Development of a Hybrid Flywheel/Battery Drive System for Electric Vehicle Applications

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Abstract—Today's electric vehicles are severely limited in multistop and go driving range and accelerating capability by the lead acid battery's inability to handle high power peaks while maintaining maximum energy storage capability. A hybrid flywheel/battery system can be used to isolate the battery from the accelerating power peaks, and should recover a substantial part of the braking energy. This paper describes the development of a small, high speed, lightweight flywheel/ac synchronous motor alternator sealed energy storage package coupled into the battery and dc drive motor system through a simple rectifier/inverter power circuit. This system stores just enough energy in the rotor of the machine for one start-stop cycle. Provision is made to add a flywheel to store energy for several cycles, or enough energy for climbing or descending long grades. The fields of the two machines are electronically controlled to achieve optimum performance and effective energy utilization.

INTRODUCTION

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 [1]. This paper describes the development of a new type of energy storage package which may 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 system 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 described in the paper 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 Fig. 1. The main components are the inductor motor/alter-

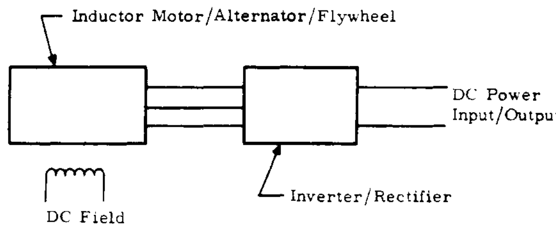

Fig. 1. Basic concept of inductor motor/alternator/flywheel package.

nator with its dc field control, and the composite flywheel which provides additional inertia above the rotational inertia 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.

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/pound), 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.

VEHICLE PROPULSION SYSTEM CONCEPTS UTILIZING FLYWHEEL ENERGY

The basic concept of the battery/flywheel propulsion system for a vehicle is shown schematically in Fig. 2. 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, and if desired, additional rotating energy capability can be added to 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.

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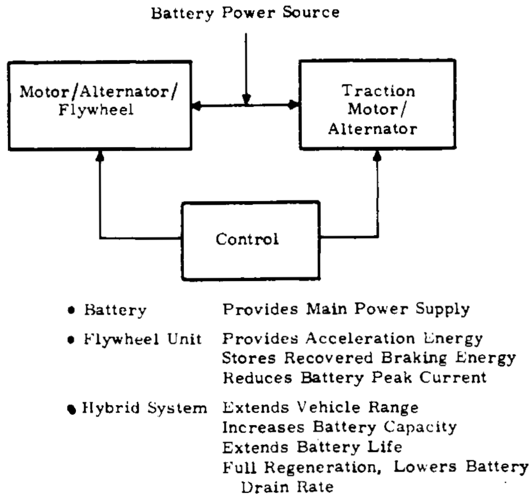

Fig. 2. Basic concept of battery/flywheel propulsion system.

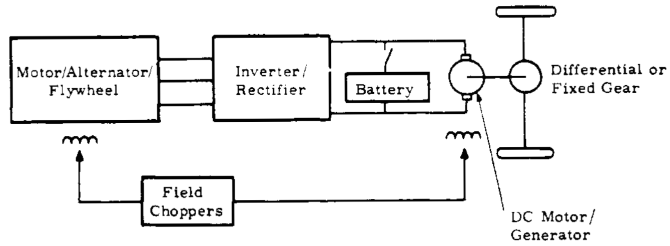

Fig. 3. Regenerative ac system with flywheel storage.

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. Also, less heat loss in the rotor makes it 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 Fig. 3. The main components are the inductor motor/alternator with its dc field 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 flywheel mass.

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. Application of this type of energy storage system is planned for a 3000 lb utility van. A typical velocity time profile for such a utility vehicle is shown in Fig. 4. This profile requires 3 mi/h/s acceleration up to about 50 percent of maximum speed (Vel_{max} = 25 mi/h) and acceleration on the natural constant voltage series motor characteristic up to full speed.

The mode of flywheel operation and to some extent the energy storage capacity required depends upon the type of vehicle drive motor used.

The separately excited dc motor, which does not require field reversal for transition into the generating mode, is capable of reaching the battery voltage level at lower motor rpm and vehicle speed than a series excited dc motor because of the independent field current control. Fig. 5 summarizes the operating conditions for the motoring mode of operation in case of a separately excited dc drive motor. Thus, a constant power acceleration at higher speed is shown. Fig. 6 shows the operation of the system during 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.

