Automotive electric drive system study
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AUTOMOTIVE ELECTRIC DRIVE SYSTEM STUDY

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A B S T R A C T

Tests have been conducted on a DC electric drive system with emphasis on obtaining efficiency data for the DC to DC thyristor control circuit and the DC drive motors. DC to DC converter efficiencies were between 80 and 93 percent over a typical operating range. Motor efficiencies ranged up to 62 percent over their operating range.

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1.0 Introduction

1.1 Background of the Project

The electric drive system dealt with in this report is essentially the same system found in the propane-electric hybrid vehicle tested by the Engine Laboratory of the National Research Council in the summer of 1974 (Ref. 1).

The electric drive system was removed from the vehicle after the completion of the test programme and mounted on a dynamometer test rig as described in Appendix E.

This report deals with the dynamometer test programme.

1.2 Test Programme Objectives

Basic and very general characteristics of the electric system were obtained from the vehicle test programme as outlined in Reference 1.

The goals of this test programme were to expand on the previous tests, and obtain detailed performance data on the drivetrain components, particularly the DC to DC converter and the DC drive motors. Tests were conducted over the full operating speed and load ranges of the components.

It was realized that the DC motors were not designed for vehicle traction purposes and hence would not be completely representative of typical vehicle drive motors.

The data was to be collected and reduced to a form suitable for input into a general hybrid and electric vehicle computer simulation.

2.0 System Components Under Test

2.1 DC to DC Converters

2.1.1 General DC Controllers

There are currently three types of DC controllers in common use.

The first, the resistive controller, uses variable resistors to control the voltage applied to the field or the armature of an electric motor. While the response may be quite smooth, the controller is highly inefficient on all but full load operation. This makes it unacceptable for electric vehicle drives, particularly where all the vehicle's energy must be carried in some form of battery storage.

The second type of controller, which utilizes a stepped voltage approach, uses switching components to connect batteries in various series/parallel combinations to obtain the

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desired voltage at the motor. While this system is efficient, it does not give good control as the total number of voltage steps is kept small in order to minimize complexity. For electric vehicles this system has the added disadvantage of placing a heavy load on the switching components which must break very high load currents with every power setting change. In spite of these disadvantages a variation of this control scheme, in which combinations of motor windings are connected to a constant voltage source, is used in many subway and trolley car controllers.

The third and most recent system to emerge is the solid state controller. These controllers, known as DC to DC converters, or choppers, use high current electronic switches to "chop" incoming DC into easily controlled pulses of varying sizes.

Solid state choppers are generally quite efficient, yield smooth motor response, and have a long maintenance-free life. It is this controller, then, which shows the most promise for the future in electric drive vehicles.

2.1.2 Types of Solid State DC Controllers

In spite of their recent appearance in the field of motor control, many types of solid state controllers already exist.

The simplest type of chopper may be modelled by a single ideal switch as shown in Fig. 2.1. Clearly, the average output voltage is a function of the duty cycle of the pulsed waveform, that is:

$$V_o = V_{IN} \times \frac{t_{ON}}{T}$$

If this pulsed voltage is applied to an averaging filter, the final result will be a constant DC voltage proportional to the duty cycle of the pulses. Such a network using an inductor and a "free wheeling diode" is shown in Fig. 2.2 During the chopper's "on" period, current through the inductor builds up, thereby storing energy. When the switch opens, the inductor releases this energy by forcing current to continue to flow through the load via the free wheeling diode. This output voltage is a constant DC value with some superimposed ripple.

Note that during the "on" period the switch carries full load current. Thus, while average input current may be considerably less than the output current, peak input current always equals output current.

The switch function is usually implemented with other transistors or thyristors. Transistors are usually restricted to small choppers, that is, those under a few kilowatts. Within this range, though, they have the advantages of high speed, low losses, and simplicity of the power circuit. This simplicity is a result of low power control signals, called "gating signals" easily switching the transistor open or closed.

This ease of control contrasts directly with that of the thyristor (usually a Silicon Controlled Rectifier or SCR) which must be turned off by external circuitry. A low power gating signal may be used to turn on SCR, but it will remain on until current through the device is forced to zero. The process of turning off an SCR is referred to as "commutation" (see Fig. 2.3).

In spite of this disadvantage, thyristors have several advantages over transistors in choppers, the most important being the power handling capability. SCR's capable of switching 700 amps at 1500 volts are common, while transistors rarely exceed 50 amps and 200 volts.

