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A microprocessor based control system for an electric vehicle

Ronald C. Moffatt

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A MICROPROCESSOR BASED CONTROL SYSTEM
FOR AN ELECTRIC VEHICLE

by

Ronald C. Moffatt

A Thesis Submitted
in
Partial Fulfillment
of the
Requirements for the degree of
MASTERS OF SCIENCE
in
Electrical Engineering

Approved by:

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(thesis advisor)

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DEPARTMENT OF ELECTRICAL ENGINEERING
ROCHESTER INSTITUTE OF TECHNOLOGY
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ABSTRACT

The control system described in this thesis is a low cost system designed to control the speed of an electric vehicle by adjusting the speed of a compound wound DC motor. The speed control method developed in this system is a combination of battery tapping, for control of the armature voltage, and pulse width modulation for field control; both generated by a microprocessor. Using a microprocessor, the control system is readily adaptable to a variety of motor voltages and motor control techniques by modifying the internal firmware of the processor.

Overcurrent protection is included to prolong battery and motor life. Regenerative braking is automatic upon release of the accelerator and has two levels for maximum energy recovery.

A display of the remaining charge in the vehicle's batteries has a continually powered memory to retain the information when the vehicle is parked. This display is also temperature compensated to reflect the characteristics of lead acid batteries over varying temperatures.

The control system was installed in a test vehicle where it was debugged and evaluated.
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I. INTRODUCTION

Although receiving considerable attention recently, electric vehicles are by no means new. They were commercially produced as early as 1894 and at the turn of the century, over 25 different companies were producing electrically powered vehicles.¹ This represented 38% of the total number of vehicles on the road.²

The early electric vehicles (EV's) boasted top speeds of 15 to 30 miles per hour and travel distances between charges of 30 to 60 miles depending on the vehicle size.³ Most utilized series wound motors of single digit horsepower with chain or gear drive. The control systems were simple on/off arrangements, although some placed resistors in series with the motors to reduce the startup jerk.⁴ These resistors were then shorted out progressively to increase the vehicles speed.

By 1930, production of road worthy EV's had ceased due to the slow speed of the vehicle and its limited travel range (as compared to the improved gasoline powered vehicles).⁵ The renewed interest in the electric vehicle occurred in the early '70's when availability of gasoline and environmental concerns began a search for an alternate fuel. These new generation EV's had characteristics almost identical with their ancestors. Even today, commercially
I. INTRODUCTION (continued)

produced EV's show little improvement in their speed, range, or control systems.\textsuperscript{6} This last area is the topic dealt with in this thesis; The speed control of a pure electric vehicle, using a state of the art control system.
II. THE CONTROL SYSTEM FOR AN ELECTRIC VEHICLE

A. WHAT NEEDS TO BE CONTROLLED?

The area of interest has been limited to varying the motor speed while leaving the transmission ratios of the vehicle constant. Additionally, the topic is confined to the pure electric vehicle. This is one that does not carry any active generation equipment, such as a gas powered alternator, on board.

The form of motor speed control used is dependent on the motor type. Alternating current motors require variation of both the applied voltage and frequency to change the motor speed, whereas direct current motors require only variation of the voltage. AC motors are seldom used in EV's due to the complexity of generating a sinusoidal AC voltage from batteries while maintaining reasonable efficiency.

There are three types of DC motors to be considered for use in an electric vehicle. They are:

1. Series
2. Shunt (self or separately excited)
3. Compound

Historically, the series motor has enjoyed the greatest
II. A (continued)

popularity due to its high starting torque\textsuperscript{8}. Figure 1 illustrates the three motor types schematically along with their corresponding speed/torque curves.\textsuperscript{9} Note the rapid increase in torque exhibited by a series motor as compared to the shunt motor. The compound motor exhibits restrained characteristics of the other two types.

There are two ways to vary the speed of a DC motor.

1. Vary the armature current (used to control the motor below its rated speed)
2. Vary the field strength (used to control the motor above its rated speed)

The armature control techniques are similar for all three motor types as the armature currents for comparably sized motors are about the same. The series motor has a field current equal to the armature current so its field control circuitry must be capable of handling these large
FIGURE 1
DC MOTOR TYPES & CHARACTERISTICS

a) SERIES

b) SHUNT

c) COMPOUND
II. A (continued)

currents. A shunt motor typically has a high resistance field, drawing less than 5% of the total motor current.\textsuperscript{10} This allows a reduction in the size of the field control components. However, from Figure 1, the starting torque of this type of motor is less suitable for the start and stop environment of an electric vehicle. A good compromise is the compound wound motor. It offers a high starting torque (although not as great as a series motor) and has a second high resistance field allowing simplified motor control. The penalty is a higher motor cost due to the two separate field windings.