The rating of the flywheel motor/alternator and the inverter/rectifier depends on both the motoring and braking conditions. The heaviest power requirement during vehicle acceleration occurs at half speed and maximum acceleration. At that point only about one-third of the flywheel energy has been consumed. Thus the alternator speed will be significantly above minimum speed and will, therefore, be capable of providing higher voltage levels than required. The rectifier part of the power converter and the alternator will have to be capable of providing a dc current of 310 A for a short time and a voltage level of $37.4 V_{L-N}$ at the alternator and a power level of 20.3 kW.

The power, the inverter and flywheel machine will have to be capable of accepting during the braking mode of operation, depends to a large degree upon the losses in the drive train and the dc motor. High losses reduce the power regenerated but also the energy storage efficiency. The calculations for the planned application result in the following voltage current and power levels:

braking power at top speed	22.4 kW
output of dc machine	16.2 kW
ac voltage at alternator	49.1 V_{L-N}
ac current at alternator	152 A/phase.

Because of the fact that the alternator is to commutate the inverter during the vehicle braking mode, the actual rating of the ac machine is also influenced by the commutating react-

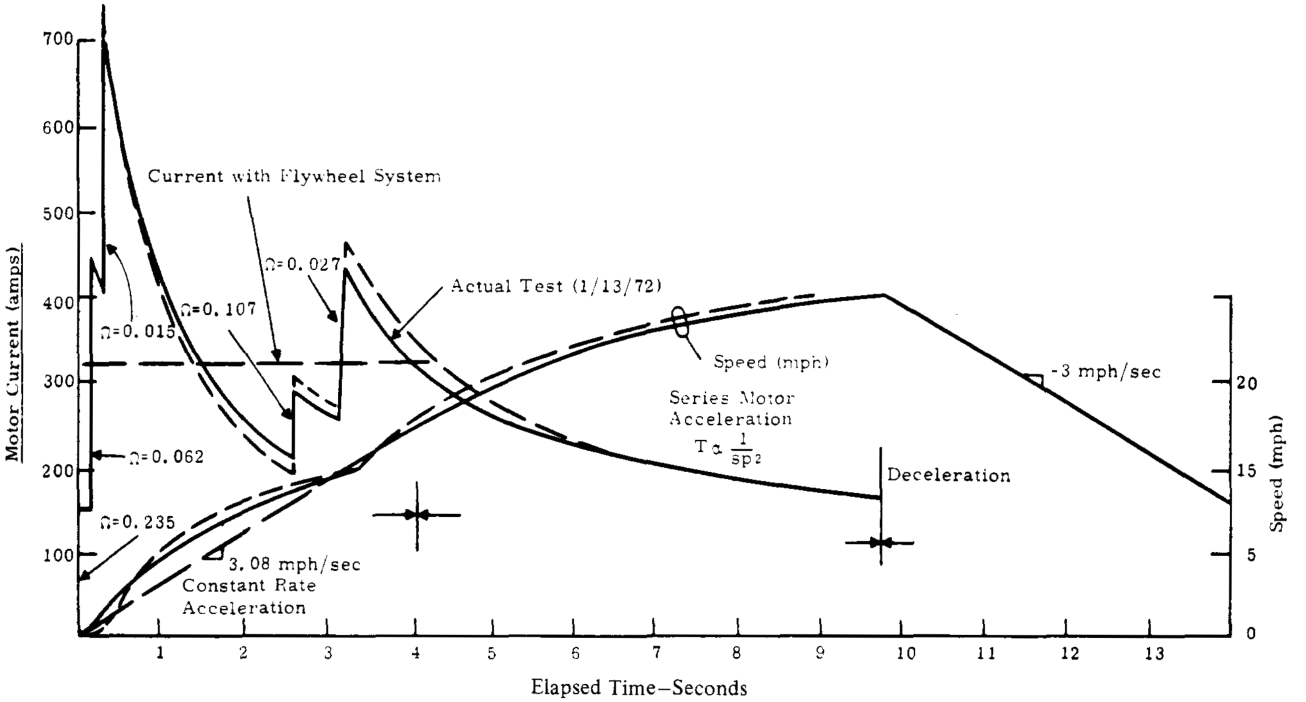

Fig. 4. QT vehicle performance: 3600 lb, 84 V.

