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ENERGY CONSERVATION

# FORD/D.O.E. SODIUM-SULFUR BATTERY ELECTRIC VEHICLE DEVELOPMENT AND DEMONSTRATION

Phase I, Quarterly Progress Report No. 37, December 1, 1977–February 28, 1978

Work Performed Under Contract No. EY-76-C-02-2566

MASTER

Research Staff
Ford Motor Company
Dearborn, Michigan

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

## U. S. DEPARTMENT OF ENERGY

## Division of Transportation Energy Conservation

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Phase 1
Quarterly Progress Report No. 37
December 1, 1977–February 28, 1978


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Program Manager





Contract No. EY-76-C-02-2566




Prepared For: The Department of Energy


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# LIST OF TABLES

## LIST OF FIGURES

## TASK 1. ELECTRIC VEHICLE DEVELOPMENT AND DEMONSTRATION

### A. New Concepts Research Department, Engineering and Research Staff, Ford Motor Company

During the second quarter (Dec 1977 — Feb 1978) of the Electric Vehicle Development and Demonstration Work Task, the engineering study and design activities were concentrated in the following areas:

1. NaS Cell and Battery Trade-off Studies.
2. Preliminary NaS Battery-Vehicle Packaging Studies.
3. Vehicle Performance and Economy Projections.
4. Motor/Controller Studies.

### A. 1. NaS Cell and Battery Trade-off Study Sub-Task

The NaS cell sizing and design trade-off studies initiated in the first quarter were continued and expanded during the second quarter. The Battery Design Group performed computer sizing and optimization studies to determine a preferred cell size based upon a cell design having all of the sodium stored within the ceramic electrolyte tube ($\beta$-alumina). A new design code was developed which accounts for nonuniformity of cells as well as cell connection losses and assumed modes and rates of cell failure. These assumptions are key to the computation of electrolyte tube length and diameter necessary to produce the required energy and power demands. The NaS cell computer studies assumed 70% utilization of cell reactants and pulse characteristics comparable to cells tested to date. The cell and battery design parameters are listed below:

| Single Cell | Specifications |
|---|---|
| • Electrolyte tube (length x diam.) cm. | 36 x 2.56 |
| • Total cell dimensions (length x diam.) cm. | 37 x 3.55 |
| • Weight, grams | 630 |

| Battery | Specifications |
|---|---|
| • Peak Power Rating, Kw. | 35.5 |
| • Total number of cells | 384 |
| • No. of cells in a sub-module | 8 |
| • Number of sub-modules | 48 |
| • Number of modules per battery | 4 |
| • Minimum Battery Dimensions: | |
| — Length, cm (in.) | 97.8 (38.5) |
| — Width, cm (in.) | 64.7 (25.5) |
| — Height, cm (in.) | 44.5 (17.5) |
| • Weight of cells, Kg. (lb.) | 242 (532) |
| • Estimated weight of electrical connections (@ 8% of cell wt.) Kg. (lb.) | 19.4 (43) |
| • Estimated insulation weight, Kg. (lb.) | 24.8 (55) |
| • Estimated support structure weight, Kg. (lb.) | 36.3 (80) |
| • Estimated installed battery weight, Kg. (lb.) | 322.5 (710) |

The above battery specifications were generated to meet 100 miles CVS range for a vehicle test weight of 2500 lb. Using these specifications, the preliminary battery sizing for vehicle packaging studies were conducted and are discussed in the following paragraph.

A.2. Preliminary NaS Battery-Vehicle Packaging Study Sub-Task

As discussed in the last quarterly report, preliminary vehicle packaging studies identified three possible interior volumes in which NaS cells might possibly fit, all volumes being behind the front seats as illustrated in Figure 1. The 37 cm height of the cell configuration chosen from the cell design studies, previously described, ruled against the use of the rearward volume, identified as Volume A in Figure 1. The over-all battery dimensions, which were estimated to be 39 in. (l) x 26 in. (w) x 18 in. (h), would permit vehicle packaging of the NaS battery by using portions of Volumes B and C, as shown in Figure 2. Figure 3 illustrates the general concepts of assembling clusters of cells into a vehicle battery. The individual cells are first assembled into sub-modules, with each sub-module containing 8 cells which are aligned in columns and electrically connected in parallel. Each sub-module is next assembled into a module that contains parallel columns of sub-modules which are prevented from direct electrical contact by electrical insulation separators inserted between parallel pairs of sub-modules. All sub-modules are series connected to produce a preselected design voltage level for each module. Next, each module is installed beside a battery containment structure which not only provides the first protective barrier to the clustered cells, but also serves the function of an inner