An example of a thyristor chopper is shown in Fig. 2.4. In this circuit the output pulse is started simply by briefly gating SCR 1. To turn off SCR 1 and thereby end the pulse, the commutation circuit is initialized by firing SCR 2, thereby charging C1 through L1 to twice the supply voltage. At this point SCR 3 is triggered to allow C1 to temporarily supply the load current. This forces SCR 1 to turn off.

This process may be carried out at rates up to several hundred cycles per second with output pulses as narrow as a few hundred microseconds.

The circuitry to control the SCR's, called the "logic circuit", may alter the t_{on} period while keeping the frequency $(^1/_T)$ constant, or it may keep a constant pulse width and vary the frequency (refer to Fig. 2.1). The first approach yields a pulse width modulated chopper and the second a frequency modulated chopper. Of course, a combination of the two may be used if desired.

Another chopper configuration, shown in Fig. 2.5, was the thyristor chopper studied at the National Research Council in 1974.

2.1.3 4-SCR Controller

This chopper differs from the previous example in that all four SCR's handle full load power and no distinct commutation circuit is required. The associated logic controls the chopper by firing pairs of SCR's alternately, that is SCR_1 and SCR_{11} simultaneously followed by SCR_2 and SCR_{22}.

To understand the operation of the chopper, assume that a steady state condition exists, so that an initial current is flowing, discharging the inductor through the load and free wheeling diode. Also assume that capacitor C, is initialized to E volts in the positive direction and that inductor L, is large, so that short term changes in inductor current are small.

Under these conditions a current pulse is initiated by firing SCR_2 and SCR_{22}. This places the capacitor, charged to E volts, in series with the power supply, thus producing 2E volts across the diode, D_1. With the diode reverse biased, the load current is supplied by the battery via SCR_{22}, C_1 and SCR_2. Because the capacitor current is constant, the voltage V_o will decrease linearly from 2E to zero. At this point the free wheeling diode once again takes over conduction of the load current, while the capacitor, and hence the SCR current immediately drop to zero. Commutation occurs automatically and hence is called "natural". This contrasts with the previous example in which "forced commutation" was used to turn off the main SCR.

Once the diode has resumed conduction the capacitor is again charged to E volts, but this time in the negative direction. Thus, the entire process may be repeated by firing the other two SCR's. This process may be repeated several thousand times per second, yielding a maximum operating frequency much higher than the previous example.

Voltage and current waveforms at various points in the circuit are shown in Figures 2.6, 2.7 and 2.8. A more detailed power circuit is shown in Fig. 2.9.

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2.1.4 Logic Circuitry for 4-SCR Controller

The logic circuit for the 4-SCR chopper studied here consists of two feedback loops along with various protection circuits.

The primary regulating loop controls input current to the chopper by sensing it, comparing it to the current demand, and adjusting the frequency at which the SCR's are fired to eliminate any difference.

The second feedback loop prevents the output and hence the peak SCR current from exceeding a safe value by overriding the primary loop when required.

Of the several protection circuits within the logic, the most important is commutation protection which inhibits firing of the next set of SCR's until the previous set has shut off. This prevents a condition known as "commutation failure" or "shoot-through", wherein all four SCR's are on applying full input voltage to the load. Under these circumstances control is lost, and may be regained only by temporarily opening the input circuit breaker to interrupt current flow. A more detailed description of the logic is given in Appendix D.

2.2 DC Motors

The motors used in this test were Delco model A-8587 30V, 400 amp direct current machines originally used as starter generators on Orenda 10 aircraft gas turbines. The only modification to these motors for application to this project was the rewiring of the shunt field so that it could be separately excited.

The motors are essentially series wound but have some degree of compounding.

Two identical units were used simultaneously, wired in series as shown in Fig. 2.9. The mechanical hook-up is dealt with in Appendix E.

3.0 Test Procedure

After calibration of the instruments, testing was done in a number of stages (see Appendix A). Runs were performed at 10 amp input current increments with an input voltage of approximately 120V giving 1200 watt input power steps. At each input power level, data were recorded at approximately 500 rpm intervals from 500 to 8000 rpm.

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The grid boundaries were defined by the motor speed limit of 8200 RPM and by the dynamometer load limit at the low RPM settings.

Throughout the test period the input voltage was kept as constant as possible in an effort to maintain constant test conditions.