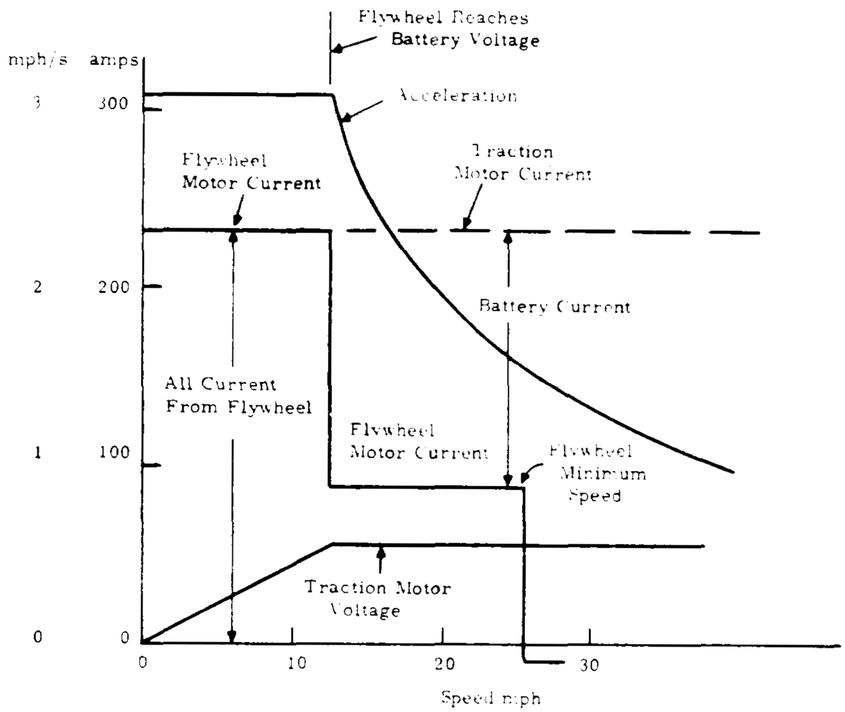

Fig. 5. Motoring operation of flywheel system.

ance of the machine. This requires a higher voltage capability of the ac machine while motoring than indicated above. The voltage capability for a practical level of commutation reactance is 63 V, which results in a maximum ac machine capability of 29.7 kVA during vehicle braking.

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 commutation 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 127 A is relatively high for a traction machine when compared to the maximum required current of 151 percent. However, this seems to be reasonable for rectifier operation since commutation is also

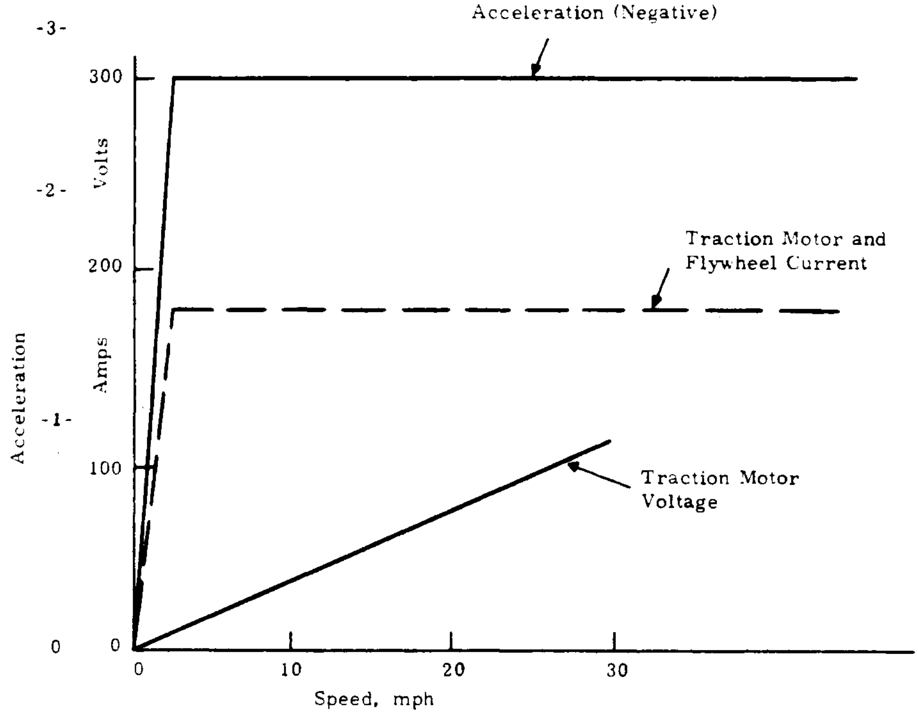

Fig. 6. Braking with flywheel.

