of

$$I_S = .4 \text{ lb. in. sec.}^2$$

The useful energy which can be stored in this rotor by a speed increase from 7,500 rpm to 15,000 rpm is

$$\Delta E = 11.6 \text{ Wh}$$

which is about one-half of the energy storage required for one start-stop cycle for a 3,000 lb. vehicle. If the slots in the two rotor halves are filled with non-magnetic material via brazing or welding, the inertia increases to

$$I_F = .814 \text{ lb. in. sec.}^2$$

The energy stored in this rotor for the same speed range then amounts to

$$\Delta E = 23.6 \text{ Wh}$$

This is approximately the stored energy needed for one start for a 3,000 pound vehicle.

5.2 Solid State Inverter/Rectifier

A solid state power conditioner that converts DC power to AC power is defined as an inverter. Similarly, equipment which changes AC to DC is a rectifier. The power conditioner for this ERDA program is defined as an inverter/rectifier to describe its two normal modes of operation.

In order to interface with the inductor motor/alternator and battery propulsion motor, the solid state power conditioner must be capable of extracting energy from the flywheel/alternator during one mode of operation (generating) and supplying energy to the flywheel/motor during the second mode of operation (motoring). The inverter/rectifier must also be capable of starting the flywheel/motor from rest and stopping the flywheel during the final coast-down to a standstill. The control electronics are designed to monitor the status of the system to ensure that the change in modes, i.e. motoring to generating, forced commutation to motor commutation, etc., are accomplished at the correct time so as to minimize disturbances to the system. In addition to the inverter/rectifier, a separate field current controller is required to adjust the level of field current in the excitation winding of the inductor motor/alternator. There are two static systems that can accomplish the conversion of AC to DC and DC to AC, they are the pulse width modulated inverter (PWM) and the load commutated inverter/rectifier (LCI).

The PWM uses controlled rectifiers as the power switching elements. They operate at a higher frequency than the fundamental motor frequency in order to provide independent control of the output voltage magnitude applied to the motor windings. For the controlled rectifiers to rapidly turn on and turn off during any one-half cycle of the motor frequency, a high efficiency forced commutation circuit must be provided. This commutation circuit uses a total of six auxiliary controlled rectifiers, three capacitors and three reactors. Additional control and protection circuitry for the auxiliary SCR's are required. System operation as an inverter (DC to AC) utilizes the feedback diodes that normally conduct during the commutation interval and with reactive loads. The auxiliary SCR's and the commutation circuit must be operative during both modes of system operation. The PWM inverter provides its own forced commutation circuit. Therefore, it can operate with either a synchronous or induction-type motor.

The second power conditioner suitable for this ERDA application is the LCI. In the system shown in Fig. 15, the polarity of the DC terminals cannot reverse. This is due to the presence of the battery and the desire not to reverse the field current in the separately excited propulsion motor. Therefore, in order to reverse the direction of power flow, the direction of the DC current must be reversed. When operating as an AC to DC system (generating), the six SCR's (shown in Fig. 15 as generating SCR's) are phased to full advance. The field of the inductor/generator operating in conjunction with the field excitation of the propulsion motor controls the DC link current and hence the developed torque of the propulsion motor. Operation of the SCR's at full phase advance (similar to diodes) maximizes the power factor of the rectifier system and improves the power transfer from the AC to DC systems. As the flywheel slows down, the generator frequency will also drop; however, the SCR gate signals will be synchronized with the variable frequency terminal voltage.

Figure 15. Rectifier/Inverter Power Circuit

During the motoring mode, the six SCR's (shown in Fig. 15 as motoring SCR's) will be operating and gated on at maximum retard angle in the inverting mode. In this case, the SCR turn-off time is reduced to a minimum consistent with the SCR selection. The commutating reactance of the machine requires that the retard angle be a function of DC link current. It is in this mode that the SCR's rely on the inductor motor to provide the commutation (leading power factor) for the SCR's. Therefore, this system would not operate with an induction motor (lagging power factor) and the elimination of the commutation circuit is one of the favorable trade-offs in using a synchronous motor.