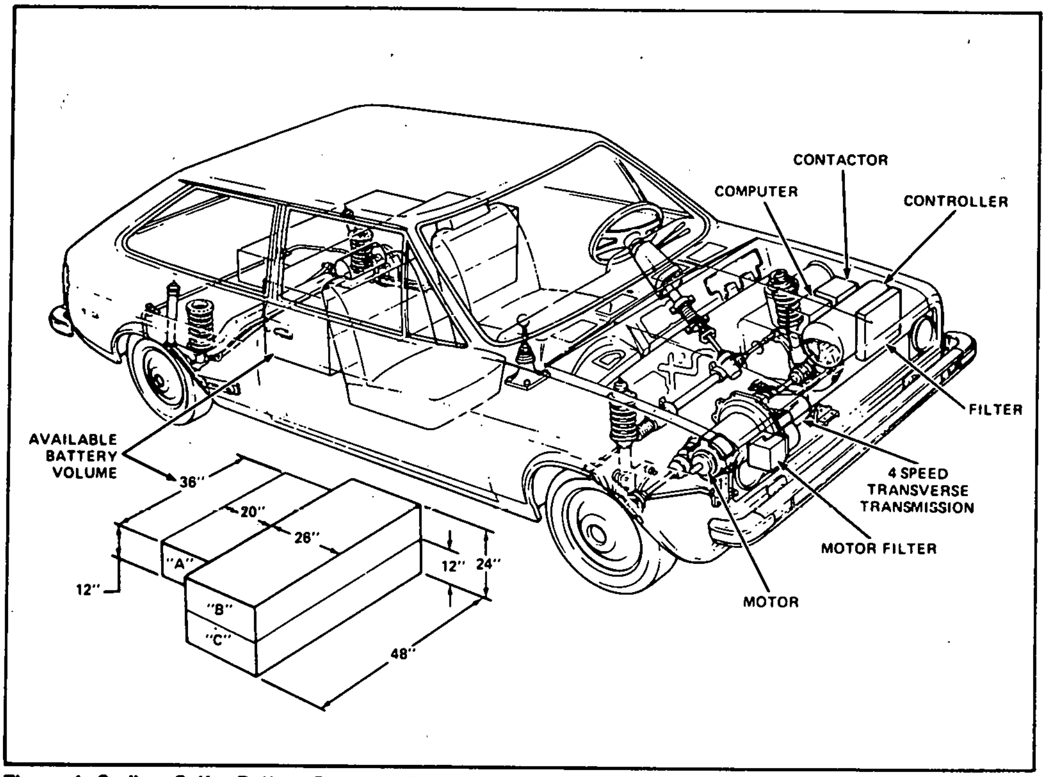


**Figure 1. Sodium-Sulfur Battery Powered Fiesta Electric Vehicle**

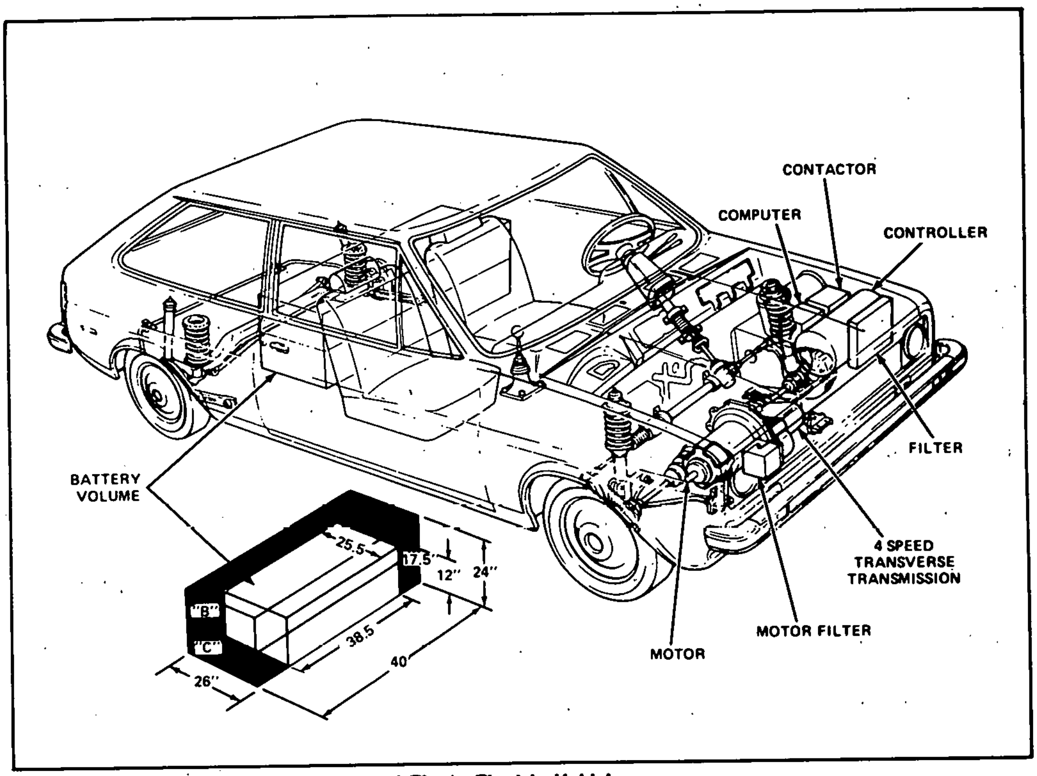


**Figure 2. Sodium-Sulfur Battery Powered Fiesta Electric Vehicle**

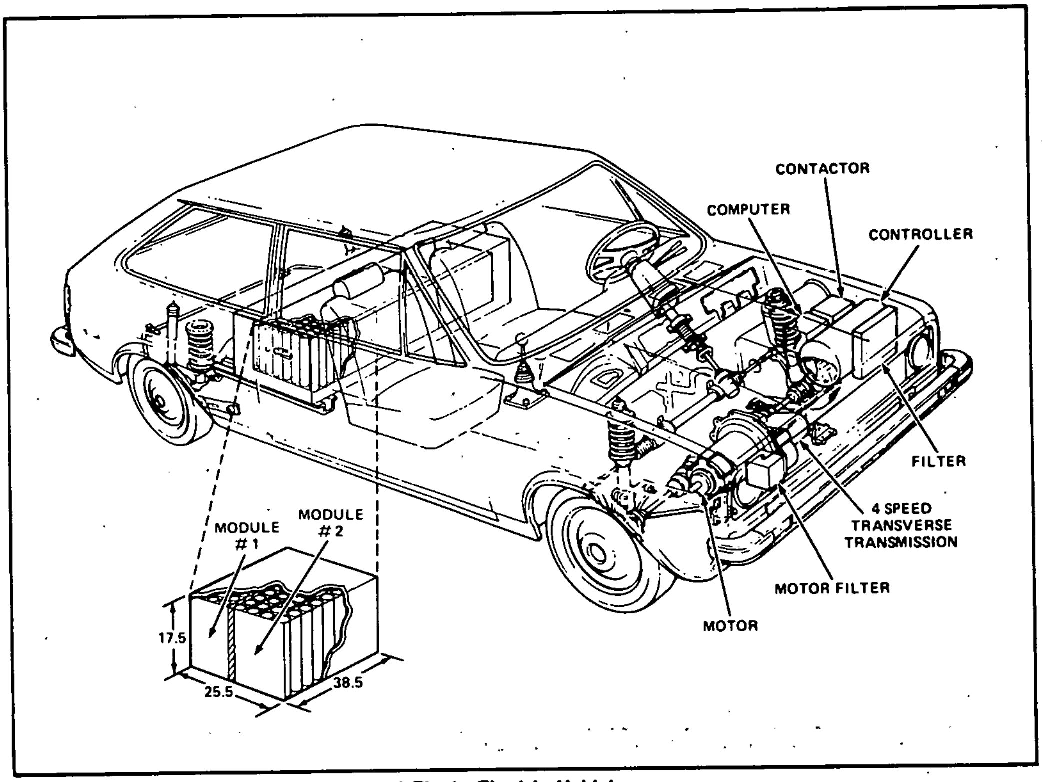


**Figure 3. Sodium-Sulfur Battery Powered Fiesta Electric Vehicle**

liner to a vacuum gap between the inner barrier and an outer protective shell. In the vacuum space between inner and outer liners, multifoil radiation and thermal conductance insulators are installed. The modules are in turn electrically insulated from one another by insulating separator sheets, as illustrated in Figure 3. By selective electrical connections and/or switching between the modules (four are presently called for), various levels of battery voltage can be provided, e.g., 24, 48 and/or 96 volts are presently being considered. Present study plans call for the conceptual design layout of various battery and container geometries which examine the following open issues:

a. Air cooling vs. liquid cooling of cells for battery thermal management.

b. No cooling provision. Power cutoff used to reduce over temperature problems.

c. Battery heating concepts, e.g., electrical resistance heating, air heating or liquid heating.

d. Cell and battery containment during vehicle impact and/or roll over.