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 0.78 lead was selected as practical. Thus, an ac voltage of 52.5 V, combined with an ac current of 127 A at a power factor of 0.78 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 the previously described application.

INDUCTOR ALTERNATOR DESIGN CONSIDERATIONS

The basic function of an inductor machine can best be explained by means of Figs. 7 and 8. Fig. 7 shows a dc field coil between two stacks of stator laminations. A direct 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 (Fig. 8) 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.

A rotor speed of 15 000 r/min was set primarily by bearing limitations. This maximum rotor speed was determined by both mechanical and electrical considerations. To minimize

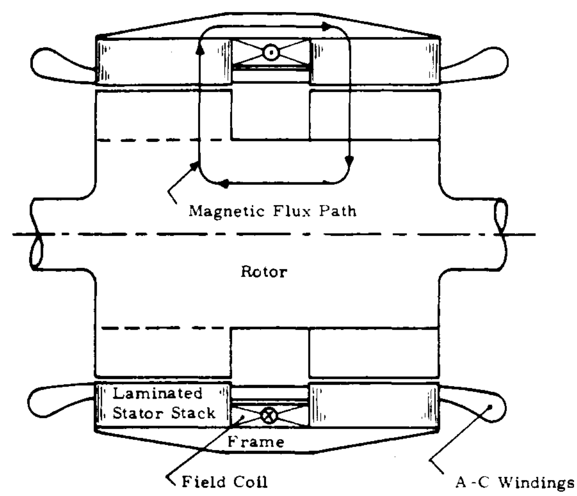

Fig. 7. Cross section of inductor/alternator.

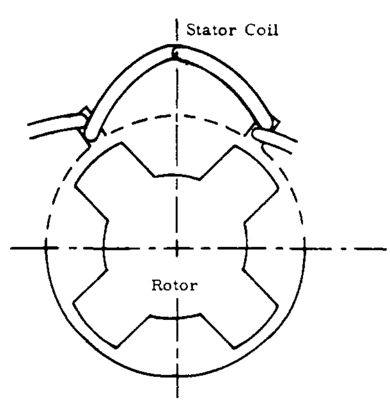

Fig. 8. End view of inductor/alternator.

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 3000 h.

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

$$\Delta E = I/2\,(n_{max}{}^2 - n_{min}{}^2) \tag{1}$$

where

ΔE useful energy,
I rotor inertia,
n_{max} maximum operating speed.
n_{min} minimum operating speed.

Fig. 9 shows this relation as a function of the speed ratio. At 50 percent of maximum speed, 75 percent 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 versus speed relationship as shown in Fig. 10. For the 50 percent speed ratio, the weight of the flywheel is 33 percent 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:

$$(P_R/n_R)^{0.75} \sim W \tag{2}$$

where

W weight,
P_R rated power (kVA),
n_R rated speed (r/min).

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 Fig. 10. Thus, depending upon the weight contributions from the flywheel and the generator, an optimum speed ratio can be established for a given ratio of stored energy and power rating. For the case of equal weight contribution, the optimum appears at 52.5 percent 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 percent speed ratio for the operation of the flywheel storage system. Based on the preliminary design specification of an upper speed of 15 000 r/min and a 50 percent speed ratio, a minimum speed of 7500 r/min results.