In addition to providing commutation, the use of an electrically-excited field on the inductor motor allows the control of the machine voltage magnitude. This allows DC current and torque control to be provided without the

need for phase angle controlled gating circuits and operation of the phase-controlled inverter/rectifier at reduced power factor and with increased harmonic current content. The reactor in series with the DC supply will filter the AC components of the voltage developed by the inverter/rectifier.

The inductor motor cannot provide commutation at standstill and very low speeds. Therefore, a source of forced commutation must be provided for initial starting. One approach is to use power switches with turn-off capability, i.e. transistors. However, the voltage, current and power level require relatively expensive transistors to just meet the electrical requirements. In order to provide for system expansion to heavier vehicles, power thyristors have been selected as the power switching elements. In order to provide commutation, the two auxiliary SCR's and single capacitor are provided. The use of auxiliary SCR's allows the forced commutation circuit to be rendered inoperative when the motor speed is sufficient by removing the gate signals from the auxiliary SCR's. This results in a higher efficiency during the major modes of operation of the system from half speed to full speed on the flywheel machine.

To summarize, a comparison between the load commutated inverter and the PWM is given in Table 1. It indicates that the load commutated inverter/rectifier results in higher efficiency, lower number of power semiconductors, and less reactive components than does a PWM inverter system.

Table 1
COMPARISON OF PWM FORCED COMMUTATED
INVERTER WITH LOAD COMMUTATED INVERTER

	PWM Forced Commutated Inverter	Load Commutated Inverter
<u>Power Semiconductors</u>		
Power SCR's	6	12
Auxiliary SCR's	6	2
Power Diodes	6	0
<u>Reactive Components</u>		
Commutation Capacitors	3	1
Commutation Reactors	3	0
DC Reactor	0	1
DC Capacitor	1	0
Operate with Lagging PF Load	Yes	No
Efficiency (full load at 1,000 Hz)	80-85%	>90%
Size		Smaller
Weight		Lower

5.2.1 Establishing the Power Conditioner Rating for the 20 KVA Application.

The motor/alternator, because of its thermal mass and overload capability, can be sized for a fraction of its peak voltage, current and power requirements. However, the controlled rectifiers have negligible thermal mass, and they must be characterized and rated for the maximum voltage, maximum current and maximum frequency on a steady-state basis. The acceleration and deceleration times (estimated at 6 - 18 seconds) out of a start-stop cycle of 80 seconds determine the thermal rating of the heat sinks and associated forced convection fans. The auxiliary SCR's and commutation capacitor for initial starting can be rated for the anticipated duty cycle (initial starting) of the flywheel motor/alternator. The current ratings of the SCR's in motoring and generating are close to the same and result in a similar design and size of each of the main SCR's. The auxiliary SCR's are rated for the same peak current and voltage as the main SCR's but at a lower RMS current rating.

5.2.2 Main SCR. The sizing of the flywheel inductor motor/alternator established the maximum DC current at 232 A. The main SCR conduction angle is 120 degrees out of a possible 360 degrees. Each of the SCR's connected to the positive bus, for example, carries the DC current for one-third of the time. This results in an average current rating of

$$\begin{aligned} I_{AVE} &= 1/3 (I_{DC}) \\ &= 77 \text{ A} \end{aligned}$$

The RMS current rating is

$$\begin{aligned} I_{RMS} &= \sqrt{1/3} (I_{DC}) \\ &= 134 \text{ A} \end{aligned}$$

The peak current rating is therefore

$$\begin{aligned} I_{peak} &= I_{DC} \\ &= 232 \text{ A} \end{aligned}$$

The peak forward and reverse voltage ratings are normally equal to

$$\begin{aligned} e_{peak} &= \sqrt{2} \cdot \sqrt{3} e_{1-n \text{ rms}} \\ &= 128.6 \text{ V} \end{aligned}$$

However, the auxiliary commutating current and commutation voltages will produce a higher peak voltage on the main SCR's.

The main SCR's must operate at a frequency of 500 to 1000 Hz during motoring and generating. Conventional "phase control" SCR's are rated for operation up to 400 Hz. Inverter grade thyristors or special units are characterized up to 10 kHz. The SCR's must be characterized for the 1000 Hz operating frequency in order to reduce the switching losses associated with operation at that frequency.