Motor and chopper data were recorded simultaneously on a continuous strip chart recorder. To test any given point the machine was started along with the motor-generator DC supply (see Appendix B). Start-up was accomplished by a special circuit described in Appendix C. The input current was set at the desired value; then the motor speed was set by varying the dynamometer loading controls.

Problems were encountered while trying to find an acceptable way of measuring power when the current and voltage waveforms are very irregular. This problem is dealt with in Appendix G.

4.0 Test Results

The data gathered during this study are presented in the form of three (Figures 4.1, 4.2, and 4.3) maps. The first two maps summarize motor characteristics. The operating point of the motor may be located on these two maps once the required output speed and output power are known. Figure 4.1, shows lines of constant motor efficiency, defined as:

$$\frac{\text{mechanical power out}}{\text{motor voltage x motor current}}$$

Fig. 4.2 presents lines of constant motor impedance, defined as:

$$\frac{\text{motor input voltage}}{\text{motor input current}}$$

From this information one can determine the motor input conditions required.

Fig. 4.3, a plot of constant power and efficiency contours, summarizes the chopper characteristics. Having obtained the required motor input power motor impedance from the motor maps, one may determine the required input power to the chopper. A sample of the calculation procedure is given in Appendix F. Figure 4.4 is included to give an indication of the voltage and current necessary to operate the motors over their full range.

5.0 Discussion

The results of tests performed were shown in Section 4.0 of this report. General trends in the data concur with what might be expected.

Major losses within the motors may be divided into two types: those dependent on speed, such as winding and core losses; and those

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dependent on current, such as I^2R and commutator losses.

For a series motor, decreasing the speed at constant power will increase current, therefore the efficiency will peak along any constant input power line. Efficiency, of course, will drop off at low power, where speed dependent losses due to friction become significant.

Losses in the chopper generally increase as the load impedance decreases, i.e. when output current becomes much greater than input current. This condition, which is accompanied by high current pulses of short duration, increases I^2R losses throughout the circuit.

The second type of loss within the chopper is related to frequency. These losses, which include SCR switching losses and snubber (dv/dt suppressor) losses, show up at high current levels. Thus, along any line of constant load impedance, efficiency increases as input and output current levels converge.

6.0 Conclusions

1. A DC electric drive system was tested on a dynamometer with emphasis on obtaining motor and controller efficiency curves suitable as an input to a hybrid vehicle computer simulation.

2. A thyristor type DC to DC converter showed efficiencies, over a typical operating range, from 80 to 93 percent.

3. The DC motors tested showed efficiencies ranging up to 62 percent.

4. The data presented should not be considered typical of all DC thyristor controllers or DC drive motors, but as characteristic of the specific components under test. Furthermore, it is recommended that testing of alternate types of motors and controllers be undertaken in order to obtain comparative data.

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A P P E N D I X   A

Instrumentation

Instrumentation for this study consisted primarily of six devices, four electrical and two mechanical, feeding a Consolidated Electrodynamics Corporation Model 5-124 recording oscillograph.

Measurements taken included chopper input voltage and current, chopper output voltage and current, and motor speed and torque. The system layout is shown in Figure A1.

Two extra traces, dynamometer voltage and current, were added to give a double check on motor efficiency figures.

Voltages to be recorded were scaled down by resistive dividers and applied to the appropriate galvanometers in the recorder. Currents were measured with shunts inserted in the circuit, again followed by appropriate voltage dividers feeding the galvanometers.

Speed of rotation was sensed by a proximity pickup located near a toothed wheel on one of the motor shafts. The resulting frequency signal was converted to a DC level by an Airpax "Tach-Pak" Model F-5450B, filtered, and applied to the chart recorder.

The motor torque was measured with a Baldwin-Lima-Hamilton Model SR4 load cell containing a strain gauge bridge, attached to the torque arm on the dynamometer. The error signal from the bridge was amplified with a high gain differential DC amplifier, and then filtered to remove the AC components induced by the mechanical vibrations of the dynamometer. Again the output was scaled by a suitable factor and applied to the chart recorder. Refer to Figure A2 for the torquemeter circuitry.

Instrument calibration was checked periodically during the test programme.

Basic calibration of the electrical functions was done with a calibrated Nonlinear Systems Model X-3 digital voltmeter. The voltage outputs were checked directly. The current outputs were checked by recording the voltage across a T & M Research Products F-500-2, 0.01020 ohm non-inductive shunt, inserted into the appropriate point in the circuit.