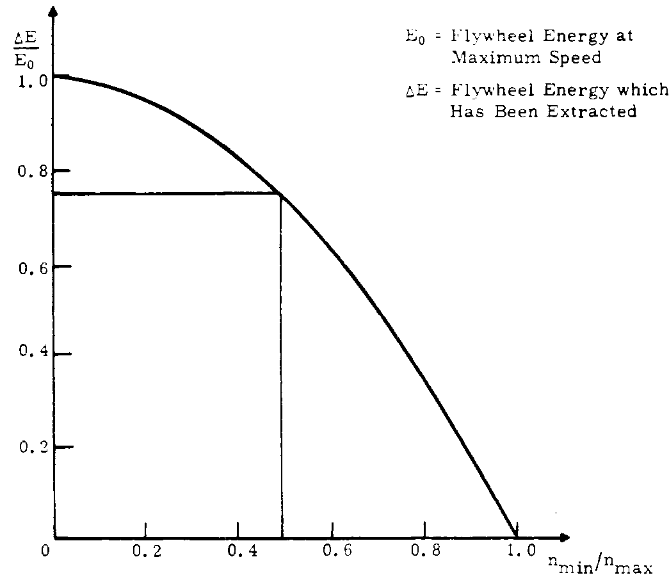

Fig. 9. Flywheel speed ratio (n_{min}/n_{max}) versus energy ratio.

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 counterbalanced 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 8 to 12 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 commutate the inverter, e.g., the machine rating reflects this in terms of a leading power factor requirement. The commutating reactance of the machine is directly responsible for this additional power requirement. The commutating reactance, which for all practical purposes can be

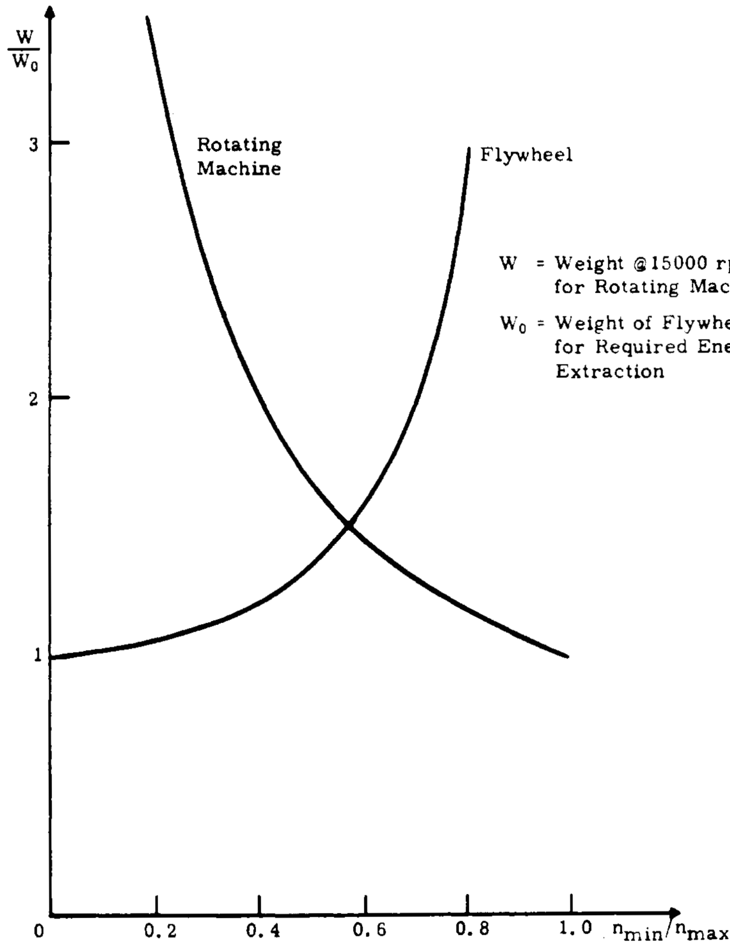

Fig. 10. Flywheel speed ratio (n_{min}/n_{max}) versus weight ratio.

equated with the negative sequence reactance of the machine, can be expressed as follows [2]:

$$X_C = X_S + X_E + C_1 X_{ad} \tag{3}$$

where

- X_C commutating reactance,
- X_{ad} synchronous reactance in direct axis,
- X_S slot leakage reactance,
- X_E end turn 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 versus frequency as follows:

$$X_C = C_S f + C_E/f + C_{ad}/f. \tag{4}$$

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 7500 to 15 000 r/min speed range, results in a frequency range of 500 to 1000 Hz.