The main SCR's will have a dv/dt and di/dt rating commensurate with their rating as inverter type SCR's. The circuit di/dt will be relatively low and will be limited by the reactance of the inductor machine. The dv/dt will be associated with the peak voltage and maximum frequency. The starting mode with the auxiliary SCR's will produce the higher dv/dt requirements.

During the operation of the power conditioner as an inverter, the system will operate at retard limit. At 1000 Hz, each degree of the fundamental is equivalent to $2.78 \mu s$. The SCR's have been specified to require $20 \mu s$ turn-off times. Therefore, the maximum retard angle is

$$\theta_m = 180 - \frac{20}{2.78}$$

$$\theta_m = 172 \text{ degrees}$$

This is a maximum value. Sufficient margin must be used to account for overlap, and the level of DC current to be commutated. These additional times will result in an SCR firing angle in the range of 120 - 150 degrees.

The center-tapped reactors shown between the SCR's and the motor in Fig. 15 are to limit the buildup of fault current if there is a DC fault caused by a misfire of the main SCR's. DC fault current will be interrupted by the fuse in the DC input.

5.2.3 Commutating Circuit The specification of the commutating circuit components can only be undertaken after the motor parameters are known. A first approximation to the inductor type motor will be an adjustable AC voltage (BEMF) in series with a "leakage reactance." The necessary equations for the specification of the commutating circuit have been developed. These equations are based on "first order" models and can be refined during the breadboard testing phase of the ERDA program.

The motor constants can be combined to provide a value of leakage inductance of $55 \mu H$ per phase. The commutation circuit only operates during the motoring mode and the firing angle of the main SCR's is delayed approximately 210 degrees (α) from the line-to-line voltage. The DC current has been previously calculated as 232 A. The commutation capacitor voltage must be higher than the peak AC voltage to insure that the current will be forced out of the motor and into the capacitor.

The equation for commutating capacitor voltage is

$$V_C = I_d \sqrt{\frac{L_K}{C}} - \frac{E_L}{\sqrt{3}} \sin(\alpha - \pi/6)$$

Assuming a value of $V_C = 300 \text{ V}$ gives

$$C = 33 \mu F$$

This was increased to $40 \mu F$ to use standard capacitors. The value of $40 \mu F$ reduces the voltage on the capacitor from 300 V to 272 V. This is still

larger than the peak AC voltage and is sufficient.

The main SCR maximum forward voltage is:

$$\begin{aligned} V_F &= V_C - \frac{E_L}{\sqrt{3}} \sin(\alpha - \pi/6) \\ &= 272 \text{ V} \end{aligned}$$

The main SCR maximum reverse voltage is

$$\begin{aligned} V_R &= V_C + \frac{E_L}{\sqrt{3}} \cos(\alpha) \\ &= 207 \text{ V} \end{aligned}$$

The auxiliary SCR forward voltage is

$$\begin{aligned} V_F &= V_C + \frac{E_L}{\sqrt{3}} \\ &= 346 \text{ V} \end{aligned}$$

The auxiliary SCR reverse voltage is

$$\begin{aligned} V_R &= V_C - \frac{E_L}{\sqrt{3}} \cos(\alpha) \\ &= 336 \text{ V} \end{aligned}$$

The main and auxiliary SCR's rate of change of voltage is

$$\begin{aligned} \frac{dv}{dt} &= \frac{I_d}{C} - \frac{\omega E_L}{\sqrt{3}} \cos(\alpha - \pi/6) \\ &= 5.6 \text{ V}/\mu\text{s} \end{aligned}$$

The commutating capacitor and leakage reactance form a resonant circuit with a natural half-period and resonant frequency.

$$\begin{aligned} t &= \frac{\pi}{2} \sqrt{L_K} \cdot C \\ &= 73.7 \mu\text{s} \end{aligned}$$

$$\begin{aligned} \omega_o &= \frac{1}{\sqrt{L_K C}} \\ &= 21,300 \text{ rad/s} \end{aligned}$$