As the motor increases in speed, the armature generates a back electro-motive force (EMF) which opposes the applied voltage.\textsuperscript{11} Hence, the motor armature current decreases to a value proportional to the load. If while under constant load the field strength is increased, the generated EMF also increases, thereby decreasing the armature current further. Therefore the armature is not required to turn as fast to produce the same back EMF (i.e. the motor speed, assuming a constant load, will decrease). If the field strength is increased to the point where the generated EMF exceeds the applied armature voltage, the armature current reverses direction and the motor acts as a generator.
II. A (continued)

supplying power back to the source. It is this mechanism that is exploited in the inclusion of regenerative braking in an electric vehicle. The power delivered to the source is extracted from the kinetic energy of the load, in this case the vehicle, with the net result being a decrease in the energy of the load (slowing of the vehicle).

In a series motor, as the armature current decreases, the field strength will also decrease. A decreasing field strength requires a higher armature speed to maintain the back EMF. At no load, the motor speed would theoretically have to approach infinity. This overspeed condition is one reason series motor powered vehicles utilize direct drive from the motor to the wheels, as the motor would be destroyed if allowed to run unloaded.

In a shunt motor, the field strength is unaffected by the motor load and results in a constant speed motor, even with widely varying loads. The compound motor, due to its dual fields, has a speed that varies with load although not as severly as the series motor. In addition, its shunt winding allows easy application of regenerative braking.

Summarizing, for the control system, it is desirable
II. A (continued)

to control both field strength and armature current for greatest range of motor speed and the added benefit of regenerative braking. The compound motor is a good compromise when choosing a motor for an electric vehicle.
II. THE CONTROL SYSTEM FOR AN ELECTRIC VEHICLE
(continued)

B. TECHNIQUES FOR MOTOR CONTROL

To vary the vehicle speed, it is sufficient to control the armature and field voltage of the motor. There are several techniques that can be used to achieve voltage control. They are:

1. insertion of a series resistance
2. battery tapping
3. pulse width modulation

Figure 2 illustrates these techniques applied to both armature and field control of a compound motor.

The smoothest control is obtained by the continuously adjustable pulse width modulation technique (PWM). In a PWM system, the voltage is turned on and off at a high rate (typically 200 hz.) with varying duty cycles. The average voltage seen by the motor is determined by the duty cycle and determines the motor speed. An SCR or transistor is used for the switching element. The main disadvantage in a system of this type is cost. A large amount of power must be controlled in an electric vehicle. Startup currents (i.e. when vehicle is initially at rest) can range as high as 600 amps. Semiconductors able to handle this amount of current are presently very expensive. Additionally, in a PWM system, although the average currents may be tolerable,
FIGURE 2  SPEED CONTROL TECHNIQUES

a) FROM 0 TO RATED SPEED

b) INCREASING BEYOND RATED SPEED

c) RESISTIVE
II. B (continued)

the peak currents could be several times greater than the average current. These high current peaks increase the $I^2R$ losses in the wiring, motor, and batteries.

Battery tapping results in discrete steps of vehicle speed. This may or may not be objectional depending on the number of steps used. There are two limiting factors, the cost of additional step switches, and the minimum voltage step available. Also, the batteries in the lower voltage half of the battery bank are subjected to more severe discharge rates than those of the higher bank. This is due to the large motor current on startup. Over a period of time this can lead to premature failure of these batteries. If the batteries are periodically 'rotated' this problem can be reduced.

The resistive approach to speed control dissipates the power, that would normally go to the motor, as heat. With the amount of power required and the limited amount of energy carried by an EV this is not a practical solution.

When controlling the field of the EV motor, the magnitude of the current is much smaller. Now, any of the three approaches shown in Figure 2 is viable.
II. B (continued)

The focus of this thesis will be on a battery tap technique for armature (and series field) control, with a PWM shunt field control used not only at full motor voltage, but at intermediate steps of armature voltage to reduce the tap change jerk.
II. THE CONTROL SYSTEM FOR AN ELECTRIC VEHICLE (continued)

C. WHY USE A MICROPROCESSOR?

The Electric Vehicle speed control system described to this point could be implemented by a mechanical linkage of contacts and variable resistances. However there are other parameters that are of considerable importance.