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 lower, 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 air-gap 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

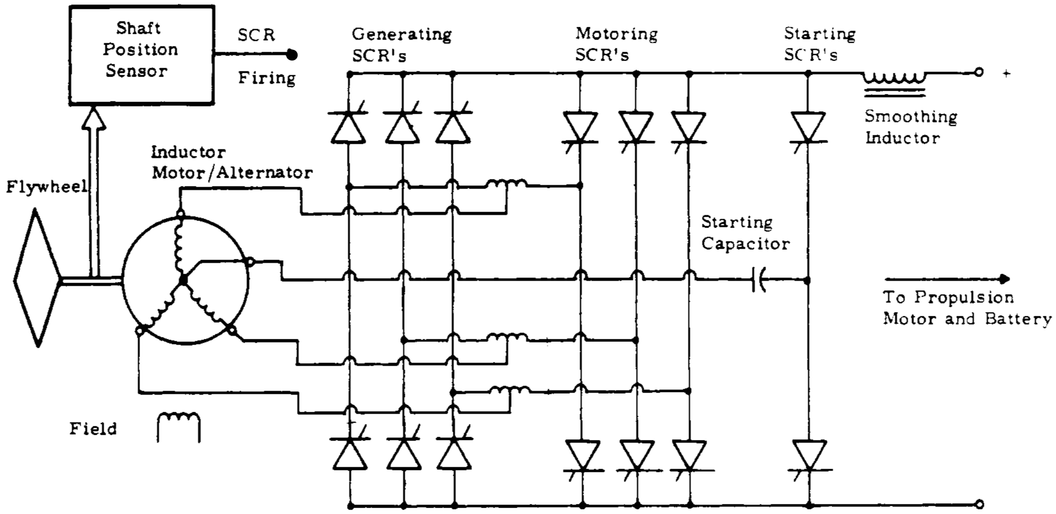

Fig. 11. Rectifier/inverter power circuit.

this type of machine. Initial design calculations have established that a rotor diameter of 7.45 in and an active stack length of 3.5 in 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 $I_s = 0.4$ lb in s^2. The useful energy which can be stored in this rotor by a speed increase from 7500 r/min to 15 000 r/min is $\Delta E = 11.6$ Wh which is about one-half of the energy storage required for one start-stop cycle for a 3000 lb vehicle. If the slots in the two rotor halves are filled with nonmagnetic material via brazing or welding, the inertia increases to $I_F = 0.814$ lb in s^2. The energy stored in this rotor for the same speed range then amounts to $\Delta E = 23.6$ Wh. This is approximately the stored energy needed for one start for a 3000 lb vehicle. It emphasises the point that what generally is considered a disadvantage of an inductor alternator—namely, that it is for the same speed and power rating, twice as large as a conventional ac machine—turns out to be an advantage for this type of application. The rotor inertia can easily be used to be sufficient for providing the required energy storage capability. Thus no separate flywheel is required. Furthermore, the stator of the inductor alternator has sufficient thickness to act as a safe containment should the flywheel fail.

SOLID STATE INVERTER/RECTIFIER

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.

A study of power conditioners suitable for reversible ac to dc conversion identified the load commutated inverter/rectifier (LCI). The power circuit is shown in Fig. 11.

In the system shown in Fig. 11, the polarity of the dc terminals cannot reverse 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 direct current must be reversed. When operating as an ac to dc system (generating), the six SCR's (shown in Fig. 11 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.

During the motoring mode, the six SCR's (shown in Fig. 11 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 direct currrent and torque control to be provided without the need for phase angle controlled gating circuits and operation of the

TABLE I
SUMMARY OF DESIGN SPECIFICATIONS FOR INVERTER/RECTIFIER

Input power: 84 V dc (battery pack)
Output power: 52.5 V, three-phase ac variable frequency–500 to 1000 Hz
Calculated power conditioning efficiency: 94 percent
SCR average current: 77 A
RMS average current: 134 A
Peak current: 232 A
Peak voltage: 128.6 V
Maximum retard angle: 172°
Leakage reactance per phase: 55 μh
Commutating capacitor: 40 μF
SCR turn-off time: 22 μs
Power factor: 0.78 lead

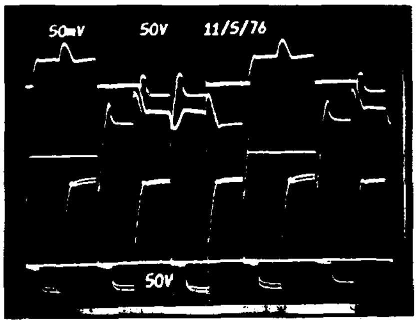

Fig. 12. Main SCR and auxiliary SCR voltage and load current during forced commutation: i load = 20 A/div, e main SCR = 50 V/div, e aux SCR = 50 V/div, time = 0.5 ms/div.