The calculation of SCR turn-off time during conditions of forced commutation is as follows:

$$i_c = \left(I_D - \frac{\sqrt{3} E_M}{\sqrt{L_K/C}} \sin \alpha \right) \sin \omega_0 t$$

$$t = 44.2 \mu s$$

$$\Delta e = \frac{1}{C} \int_0^t 286.8 \sin \omega_0 t$$

$$\Delta e = 128.7 \text{ V}$$

$$t_q = \frac{C}{I} \Delta e$$

$$t_q = 22.2 \mu s$$

This value of turn-off time occurs only with maximum DC current. During the initial starting interval, when forced commutation is required, the DC current can be reduced in magnitude to increase the turn-off time.

5.3 Control Circuit

Figure 16 is a control circuit block diagram indicating feedback signals and operator inputs. The operator selects the desired mode of operation, subject to starting constraints. These feedback and mode selection signals enable operation of those portions of the control that are necessary for the selected mode of operation.

The feedback signals are shown as the commutating capacitor voltage, motor shaft position, motor speed and DC link current. These signals with appropriate stabilization networks are combined into a command signal to the SCR gating circuits. The SCR gate signals turn on the appropriate motoring, generating, or commutating SCR at the correct phase angle and time with respect to the motor/alternator voltage.

5.3.1 DC Field Supply. The DC field winding of the inductor motor/alternator must be supplied with an adjustable field current in order to provide for excitation. The machine must operate at a leading power factor when operating as a motor in order to provide commutation for the load commutated inverter. During the generating and motoring modes, the level of two field currents control the magnitude of the DC current delivered to the propulsion motor.

The field coil will be designed to operate from 84 V DC in order that the supply for the field controller can be the same as the vehicle battery.

Figure 16. Control Circuit Block Diagram

The field winding will be designed with sufficient conductor area to provide for leading power factor excitation with sufficient margin available for field forcing.

Figure 17 shows the power and control circuit schematic diagrams for the field current controller. The operating frequency of the system is up to 10 kHz and should provide sufficient bandwidth for the control of the inductor machine.

Figure 17. Inductor Motor/Alternator Field Current Controller

5.4 Composite Flywheel

At the operating speed of 15,000 rpm, only a small amount of energy will actually be stored in the rotor of the inductor motor/alternator. Since the diameter of the rotor is only 7.45 inches, it can operate at a much higher rpm without exceeding stress limits.

To obtain additional energy storage, it is planned to add a composite flywheel as part of the rotor assembly. The flywheel will increase the rotor inertia. The operating parameters for the flywheel/motor/alternator, as well as the practical limitations of application/installation requirements, directly influence the selection of the composite flywheel dimensions and its weight. These, as well as the stress carrying capabilities of the composite flywheel configuration, determine the limits of stored energy. Three requirements dominate the design of the composite flywheel:

- 1) The stress distribution within the flywheel at full design speed and at permitted overspeeds when rotating as a free body.
- 2) The addition of dynamic stresses and stress concentrations involved in and resulting from a proper attachment of the flywheel to the shaft.
- 3) Assuring concentricity and dynamic balance at all speeds to assure quiet, safe operation, and long bearing life. These involve thermal as well as dynamic differential strain considerations.

The two specifications that must be determined with regard to the flywheel are:

- 1) The weight of the flywheel that can be added to the inductor motor rotor. This weight affects the bearing life.
- 2) The allowable diameter selected for the flywheel. The diameter is closely tied to the design speed of the drive motor rotor which in turn is influenced by the combined weight of the rotor and composite flywheel. The maximum operating tip speed of a composite flywheel will also influence the maximum diameter.

The lightweight fiber composite flywheel relies on high spin speed rather than high mass for storing energy. This means that a fast spinning, lightweight, fiber composite flywheel can withstand large stresses and yet store as much if not more energy than a heavier metal flywheel. In such composite flywheels, the fibers such as E-glass in an epoxy composite, can have fiber stresses which exceed 125,000 psi provided that the internal configuration of the composite construction is such as to limit the stresses in the epoxy binder matrix to a safe value of its own strength.