A design study is currently in progress which will investigate the feasibility and practicality of a battery and battery containment vessel which uses air cooling and electrical resistance heaters for thermal control, multifoil super-insulation and side rail support of the battery pack in the vehicle. This work will be completed in the third quarter.

A. 3. Vehicle Performance and Economy Projection Sub-Task

The vehicle performance and economy (P&E) computer studies, initiated in the previous quarter and discussed in the last quarterly report, were continued and expanded in this quarter. Studies of battery weight requirements to achieve 100 miles over the Federal Urban Cycle (CVS) were performed for various vehicle test weights wherein the weight penalties over an equivalent ICE Fiesta ranged from 400 lbs. through 800 lbs. A sample of the results of several P&E computer

TABLE I

COMPARISON OF 198X — E.V. AND ICE "FIESTA" VEHICLE

| | 1977 FIESTA | 198X FIESTA | EV-1 KWH/MILE | EV-1 MPG | EV-2 KWH/MILE | EV-2 MPG | EV-3 KWH/MILE | EV-3 MPG | REF. EV-4 KWH/MILE | REF. EV-4 MPG | EV-5 KWH/MILE | EV-5 MPG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ECONOMY, MPG-CVS | 34 | 38.7 | .312 | 41.1 | .303 | 42.3 | .297 | 43.2 | .287 | 44.7 | .283 | 45.3 |
| -HWY | 46.8 | 51.2 | .372 | 34.5 | .367 | 34.9 | .366 | 35.0 | .358 | 35.8 | .357 | 35.9 |
| -M-H | 38.8 | 43.9 | .366 | 38.2 | .329 | 39.0 | .325 | 39.5 | .315 | 40.7 | .312 | 41.1 |
| RANGE (MILE) - CVS | 340 | 136.6 | 101.41 | | 102.64 | | 100.04 | | 102.76 | | 93.48 | |
| - HWY | 460 | 180.7 | 84.99 | | 84.77 | | 81.29 | | 82.38 | | 74.15 | |
| - M-H | 385 | 154 | 93.39 | | 93.39 | | 90.61 | | 92.06 | | 83.55 | |
| ACCELERATION TIME (SEC.) 0-50 MPH | 8.8 | 11.7 | 11.81 | | 11.53 | | 11.62 | | 11.12 | | 11.96 | |
| WEIGHTS - CURB (LBS.) | 1760 | 1666 | 2466 | | 2366 | | 2266 | | 2166 | | 2066 | |
| - TEST (LBS.) | 2060 | 1966 | 2766 | | 2666 | | 2566 | | 2466 | | 2366 | |
| EV WEIGHT PENALTY (LBS) | - | - | 800 | | 700 | | 600 | | 500 | | 400 | |
| BATTERY — % TEST WEIGHT | - | - | 24.95 | | 25.51 | | 25.33 | | 26.16 | | 24.52 | |
| — KW (F=0) | - | - | 40.59 | | 40.0 | | 38.23 | | 37.94 | | 34.0 | |
| — KWH (C20) | - | - | 33.28 | | 32.73 | | 31.30 | | 31.10 | | 27.9 | |
| — POWER DENS. (W/LB.) | - | - | 58.82 | | 58.82 | | 58.82 | | 58.82 | | 58.61 | |
| — REQ'D BAT. KWH: CVS- | - | - | 27.78 | | 27.32 | | 26.13 | | 25.96 | | 23.29 | |
| HWY- | - | - | 27.78 | | 27.32 | | 26.13 | | 25.96 | | 23.29 | |
| — REQ'D BAT. KW: CVS- | - | - | 38.40 | | 37.09 | | 35.77 | | 34.45 | | 33.16 | |
| HWY- | - | - | 34.14 | | 33.12 | | 32.22 | | 31.16 | | 30.49 | |
| ENGINE — DISPLACEMENT | 1.6 | 1.1 | - | | - | | - | | - | | - | |
| — POWER | 66HP | 50 HP | - | | - | | - | | - | | - | |
| MOTOR — HP MAX (1 MIN RATING) | | | 70.64 | | 70.64 | | 70.64 | | 70.64 | | 70.64 | |
| — HP CONT. | | | 28.26 | | 28.26 | | 28.26 | | 28.26 | | 28.26 | |
| AVAIL. WEIGHT OF EV PROPULSION SYSTEM:* | - | - | 1186 | | 1086 | | 986 | | 886 | | 786 | |
| — BATTERY WT. (LBS.) | - | - | 690 | | 680 | | 650 | | 645 | | 580 | |
| — MOTOR-CONTROLLER WT. (LBS) | - | - | 206 | | 206 | | 206 | | 206 | | 206 | |
| — AVAIL. STRUCTURE/COMPONENT WEIGHT (LBS.) | - | - | 290 | | 200 | | 130 | | 35 | | 0 | |

1. VEHICLE BASE WT. = 1280 LBS.
2. PAYLOAD = 300 LBS.
3. ALL EV'S HAVE 4-SPD. MAN. TRANS. WITH 1ST THROUGH 4TH GEAR RATIOS OF 3.58, 2.06, 1.29, AND 1.00 AT N/V = 56.8
4. ONE (1) KWH = .078 GAL. OF GASOLINE
5. SHIFT SPEEDS *: 1ST-2D; 37 MPH;2D-3RD; 44 MPH; 3RD-4th: 54 MPH

analyses is presented in Table I. In addition to identifying battery weight requirements, the weight allowance for battery support structure, electrical connectors and instrumentation were also of interest. As can be seen in Table I, for the battery power density assumed (58.82 w/lb.), the reference NaS powered EV Fiesta (EV-4 in Table I) requires 645 lbs. of NaS battery (clustered cells) which only allows 35 lbs. of weight for structure and miscellaneous components. To obtain sufficient weight allowance for the battery container, insulation, supporting brackets, etc., which is estimated to be no less than 150 lbs., would require a relaxation in the 500 lb. weight penalty limit previously established as a marketing objective. A vehicle having a test weight in the range of 2666 lbs., i.e., EV-2 in Table I, would be required to allow a 200 lb. weight allowance for structure, components and other miscellaneous items, unless the battery cell weight can be reduced by virtue of cell performance improvements which would permit cell and/or clustered cell modular power densities in the neighborhood of 79 watts/lb.