The torquemeter was calibrated using standard weights suspended from the load cell. It was checked at four pound intervals on the high sensitivity scale and twelve pound intervals on the low sensitivity scale, and was determined to be linear within one percent.

The tachometer was calibrated from 0-10,000 RPM against a digital frequency counter. Readings were spot checked periodically with a Hahn & Kolb hand tachometer and a mechanical revolution counter.

APPENDIX B

DC Power Source

DC power for the chopper and motor test programme was supplied by a 400 Hertz alternator driven by a 50 horsepower motor. The three phase output of the alternator was rectified and directly wired to the chopper with a pack of ten twelve-volt automotive type batteries floating on the system. The mechanical description of the motor generator set may be found in Appendix E. Figure B1 shows the power circuit connections for this arrangement.

The alternator field was controlled via a smaller DC machine built into the alternator, and by a switching mode regulator circuit shown in Figure B2. This regulator consists of a primary feedback loop to maintain constant output voltage, and a secondary overriding loop to limit the maximum current available.

In operation, output voltage is sensed and compared to a reference by op.amp A1. If the output voltage is below the reference level, the output goes negative, and voltage is applied to the field via transistors Q1 through Q4. When the output then increases to exceed the reference, the op. amp switches again and the field voltage is removed. Thus, the regulator is self-oscillating.

The output current limiting works in a similar fashion. When the current signal applied by A2 exceeds the reference value, the op. amp A3 switches and forces the voltage reference on A1 to a negative value thereby turning off the field. As in the primary loop, once the output current falls below the desired value, the field is allowed to turn on again.

The final piece of circuitry in the controller is the overvoltage trip. This circuit serves to shut down the alternator in case the generated voltage exceeds a preset value of approximately two hundred volts. In case of a failure in the regulator, the alternator is shut down before significant damage can be done by excessive voltage.

This function is implemented by using a latch made up of gates G2 and G3 driven by another CMOS gate G1, which detects the overvoltage condition. The initial state of the latch is determined by the RC network on the "reset" input to the latch. This ensures that the controller will not start up in the "tripped" state.

A P P E N D I X   C

Starter Assembly

The starter assembly consists of circuitry to turn the chopper components on and off in the correct sequence.

During the start-up of the chopper, the logic must be turned on and allowed to settle before the main power is connected to the circuit. Any circuit used to trickle-charge the battery pack should be disconnected before the pack is connected to the chopper.

To shut down, the reverse procedure should be followed, that is power off first, followed by the logic and then by reconnection of the charger. The circuit illustrated in Figure C1 accomplishes this sequence. Two switches are provided for the operator. The logic switch starts the on or off sequence, while the power switch holds the main power off while allowing the logic to run.

A P P E N D I X   D

Chopper Logic

The chopper logic consists primarily of a voltage controlled oscillator (VCO), current sensing amplifiers, gate pulse steering circuitry, and pulse amplifiers. Also included are commutation protection and shoot-through detection circuits.

This section, then, will attempt to clarify some of the details of the logic circuitry. Note that all component designations refer to Figures D1 and D2. Furthermore, unless otherwise noted, all logic is implemented with Motorola "High Threshold Logic" (HTL), and all amplifiers are general purpose internally compensated op. amps.

The main input current regulating loop consists of a chain of amplifiers A1 through A3, feeding the VCO to determine the chopper frequency.

Input current is sensed by a special Hall effect current probe, whose output is amplified by A1, then further amplified and filtered by A2. The inverting configuration of A2 ensures that the current flowing into the chopper will give a negative voltage at the output of A2. This negative voltage is then summed with a positive reference and integrated by A3, whose output is applied to the VCO. In steady state operation, the current signal and the reference sum to zero, so the integrator output and consequently the VCO frequency remain constant.

If a sudden increase in current demand occurs, then the sum of the current plus the reference will become positive, causing the integrator output and hence the VCO frequency to increase in magnitude. This, in turn, will cause an increase in the input current, returning the sum of the input plus reference to zero, and therefore, returning the system to steady state.

A similar amplifier - integrator combination is used to limit the output current. This current is sensed by differential amplifier B1 connected across a current shunt in the output path. The signal is then compared to the reference by B2. If the current signal exceeds the reference, the output of B2 will go positive, and take over control of the VCO via diode CR1.