The General Electric Company has completed preliminary high speed spin test evaluations on various S-glass and E-glass epoxy composite flywheels to demonstrate structural integrity. Two basic General Electric Company conceptual flywheel design approaches were considered for the composite flywheel design in this ERDA program. These approaches include a "cross ply" configuration fabricated from E-glass composite and a "shaped disc" flywheel concept.

Both of these configurations have achieved tangential operating speeds of 1,950 ft/s in preliminary development tests. Each of these development configurations provide for volumetrically efficient modular stacking of cylindrical flywheel discs of 1/2 to 1 inch in thickness. The number of discs selected and secured to the rotor will be determined by the flywheel weight limitation and/or the stored energy requirement.

Based on the selected speed of 15,000 rpm for the motor/alternator/flywheel and a flywheel tip speed limitation of 1,950 ft/s, the maximum flywheel diameter is 30 inches. The inertia of such a composite disc-type flywheel is then

$$I = 1.030 \text{ lb. ft.}^2 \text{ per inch of axial length.}$$

The useful energy to be stored in this flywheel, assuming 15,000 rpm maximum and 7,500 rpm minimum is:

$$E = .359 \text{ kWh/inch of axial length.}$$

The per unit weight of such a composite flywheel mounted on a 4 inch shaft is

$$W = 43.4 \text{ lbs./inch of axial length.}$$

Thus, a maximum axial flywheel length in conformance with the specified 200 lb. flywheel weight limit would be

$$L_{\text{max}} = 4.61 \text{ inches.}$$

The resulting useful energy of a 200 lb. composite flywheel could therefore be as high as 1.65 kWh.

It is not deemed necessary to have such a heavy, high speed, rotating assembly to demonstrate the inductor motor/alternator/flywheel concept. The above numbers are maximum limits only and will not necessarily be selected as specifications for the following reasons:

- 1) Bearing life is a continuous function of the bearing load. There is no cutoff point and therefore a lighter flywheel will have a lower bearing load and will produce longer bearing life.
- 2) Shaft critical speeds which are a function of total bearing span are generally higher for a shorter span provided the shaft's thickness and the mass distribution are the same.

- 3) The initial balancing of the composite flywheel and the maintaining of this balance during operation are areas of concern. To date, most composite flywheels have been suspended vertically from a drive turbine and find their own center of rotation. In this demonstration the composite flywheel will be secured between bearings. The lighter flywheel will minimize balance problems.

After considering the possible tradeoffs of bearing life, rotor weight, critical speeds, etc., it was decided that flywheel weight will be established at 132 lbs. The total rotating assembly (solid state rotor plus flywheel) will therefore weigh approximately 192 lbs. This will allow a composite flywheel inertia of 1 kWh with a flywheel 3 inches thick by 30 inches in diameter. Note that as flywheel technology improves, a 30 inch diameter composite wheel can store more energy (increases as rpm^2).

Present plans are to use the "cross ply" construction since this concept has been evaluated in tests. An analysis of the "cross ply" concept indicates that a low level of stress concentration should be present at the bolting connections to the motor/alternator flange and that concentricity and balance can be successfully provided by a central pilot pin or shaft extension through the modular flywheel stack. It should be noted, however, that differential strain must be accommodated by this shaft attachment between the motor shaft flanges and the flywheel discs. The low stress concentration and the flat disc form of this approach result in a very highly damped, dynamically stable flywheel.

An alternate flywheel concept which has not yet been proven adequately is the "shaped disc" configuration. Analysis of the "shaped disc" construction in the performance of initial development tests indicate that there should be little or no differential strains between the central portions of the flywheel and the motor alternator shaft flange. Also, this construction would permit virtually any desired form of rabbetted and bolted hub attachment to be used since no average radial stresses are transferred by the outer portions of the flywheel to the hub portions of the flywheel.

High speed rotors are of general concern because of the short time energy release in the event of rotor failure. Composite materials reduce the possibility of catastrophic failure. Thus, they are inherently safer than metallic materials. The fracture mechanics of composites differ widely from that of isotropic metal structures. Crack propagation is discontinuous in composite materials, and the fracture of individual fibers a few thousands of an inch in diameter result in few if any composite fragments of any significant mass or size. In the event of any composite flywheel delamination, sufficient to engage the enclosure, the composite material has high abrasion resistance and is essentially self-protecting.