The P & E battery weight is approximately 12% heavier than the battery generated from the cell sizing studies (645 lb. vs. 575 lb.). The difference is the result of the following:

- In order to meet CVS acceleration demands the battery needs to supply 38 kw, whereas the cell sizing assumed a peak power of 35.5 kw. Therefore, a 7% increase in battery weight is required for CVS driving.
- An assumed power density of 59 W/LB was used in the P & E studies whereas the cell sizing study assumed a power density of 62 W/LB, which accounts for a difference of 5% in battery wt.

Further P&E studies are planned to:

a. Evaluate range and wide open throttle (WOT) performance for new updated Fiesta weights which have been received recently from the Fiesta Vehicle Office.

b. Evaluate Fiesta EV performance in driving cycles other than Federal Metro (CVS) and Highway, e.g., SAE, Taxi, and UPS.

A. 4. <u>Motor/Controller Study Sub-Task</u>

The goals for the motor/controller phase of the NaS vehicle development were finalized and include:

1. Preparation of a comparative evaluation of candidate motor/controller systems suitable for use with a NaS battery and constructed of "State-of-Art" components.
2. Compare candidate systems in terms of technical performance, initial cost, energy efficiency, system weight, and relative reliability.
3. Describe technical and economic problems of candidate systems when used in a marketable vehicle.
4. Choose the optimum type of motor/controller.
5. Prepare a detailed design for the chosen motor/controller.
6. Obtain current cost and delivery estimates for all components in the chosen system.
7. Obtain a motor suitable for use in the prototype NaS car.
8. Prepare weight and volume estimates of the chosen system for use in the NaS car packaging studies.

(a) <u>Types of Motor/Controller Systems</u>

A great many motor and controls systems have been proposed for use in EV's. These may be divided into two general classifications, conventional and brushless. The conventional systems make use of a DC commutator motor and have been used in almost all electric vehicles and mass transit systems built up to this time. Brushless systems use the so-called "AC motors" and except for systems based upon the slip-ring induction motor, are relatively recent developments. The conventional systems vary in complexity from the simple resistance/contactor systems used in streetcars to very sophisticated electronic control schemes. Brushless systems are generally more complex and more costly than most of the conventional systems, but offer the promise of very low system maintenance by eliminating the mechanical brush-commutator system and by the use of motors with much simpler electromagnetic structures and much lower specific weights. A number of brushless systems using both induction and synchronous motors have operated in experimental vehicles and trains, but, as far as is known, there is no commercial application at the present time of brushless drivetrains. Although there have been numerous examples of brushless systems using squirrel-cage induction motors (e.g., the GM Electrovaire, the Garrett BART locomotive), synchronous machines offer certain efficiency, weight, and control advantages. Therefore it was decided to evaluate only the synchronous motor class of brushless systems. There is a third category of machines that is often proposed for EV applications which does not generically fall into either conventional or brushless categories; namely, the DC homopolar or acyclic machine. This is the only true DC machine (the commutator machines have voltages and currents internally) and requires slip rings instead of the brush/commutator system of the conventional motor. It was evaluated extensively by Ford Motor Company in the 1960's and was found to have good properties for traction applications. Therefore, it will be included in the evaluation.

The types of motor/controller systems to be evaluated during the course of this study are shown in Table II. Partial evaluation of several of these systems have been made during this reporting period and Table III presents a preliminary, qualitative summary of this evaluation. The contactor/field controller has been selected as the reference against which the other concepts have been evaluated.

(b) Electronic Controllers

One of the most significant parameters in the evaluation of EV motor/controller systems is the projected costs of the power semiconductors

TABLE II

CANDIDATE EV DRIVETRAINS

| | MOTOR | CONTROL | TRANSMISSION |
|---|---|---|---|
| A. | Conventional | | |
| | 1. DC — Shunt | Contactor/Field | Yes |
| | 2. DC — Shunt | Arm. Chopper/Field | Optional |
| | 3. DC — Series | Chopper | Optional |
| | 4. DC — Series | Electromechanical | Optional |
| B. | Brushless | | |
| | 5. AC — Synchronous | Inverter | Optional |
| | 6. Disc | Pulse | Yes |
| C. | Homopolar | Electronic | No |

TABLE III

PRELIMINARY EVALUATION OF MOTOR/CONTROLLER CANDIDATES FOR EV's

| CONTROLLER | MOTOR | INITIAL COST | SYSTEM WT. | AVE. EFF | COMPLEXITY SCALE BASE REF. = 1.0 |
|---|---|---|---|---|---|
| CONTACTOR/FIELD | SHUNT DC | 1.0 | 1.0 | AVE. | 1.0 |
| ARM./FIELD | SHUNT DC | 1.5 | 1.2 | GOOD | 1.5 |
| CHOPPER | SERIES DC | 1.2 | 1.2 | AVE. | 1.5 |
| INVERTER | SYNCH. AC | 2.5 | 0.9 | HIGHEST | 2.0 |
| CHOPPER | DISC | 1.2 | 0.8 | GOOD | 1.5 |

required in electronic motor control schemes. There are many desirable features of electronic control in both conventional and brushless systems, e.g., continuously-variable speed and torque control, relatively light weight, high energy efficiency, ease of maintenance, small volume, and (in some systems) very high reliability and long operating lifetime. The brushless systems all require various levels of high-power semiconductor circuitry. An advantage of the brushless systems is that regenerative braking is usually an inherent property of the control circuitry even if designed only for motoring operation, which is not the case for the conventional electronic controllers. In these controllers, the ability to supply control during regenerative braking generally doubles the number of power semiconductors required as compared to a controller for motoring operation only. The potential feasibility of electronic control for the NaS car (and in EV's in general) is primarily a question of the expected costs of power semiconductors. Power semiconductors have been used for many years in the control of motor speed and torque in industrial applications, and there is little doubt of the technical merits of these systems, both in conventional and brushless systems. In 1972, an extensive study of EV motors and controllers was made by the Ford Scientific Research Staff and published as "The Electric Vehicle Systems Study". This was the first effort to predict costs of EV's and to compare them with ICE vehicle costs. A major portion of the economic studies contained in this report was devoted to the prediction of power semiconductor costs, and this was done with considerable aid from the General Electric Co. and the (then) Ford-Philco Division. A summary of projected motor controller costs is shown in Table IV. The cost reduction of SCR's predicted in 1972 study have not materialized