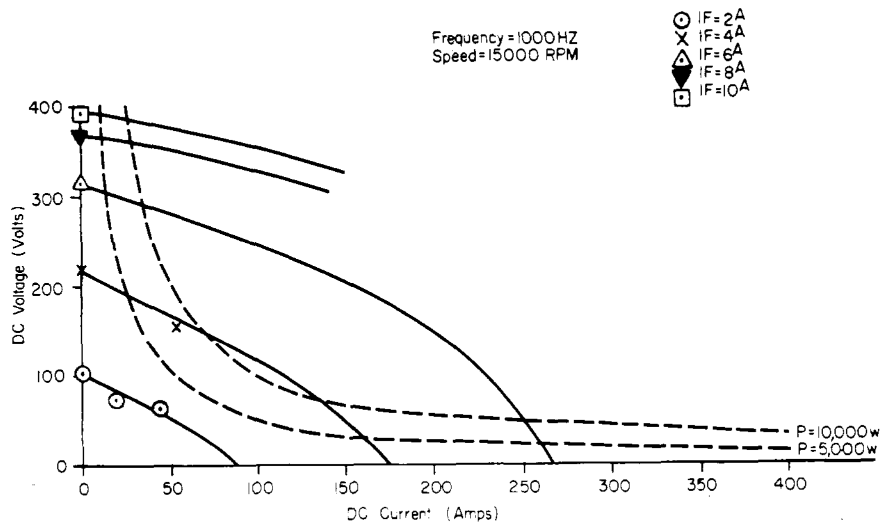

Fig. 13. DC voltage versus dc current for constant field current with rectifier load.

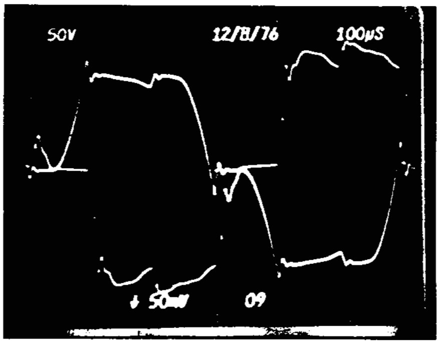

Fig. 14. Line current and line-to-line voltage: i = 20 A/div, v = 50 V/div, generator speed = 15 000 r/min, field current = 4 A.

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 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.

RECTIFIER/INVERTER SPECIFICATIONS

The system specifications and requirements for sizing the system have been previously described. These can be related to the requirements for the power semiconductors for the load commutated inverter. Table I summarizes the electrical requirements.

RECTIFIER/INVERTER TEST DATA

Preliminary data has been obtained on the inverter/rectifier power conditioner in two main areas: 1) operating as a forced commutated inverter with a static load and 2) operating from the inductor machine in the rectifying mode.

The operation of the main and auxiliary SCR's during forced commutation operation is shown in Fig. 12. The operation of the auxiliary SCR at three times the fundamental motor frequency is shown.

Test data for the inductor machine operating with a rectifier type dc load is presented in Fig. 13. Data on open circuit, short circuit, and with a finite load resistance is shown for a fixed speed and fixed dc field current. The data for maximum speed (15 000 r/min) and field current from 2 to 10 A is presented. The load points were limited by the power capability of the dc drive motor supplying mechanical power to the inductor machine. An additional test performed on the machine is the effect of rectifier commutation on the machine voltages and its reduction in the power capability of the machine. The machine terminal line-to-line voltage and line current is shown in Fig. 14 for full speed and 7500 W output. This figure clearly shows the long commutation times together with the reverse recovery of the rectifiers.

Additional system test data during dynamic operation with an energy interchange between the flywheel and the propulsion motor are planned.

CONCLUSIONS

Sufficient progress has been made in the program to draw the following conclusions.

1) An energy storage and recovery system should significantly increase the range of a multistop and go battery powered electric vehicle.

2) A flywheel system augmenting a battery powered vehicle should make a viable hybrid combination.

3) A high speed ac driven flywheel system will provide decreased machine weight, increased efficiency, and more optimum shape of the flywheel.

4) The load commutated interter/rectifier provides a high efficiency, reversible power flow and a flexible link between the inductor machine and the dc battery and propulsion motor.

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