While composite flywheels are inherently safe because of their fine shredding-type fragmentation, a suitable safety enclosure for the inductor

motor/alternator/flywheel will still be evaluated. The safety enclosure will be considered part of the design of a normal environmental enclosure for the inductor motor/alternator.

Figure 18 shows a photograph of a cross-ply glass filament flywheel of the type which is currently planned for use in this ERDA demonstration.

Figure 18. Photograph of Cross Ply Composite Flywheel

5.4.1 Selection of Bearing System. The bearing system of the 1 kWh flywheel system is designed around upper and lower angular contact (25° contact angle) extra precision ball bearings with sufficient preload to insure the absence of ball skidding, which greatly reduces bearing life. Life estimates were made for a flywheel weight of 250 lb., unbalance and magnetic loads of 20 lb. each, and short duration gyroscopic forces of 800 lb. Equal times were assumed to be run at 15,000, 13,500, 12,000, 10,000, and 7,500 rpm. The lower bearing is the more heavily loaded. Table 2 summarizes the manufacturer's life estimates and an estimate of the frictional power loss of several bearings

The last three bearings in the table are considered adequate for the application. These bearing performance figures presume an adequate supply of lubricating oil as this speed is well above the range where grease lubrication will produce an acceptable life. Approximately 0.35 gpm of oil will be supplied to the bearing. In the ultimate machine a small oil pump will be geared to the lower flywheel shaft producing an additional power consumption of under 20 W.

Table 2
PREDICTED BEARING PERFORMANCE AT MAXIMUM SPEED
OF 15,000 RPM

BEARING POSITION	SIZE (OD x ID x T)mm	LIFE (HR.)	POWER LOSS (w)
Lower	62 x 30 x 16	1340	100
Lower	72 x 35 x 17	3090	115
Lower	80 x 40 x 18	5300	135
Upper	62 x 35 x 14	6080	65

6.0 SUMMARY OF DESIGN SPECIFICATIONS

Based on the tradeoff studies made for each of the components in the overall energy storage system, the following is a tabulation of specifications for the system to be built and demonstrated on this ERDA program.

The application is directed towards a hybrid battery/flywheel electric vehicle having a gross weight of 3000 lb. The system is sized to accelerate the vehicle at 3 mph/s maximum up to a vehicle speed of 25 mph. Specifications for components in the energy storage system are as follows:

6.1 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 in.

Active stator stack length: 3.5 in.

Rotor inertia; 0.4 lb. inch sec.²

Rotor stored energy: (15,000 rpm to 7500 rpm) .0116 kWh

Rotor weight: 60 lb plus 132 lb of composite flywheel

Calculated machine efficiency: 82%

Oil lubricated bearings

6.2 Solid State Inverter/Rectifier

Input power: 84 V DC (battery pack)

Output power: 52.5 V, 3 phase AC
variable frequency - 500 to 1000 Hz

Calculated power conditioning efficiency: 94%
SCR average current: 77 A
RMS average current: 134 A
Peak current: 232 A
Peak voltage: 128.6 V
Maximum retard angle: 172 degrees
Leakage reactance per phase: 55 mh
Commutating capacitor: 40 μ F
SCR turnoff time: 44.2 μ s
Power factor: 0.78 lead

6.3 Flywheel

Diameter: 30 in
Energy storage capacity: 1 kWh (15,000 to 7,500 rpm)
Weight: 132 lb
Maximum RPM: 15,000
Construction: GE Alpha-5 "cross ply"
Material: E-glass polyester composite
Thickness: 3 in

7.0 TEST PLAN

Tests of the flywheel, motor/alternator and inverter/rectifier are designed to achieve five major objectives, as shown in Figure 17:

- establish energy storage capacity
- measure energy flow rates
- determine light load losses
- measure efficiency of energy transfer
- verify design equations

Achievement of these objectives will allow one to establish the suitability of this flywheel energy storage system for various applications. Also, the tests will allow modification of the design equations, if necessary, to accurately predict the performance of similar designs for other applications, energy storage capabilities, and energy transfer rates.