TABLE IV

SUMMARY OF OEM COSTS OF MAJOR COMPONENTS AND SUBSYSTEMS OF VARIOUS POWER CONTROLLERS

| Type of Controller | Required Components | OEM COSTS 1975 Price 10,000 Units | OEM COSTS 1975 Price 1 Million Units |
|---|---|---|---|
| DC Chopper for 40 hp D. C. Motor without regeneration. | SCRs | | |
| | 2 ea C 394 | 2 x $33 = $ 66 | 2 x $17 = $ 34 |
| | 1 ea C 398 | 1 x $36 = $ 36 | 1 x $18 = $ 18 |
| | 1 ea C 385 | 1 x $17 = $ 17 | 1 x $ 9 = $ 9 |
| | Diodes | | |
| | 2 ea A396 | 2 x $10 = $ 20 | 2 x $ 4 = $ 8 |
| | Commutating Capacitor | | |
| | 1 ea 500μfd at 200 VDC | 1 x $36 = $ 36 | 1 x $15 = $ 15 |
| | Logic and peripheral system. | $ 29 | $ 20 |
| | TOTAL COST | $204 | $104 |
| Modulating inverter for 115 hp induction motor without regeneration. | SCRs | | |
| | 6 ea C 398 | 6 x $41 = $246 | 6 x $20 = $120 |
| | 12 ea C 380 | 12 x $24 = $288 | 12 x $12 = $144 |
| | Diodes | | |
| | 6 ea A 396 | 6 x $12 = $ 72 | 6 x $ 6 = $ 36 |
| | Commutating Capacitor | | |
| | 1 ea 100μfd | 1 x $60 = $ 60 | 1 x $30 = $ 30 |
| | Logic and peripheral system | $110 | $ 69 |
| | TOTAL COST | $776 | $399 |
| Parallel controller for 40 hp disc motor (3 phase, includes regeneration) | SCRs | | |
| | 6 ea C 394 | 6 x $33 = $198 | 6 x $17 = $102 |
| | 6 ea C 385 | 6 x $17 = $102 | 6 x $ 9 = $ 54 |
| | Diodes | | |
| | 3 ea A 396 | 3 x $10 = $ 30 | 3 x $ 4 = $ 12 |
| | Commutating Capacitor | | |
| | 3 ea 40μfd at 600 VDC | 3 x $18 = $ 54 | 3 x $ 8 = $ 24 |
| | Logic and peripheral system | $ 75 | $ 46 |
| | TOTAL COST | $459 | $238 |

TABLE IV

SUMMARY OF OEM COSTS OF MAJOR COMPONENTS AND SUBSYSTEMS OF VARIOUS POWER CONTROLLERS

| Type of Controller | Required Components | OEM COSTS 1975 Price 10,000 Units | 1975 Price 1 Million Units |
|---|---|---|---|
| Series controller for 40 hp disc motor (3 phase, includes regeneration) | SCRs | | |
| | 6 ea C 508 | 6 x $30 = $180 | 6 x $16 = $ 96 |
| | 6 ea C 385 | 6 x $17 = $102 | 6 x $ 9 = $ 54 |
| | Series Capacitor | | |
| | 3 ea 135$\mu$fd at 600 VDC | 3 x $28 = $ 84 | 3 x $12 = $ 38 |
| | Logic and peripheral system | $ 75 | $ 46 |
| | TOTAL COST | $441 | $232 |
| Additional requirements to provide regeneration in DC chopper for 40 hp DC motor | SCRs | | |
| | 4 ea C 501 | 4 x $26 = $104 | 4 x $15 = $ 60 |
| | Diodes | | |
| | 4 ea A 390 | 4 x $ 9 = $ 36 | 4 x $ 4 = $ 16 |
| | Additional Logic | $ 25 | $ 15 |
| | Sub-total | $165 | $ 91 |
| | Cost of Basic Chopper | + 204 | + 104 |
| | TOTAL COST | $369 | $195 |

and, at the present time, large volume price predictions are considerably higher than those shown in Table IV even when inflationary effects have been eliminated. Therefore, Table IV represents a long range projection, and there is no indication, at the present time, that these projections will be realized in the near future. Therefore, Table IV tends to direct the EV controller design choice towards systems that minimize the number of high power semiconductors required, and this trend is greatly accelerated if the energy savings of regenerative braking are to be achieved. This consideration has probably been the dominant influence on the course of this study of motors and controls for the NaS car. However, a considerable effort has been made to study recent developments in high power semiconductors and to compare the technical merits of the electronic controllers with those of the controllers not containing power semiconductors.

Table V lists a number of controllers available for the control of conventional systems. These are usually called "choppers", and are widely used in industrial motor control, golf carts, industrial EV's, and in both the BART and the Japanese Tokyo trains. Chopper armature controllers also have the potential for eliminating the need for a mechanical transmission in an EV, although this results in a considerable penalty in motor and controller size and weight and, possibly, battery weight, and therefore may not result in a lower weight drivetrain. The most hopeful area of chopper controller development is in the power transistor or Darlington semiconductors. These are now being developed for the current and voltage ratings

TABLE V

CHOPPERS FOR EV APPLICATIONS

| | |
|---|---|
| A. SCR — NON REGENERATIVE | B. SCR — REGENERATIVE |
| 1. MORGAN | 1. REVANKAR AND PALSETIA |
| 2. JONES | 2. BERMAN (TRW) |
| 3. FULL SCR (CORTINA) | 3. CABLEFORM |
| 4. DALE — LACE | C. POWER TRANSISTOR |
| 5. SERIES | D. POWER DARLINGTON |
| 6. MULTI — PHASE | |

needed for EV motor control and provide several advantages over the SCR choppers, e.g., elimination of the complicated communication circuitry, higher operating efficiency, and greatly reduced volume. However, at the present time, transistors are very costly, and there is almost no data available to reliably predict future cost trends of these devices. Three high-current transistors have been recently developed for EV applications, and these are summarized in Table VI.