The VCO itself consists of op. amp B3 and surrounding gates. The op. amp, connected as an integrator, generates a ramp with the slope proportional to the input voltage. When this ramp exceeds the threshold of gate C4a, a single-shot formed by gates C4b and C4c fires, discharging the integrating capacitor and returning the ramp to zero, at which point the process may start again. Thus a pulse train whose frequency is proportional to the input voltage is produced. This pulse train is applied to the steering network composed of gates C2 and JK flip flop C3 to produce the alternating gating signals required by the chopper.

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The pulse amplifiers, the last block in the chain, simply convert the 15 volt logic level signals into half-ampere gating pulses which may be applied to the SCR's. Pulse transformers are used to give isolation.

Commutation protection is accomplished by waiting for the last set of SCR's to turn off before gating the next set. This condition is sensed by watching the voltage across the free wheeling diode. That is, as long as the diode is reverse biased, the SCR's must still be conducting. The voltage across the diode is sensed and whenever it is positive, the VCO is inhibited by the second input to the gate C4a. The combination of the gates D1 and the comparator D2 prevent the commutation protection from operating at low current demands when generated voltage from the motor load may reverse-bias the free wheeling diode, even through current is not flowing.

The last section of the circuit is the shoot-through detector, which allows the operator to distinguish shoot-through, or commutation failure, from spurious circuit breaker trips. It operates by watching for sudden large values of input current, indicated by large voltage swings on the output of A1. This voltage is amplified by D4 and used to set latch D5 when the limit is exceeded. Once set, the latch shuts off gating signals by inhibiting the VCO, and turns on the associated panel indicator.

APPENDIX E

Mechanical Rig Description

As shown in Figure E-1, the test rig consisted of two major components, the power supply and energy absorbing unit.

The power supply consisted of a 50 HP, 1750 RPM Westinghouse AC motor driving a Westinghouse model A50J207-2 40 KVA alternator through a timing belt arrangement of 3.23 step-up ratio.

The loading rig consisted of the DC motors driving through a pair of two-inch timing belts with a 2.77 reduction into a Plint and Partners 40 HP electric dynamometer.

APPENDIX F

Sample calculation of required chopper power

Step 1: Find required motor output power and speed.
For example take 3KW (4.02 hp) and 5000 rpm.

Step 2: Locate operating point on Figure 4.1 and find corresponding efficiency, in this case 57%.
With this information find the required motor input power.

$$\text{Motor input power} = \frac{\text{motor output power}}{\text{motor efficiency}},$$

In this case 5.26 KW.

Step 3: Locate same point on Figure 4.2 and find the corresponding load impedance, in this case 0.5 ohms.

Step 4: Using the results of steps 2 and 3, find the point corresponding to this chopper output power (motor input power) and this load impedance and read the corresponding chopper efficiency, in this case 89.8%. Required chopper input power may now be computed.

$$\text{Chopper input power} = \frac{\text{chopper output power}}{\text{chopper efficiency}},$$

In this case 5.86 KW.

APPENDIX G

Average vs. RMS

Of the eight different measuring points recorded in this study, the four chopper readings posed a special problem. All of these waveforms were composed of a DC component with some amount of ripple superimposed.

Since the desired result was to measure average power, defined as

$$P_{av} = \frac{1}{T}\int_0^T V(t)I(t)dt,$$

correct measurement would have entailed multiplying the current and voltage signals with an analogue multiplier, then averaging, and finally recording.

However it was discovered that this technique was not necessary for either the input or output power. In fact simple averaging filters were sufficient.

In the case of input power measurement, input voltage may be considered constant, as actual ripple is typically in the order of five percent. Thus the power becomes,

$$P = \frac{1}{T}\int_0^T VI(t)dt$$

$$= V\frac{1}{T}\int_0^T I(t)dt.$$

That is, power is the product of voltage and average current.

Unfortunately no such simplifications could be made for the case of the output power, as can be seen in Figure 2.7a. However, ripple on the current and voltage waveforms seem to be reasonably in phase, so once again averaging and multiplying can be justified. To test this assumption, a sample waveform similar to Figure 2.7a was processed in the two different ways and the results compared. First, to find the true average power, the current and voltage were sampled at a number of points on the trace, multiplied together to give instantaneous power, and then averaged over one period. Secondly, each waveform was averaged over one cycle, and then the results multiplied. The difference between the two results, which was of the order of 0.05 percent, was considered to be negligible.