System tests will basically fall into two categories:

- test of the motor/alternator/flywheel with sine wave power
- test of the complete system

The tests in category one serve two purposes, one of which is the verification of the design calculations. The other is the establishment of the non-electrical losses and the electrical limits of the machine.

7.1 Test Setup

The tests will be run using the plan diagrammed in Figure 19.

The motor/alternator/flywheel will be coupled to a DC load motor so that constant speed tests can be made. Two alternate AC power sources will be used. The field excitation for both machines will be supplied from laboratory power supplies. Appropriate instruments will be used to measure electrical quantities.

Figure 19. Test Plan

7.2 Sine Wave Tests

These tests will consist of the following:

- resistance and reactance measurements
- no-load excitation data
- no-load losses
- reactive load data

Resistance and reactance measurements are necessary to obtain the winding resistances of both windings (AC and DC) and the commutating reactance of the AC winding. Since the commutating reactance is equal to the negative sequence reactance, the same tests are used as for conventional synchronous machines. When measuring this reactance, care must be taken to measure the proper value with respect to saturation and magnetization level.

The no-load excitation curve which is obtained by standard test methods will show the actual saturation behavior. This test should be extended well into the saturated region to find any possible excitation maximum. The no-load losses will be measured in the same test setup. These consist of iron and the bearing friction and windage losses. Performing these tests at various levels of excitation will allow the separation of losses.

The reactive load curve is favored over the mixed load curve because the driving power requirements are low. During this test, the overload capability of the machine is tested (preferably at two different speed levels) including the short circuit test at an excitation current equivalent to the rated no-load excitation current. This short circuit current test allows the determination of the synchronous reactance in the direct axis (saturated value). Loss measurements for the same operation allow the establishment of stray load losses for sinusoidal operating conditions.

The test procedure is as follows:

- a) Measure armature and field winding resistance using the volt-ampere method. Current at time of measurement should be between 10% and 20% of the rated currents for armature and field respectively. Measure the reactance of the armature winding (single phase) for the two extreme rotor positions; rotor in line with phase and rotor in quadrature with phase.

Measure at two different frequencies, preferably minimum and maximum operating frequency. Insure proper saturation level within the machine.

- b) Couple the machine to a drive motor and measure no-load voltage versus excitation current at minimum operating speed. Maximum excitation current is given either by the thermal limit of the field winding or by the value of I_E where the generated voltage starts to decrease.
- c) Measure no-load losses at two speeds for different excitation levels in order to separate mechanical losses from electromagnetic losses. This test can be done in either motoring or generating mode.
- d) Operate the machine in the motoring mode. Add inductors in parallel with the machine. Adjust the excitation in such a way that the current drawn from the power supply is in phase with the line voltage.

Measure the necessary excitation current at various voltage levels.

- e) Measure the power into the machine under these conditions to establish the stray load losses. The short circuit current test is best done in the generating mode. Initially adjust the excitation such that no-load voltage is obtained. Thereafter, short circuit the machine and measure the short-circuit current. Repeat for a second speed. The synchronous reactance then is obtained as the ratio of no-load voltage to short-circuit current.

The sine wave tests will establish the accuracy of the motor design equations and establish the rate of energy loss during idle periods.

7.3 Tests with Inverter Power

A series of tests using the inverter/rectifier power supply are required to determine the maximum energy flow rates under various operating conditions. Also, additional system power losses will be contributed by the inverter. The primary limitation on the energy flow rate into the flywheel is the capability of the motor/alternator to commutate the inverter. The commutation capability is dependent on motor frequency (speed), field excitation level, motor commutation reactance, and motor stator current. A no-load test under inverter power excitation will help establish system power losses.

The motor/alternator will be run at constant speed in the motoring mode, i.e., power flow into the motor/alternator. The stator current will be varied to establish the necessary inverter firing angle as a function of load. The field excitation current will be varied along with the motor speed to determine inverter firing angle versus motor current. The desired system operating point will be at approximately 84 V on the DC input to the inverter.