(c) Motor Analysis

The economic aspects of control systems has led this study to the contactor/field type of control of a conventional motor as the prime candidate for the NaS car. This conclusion has been substantiated by many other investigators, including most of the papers and their discussors at the present SAE Convention in Detroit, February 27 — March 3, 1978. As a result, most of the motor evaluation in this NaS Car Study has been related to motors adaptable to this type of control. Potential "State-of-Art" motors for this application are summarized in Table VII. It should be noted that although there are many other motors with suitable technical characteristics for the NaS vehicle

TABLE VI

HIGH CURRENT TRANSISTORS FOR EV APPLICATIONS

| | Toshiba | RPM | GE |
|---|---|---|---|
| Max. voltage ($V_{ceo}$) | 300 | 120 | 400 |
| Max. DC Current ($I_{c-ave}$) | 400 | 200 | 350 |
| Current Gain ($h_{FE}$) | 100 ($I_c$ = 400) | 1000 ($I_c$ = 200) | ≈ 5000 |
| Power ($P_T$) | 2500 | 500 | ? |
| Pulse Frequency | 0.3 MHz | ? | 1.0 MHZ |

## TABLE VII

## DC COMMUTATOR METERS FOR POTENTIAL EV APPLICATION

| Designation | Wt. (lbs) | Tmax (ft-lb) (one-minute) | Break Speed (RPM) | Max Speed (RPM) | H.P. @ Brk. RPM (one-minute) | Volts |
|---|---|---|---|---|---|---|
| GE — Cortina * | 150 | 106 | 6000 | 10000 | 121. | 106 |
| GE — Erie | 140 | 52 | 1800 | 6000 | 17.8 | 48 |
| GE — Fort Wayne | 75 | 42 | 2200 | 7500 | 17.6 | 48 |
| Jack & Heintz | 65 | 58 | 1800 | 7000 | 10.8 | 48 |
| Garrett/Airesearch | 105 | 44 | 3200 | 10000 | 26.8 | 106 |

* Special Model No. MB48-1038

applications, they have either excessive weight or high cost projections. Also, there are specialty motors made by other manufacturers not shown in Table VII which essentially duplicate the characteristics shown.

The analysis of motors has been aided by several previously Ford developed proprietary digital computer programs. These are:

1. DCMACH. BAS, a relatively simple DC commutator motor design program. The motor is designed on the basis of required speed range, torque, and type of motor control.

2. FLD. BAS, a program to calculate the current, torque, efficiency and many other motor parameters of a motor controlled by the contractor/field control system from a battery source.

3. GESHUN. F4, a motor performance calculation program based upon the original design calculations for the GE Cortina motor (# 1 in Table VII).

4. D2.F4: This is the main EV design and analysis program used at Ford for both performance projections and design analysis of EV's. It was one of the first EV design programs developed and is described in "Electric Vehicle Systems Study" and Reference 1. This program has been modified and improved in many respects during the course of this study.

(d) Drive Scenarios

Drive scenarios have been prepared for four types of conventional motor/controller systems. Drive scenarios describe the vehicle operator functions required for normal and abnormal vehicle operating modes, and the vehicle response to the operator functions. The scenarios developed as of this time are:

1. contactor/field control system with manual transmission
2. contactor/field control system with automatic transmission
3. armature chopper/field control system with manual transmission
4. the Cableform control system for a series motor with no transmission

Also, motor operation in all possible operating modes have been described for both the series and separately excited motors. The principal difference among the above four systems in terms of vehicle driveability is in the transition from driving to braking operations. In the separately-excited motor systems (the first three above), this transition occurs smoothly with no time delays. In series motor systems, the transition is discontinuous and requires some time delay. It should also be noted that in the third system above, smooth regenerative braking control is achieved at a very high cost in power semiconductors and chopper complexity.

(e) Potential Systems For The NaS Car

There are two major merits of armature contactor-field chopper type of motor control for electric vehicle applications; namely, (1) low cost since no high power semiconductors are required, which may eventually permit EV's to be commercially marketable; and (2) excellent characteristics in regenerative braking operations which will permit good energy efficiency — another probable requirement of future vehicles. Therefore, this system has been chosen as the most preferred for the NaS car, although this decision is not final and will be continuously re-evaluated as the comparative evaluation of motor/controller systems proceeds in more detail. There is one other system that has potential for both low initial cost and good regenerative performance, and that is the Disc Motor system. However, this is not a "State-of-Art" system and cannot be considered for near term vehicles. The merits and problems of the contactor/field type of control are summarized in Table VIII.

The motor chosen for use in the NaS car is the GE Cortina motor. This motor is so named since it was used in the Ford Cortina electric car conversion of the 1960's. The motor is larger than required for a Fiesta size vehicle, but it is felt that, in a prototype vehicle which is to be used for many types of tests, it is wise to start out with some extra capacity. Also, the characteristics of this motor are well defined from tests performed during the Cortina conversion,

TABLE VIII

CONTACTOR/FIELD CONTROL

ADVANTAGES

NO HIGH — POWER SEMICONDUCTORS

— MINIMUM COST

— MINIMUM WEIGHT

— MINIMUM AUXILIARY COOLING

- EASE OF REGENERATION
- STEADY DC IN BATTERY

PROBLEMS

- CONTROL OVER A LIMITED SPEED RANGE
- LESS EFFICIENT AT LOW MOTOR SPEEDS
- MAY REQUIRE STARTING RESISTOR

there are two motors on hand from which packaging information can be obtained, and the characteristics of this motor have been the basis for much of the EV analysis at Ford in past years. But most important of all, the Cortina motor is a high quality motor that was specifically designed for EV applications (it was used in the Autolite "Lead Wedge" vehicle as well as the Cortina), and there is no other DC motor presently available with as good characteristics as this machine.

Figure 4 is a schematic diagram of the control system; the simplicity of the power circuit is evident from this diagram. The required control signals are also shown. Figures 5 and 6 illustrated some of the calculated motor control characteristics. The smooth transition between motor and generator operation is illustrated in Figure 7.

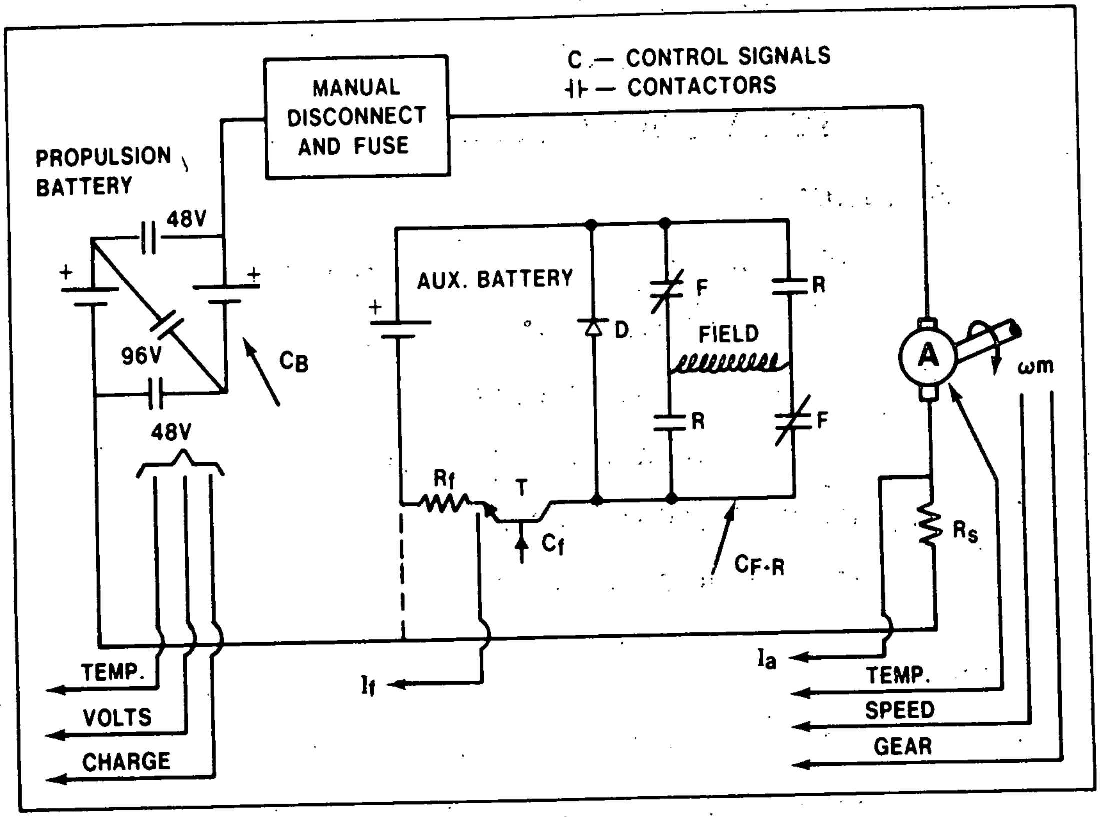


Figure 4. Field Control — Contactor Motor Control

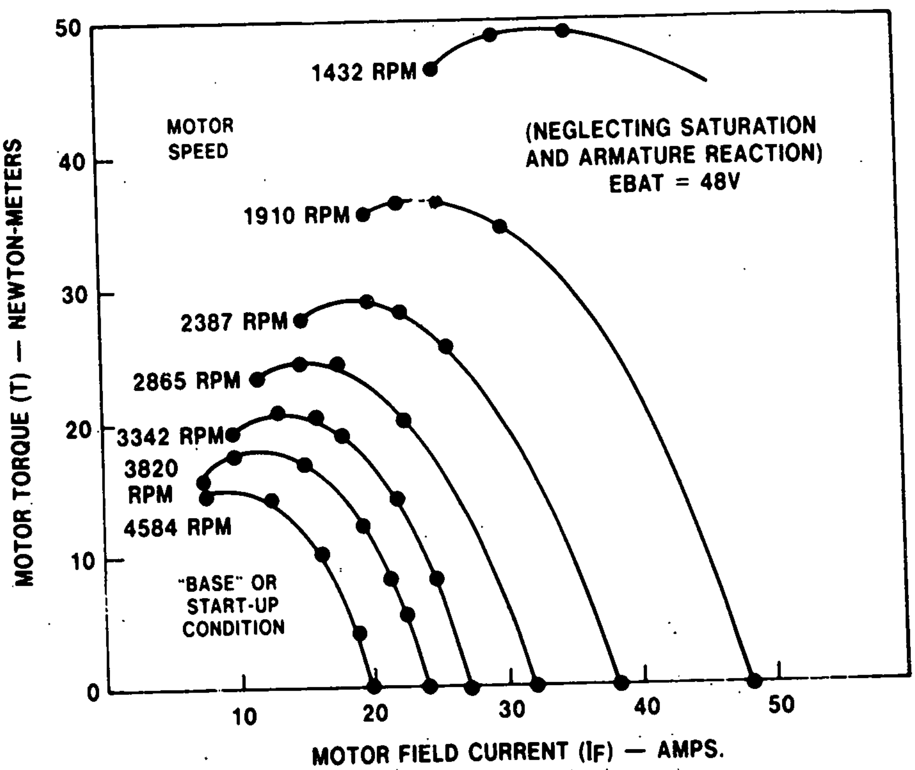


Figure 5. Cortina Motor — Motor Torque (T) vs. Field Current (If)