The result of these tests will establish the maximum energy flow rate into and out of the flywheel.

Thermocouples will be located at critical points in the motor/alternator assembly to monitor the temperature rise. This temperature data will aid in establishing the thermal rating of the motor/alternator.

7.4 Energy Storage Capacity

Tests will be conducted to determine energy storage capacity as a function of rpm, determine rotational losses, and obtain data with and without the composite flywheel's additional storage unit in place. Test measurements will be compared with the predicted performance. A measure of watt-hours/pound for the total system will be determined.

Quarterly Progress Report #1

Purpose

This report is submitted to summarize the status of research conducted by the contractor during the reporting period 6/28/76-9/28/76.

Items Accomplished

1. A Program Plan and Milestone Chart have been prepared.
2. Work on Task 1, "Establish Specifications for Inductor Motor/Alternator/Flywheel and Conduct Trade-Off Analysis," has been completed as originally scheduled. A first quarterly technical report has been prepared and is submitted as an attachment to this document.

The main objectives of Task 1 have been to establish a set of requirements, prepare equipment specifications and formulate a test plan for a machine nominally rated at 20 KVA.

3. A review meeting, originally scheduled for Wednesday, August 11, 1976, has been rescheduled for Monday, September 27, 1976. Dr. G. Chang will visit CRD, Schenectady, N.Y., for the review meeting.

Status of Work

The program is on schedule. Task 1 has been completed and a technical report prepared. Work on Task 2 and Task 3 will begin after the review meeting.

Work to be Accomplished in the Next Reporting Period

1. Initiate work on Task 2, "Engineer and Fabricate an Inductor Motor/Alternator/Flywheel." The first step will be to prepare a set of design drawings for the unit as specified in Task 1. This will include the Flywheel, Drive Motor/Alternator and Housing.

2. Initiate work on Task 3, "Engineer and Fabricate Solid State Power Conditioning and Control Equipment." The initial step on this task will be to finalize the power and control circuit diagrams in accordance with Task 1.

Edward L. Lustenader, Manager
Advanced Systems and Programs
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Attachments

1. Program Plan
2. Milestone Chart
3. Project Expenditures

DEMONSTRATION OF INDUCTOR MOTOR/ALTERNATOR/ FLYWHEEL ENERGY STORAGE SYSTEM -- PROGRAM PLAN

CORPORATE RESEARCH AND DEVELOPMENT
GENERAL ELECTRIC COMPANY
SCHENECTADY, NEW YORK
ERDA CONTRACT E(11-1)-4010
DATE ISSUED: 8-11-76
DATE REVISED: 9-28-76

Attachment 1 Program Plan

- LEGEND:
- BOXES REPRESENT EVENTS
 - LINES CONNECTING BOXES ARE ACTIVITIES
 - TASK NUMBER AND RESPONSIBILITY LISTED UNDER LEFT CORNER OF BOX
 - EARLIEST COMPLETION DATE LISTED UNDER RIGHT CORNER OF BOX
 - LINE THROUGH BOX INDICATES COMPLETION OF THAT EVENT

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Attachment 2

ERDA CONTRACT
E(11-1)-4010

DEMONSTRATION OF INDUCTOR MOTOR/ALTERNATOR/ FLYWHEEL ENERGY STORAGE SYSTEM

CORPORATE RESEARCH AND
DEVELOPMENT
GENERAL ELECTRIC COMPANY
SCHENECTADY, NEW YORK

MILESTONE CHART

DATE ISSUED 9-28-76

Original Issue Date: 8-11-76
Date Revised: 9-28-76

LEGEND:

- ▲ = Scheduled Milestone
- ▲ = Completed Milestone
- ◇ = Modified Milestone
- ▲ — ▲ = Time Span

Demonstration of Inductor Motor/
Alternator/Flywheel Energy
Storage System.

Attachment 3

100X110 7/100 Inch Divisions

GENERAL ELECTRIC COMPANY, SCHENECTADY, N. Y., U.S.A.

FIG. 52-11 (8-50)