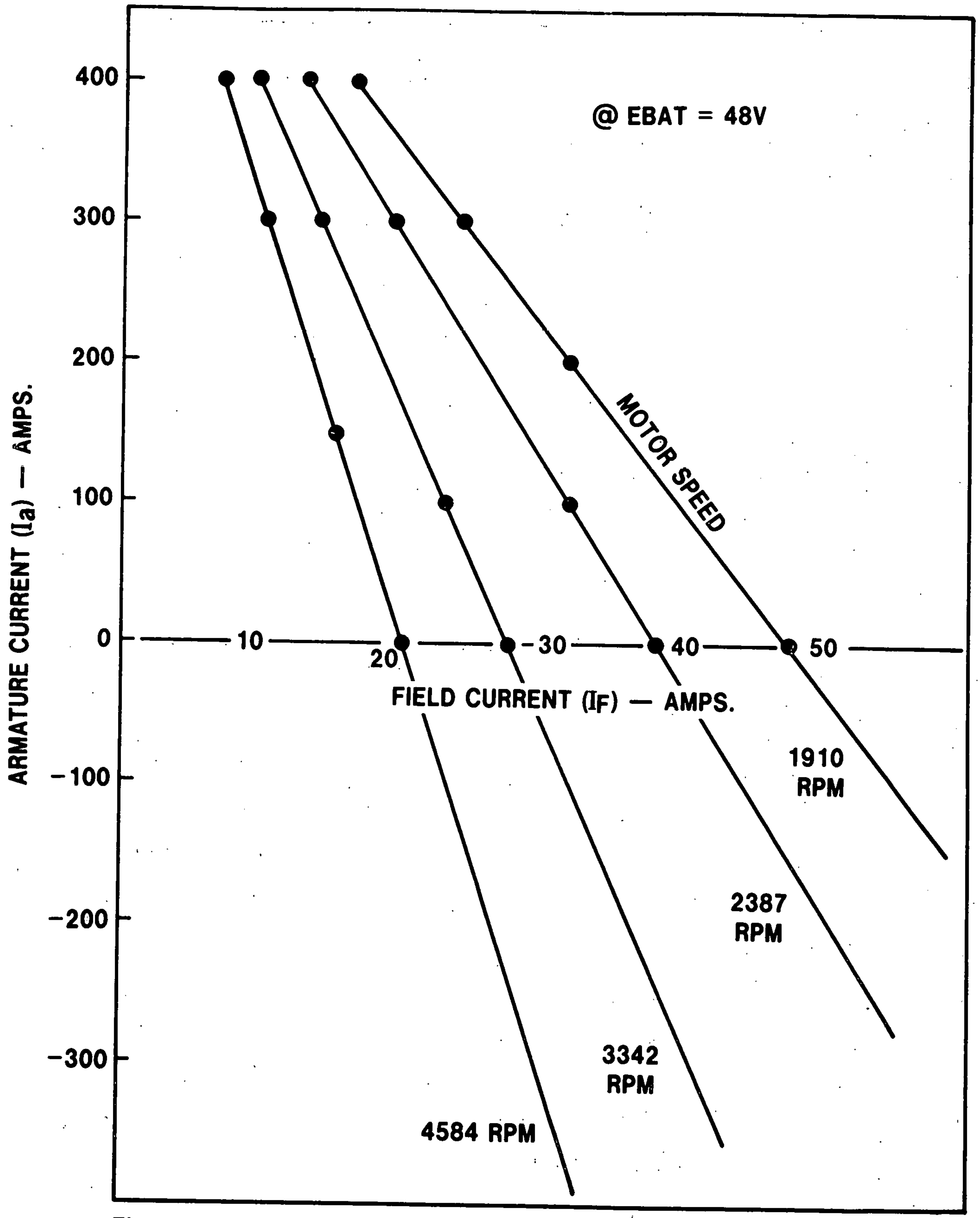


**Figure 6. Cortina Motor — Armature Current ($I_a$) vs. Field Current ($I_f$)**

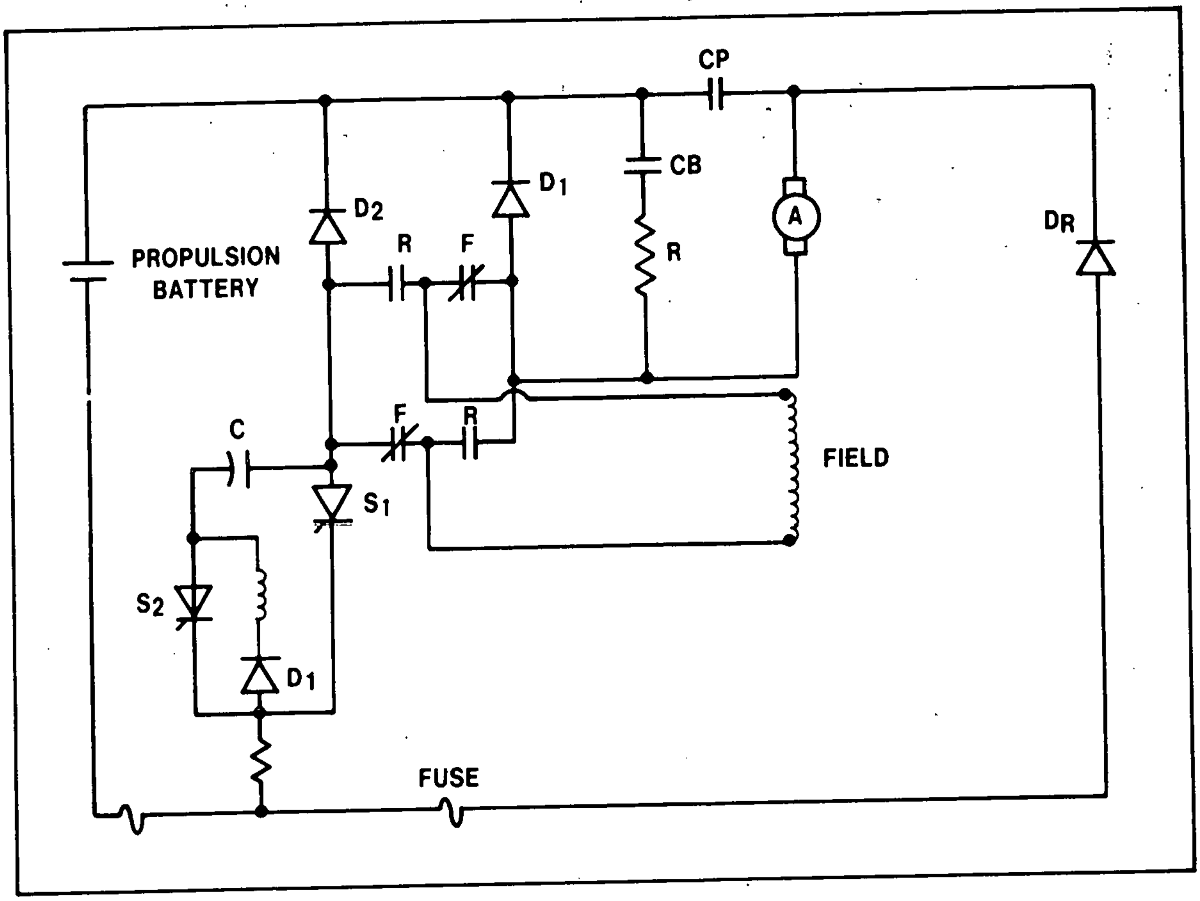


Figure 7. Cable Form — Series Motor Controller

For comparison purposes, Figure 7 illustrates the circuitry for a series motor with chopper control. This is a commercial system manufactured by Cableform Ltd., and is widely used on electric milk delivery trucks, golf carts, and industrial trucks. This is a regenerative system and requires two high power SCR's ($S_1$ and $S_2$) and four power diodes, as well as several contractors.

A preliminary weight estimates for the proposed contractor/field controller has been made:

| | |
|---|---|
| battery contactors | 4.5 kg |
| forward/reverse contactors | 3.2 kg |
| transistor and heat sink | 2. |
| diode and heat sink | 1. |
| logic box | 4.5 |
| blower | 2. |
| miscellaneous | 2.5 |
| | 19.7 kg |

A final weight of approximately 20 kg or 45 lbs is envisioned.

In contactor/field type of motor control, a mechanical transmission is almost essential. This may be either a manual or automatic transmission. In most other types of control systems, a transmission is also desirable, although not necessary. The principal merits of the use of mechanical transmissions in EV's are summarized in Table IX.

TABLE IX

MECHANICAL TRANSMISSIONS ADVANTAGES

- Greatly Reduces Required Speed Range of Drive Motor
- Greatly Increases Low-Speed Acceleration of EV
- Reduces Power Rating of Controller
- Permits Use of Low-Cost Electric Controllers
- Permits Optimizing Control Strategy for Fuel Economy
- Manual Transmission Desirable for Fuel Economy