A battery's life is proportional to the rate at which it is discharged and the depth of each discharge. Since the batteries are usually one of the costliest items in an electric vehicle, it is advantageous to increase the complexity of the control system to prolong battery life. A more ideal control system would monitor motor current. Based on the motor current and the driver's input (via the accelerator), the system would:

a.) increase or decrease the motor speed
b.) detect and correct motor overloads
c.) compute the amount of charge remaining in the batteries

These additional features suggest an intelligent system that might best be implemented using a microprocessor. Such a system will be developed in this thesis.
II. THE CONTROL SYSTEM FOR AN ELECTRIC VEHICLE (continued)

D. CHOOSING A MICROPROCESSOR

Practically any microprocessor can be used in a system thusfar described. With an analysis of the system requirements, it is possible to narrow the contenders by establishing a list of the desired features of the microprocessor (uP). For this system it would be convenient if the processor had the following characteristics:

a.) on board RAM, ROM, clock (minimal support chips required)
b.) integral timer (used for current integration and PWM generation)
c.) low power standby (to retain percent of remaining charge information when the vehicle is parked)
d.) low cost
e.) readily available and well supported by the manufacturer
f.) control oriented instruction set
g.) minimal number of required power supplies

In this application, the processor's speed is not critical. The vehicle response time will be in the hundreds of milliseconds, allowing the processor ample time for calculations.
II. D (continued)

As it meets most of the desired characteristics, Intel's MCS-48 series has been chosen to implement this system. The prototype system will use the ROM-less 8035-L whereas if produced in large quantities a masked ROM 8048-L could be used.

The -L version of the MCS-48 series designates the battery backup RAM option. Consult the Intel MCS-48 user's manual listed in the bibliography for additional information on the microprocessor.
II. THE CONTROL SYSTEM FOR AN ELECTRIC VEHICLE (continued)

E. INTERFACE REQUIREMENTS

The inputs and outputs needed for this control system, along with their characteristics are as follows:

INPUTS: accelerometer - analog voltage proportional to accelerator position
motor current - bipolar analog voltage of millivolt level proportional to current
brake - digital indication of brake on or off
temperature - analog voltage proportional to temperature

OUTPUTS: armature - on/off control of contractors for various battery taps
field - PWM control
percent of remaining charge indication - 2 digit BCD code for LED display

Note that temperature has been added as a system input. This is used to correct the percent of remaining charge value that is displayed. The capacity of a battery at 0°C is only 65% of the nameplate rating of the battery (25°C). While not essential to the control system, the additional overhead is small and the extra level of pro-
II. E (continued)

tection provided will extend the battery's service life.

With these system considerations, it is now possible to design the hardware needed to perform the desired control process.
III. HARDWARE

A. ANALOG INPUT BUFFERS

In the circuit of Figure 3, a linear potentiometer is mechanically coupled to the vehicle's accelerator pedal. As the pedal is depressed, the wiper moves towards a reference voltage, $V_{ref1}$. A resistance/capacitance network reduces noise that may be introduced in the lines connecting the potentiometer to the control circuitry. The signal is buffered by a unity gain non-inverting operational amplifier. $V_{ref1}$ is chosen to insure a 2.5 volt output when the accelerator is fully depressed. This is the full scale analog voltage needed by the analog to digital conversion system and was chosen for full scale to allow easy interface between the digital logic levels, the analog multiplexers, and the analog input buffers. This signal is applied to input port 3 of the analog multiplexer on the uP board.

![Figure 3 Accelerator Buffer](image-url)
III. A (continued)

The motor current buffer (Figure 4) utilized an operational amplifier configured as a differential amplifier. This reduces the effects of common mode voltages induced in the system ground by high motor currents. The input of the amplifier is connected to the current shunt. Vref5 adds offset to the output signal such that -300 amps of current (i.e. regeneration) is represented by an analog signal of 0 volts. This allows the use of unipolar conver-

![Figure 4 Current Shunt Amplifier](image-url)
III. A (continued)

sion routine. The shunt used is .25mohm (200 amps = 50 mV) and therefore Vref5 is adjusted to be 75 mV (300 x .00025). The gain of the amplifier is fixed at 12.5 so as to provide a 2.5 volt output with 500 amps of motor current. A feedback capacitance is used to reduce the high frequency gain of the circuit thereby reducing the noise content of the output signal. The output is fed to input port 1 of the analog multiplexer.

A 1000 ohm negative temperature coefficient thermistor is used as the temperature sensing element (Figure 5). Buffer resistors were placed both in series and parallel with the thermistor to provide a linear response to temperature change. This approximates the discharge characteristics of a lead-acid battery versus temperature. Refer to Appendix 3 for a discussion of battery performance and the resistor/thermistor approximation used here. Knowing the thermistor resistance at both -20 and 25 degrees, the necessary thermistor current for the proper span was calculated from the equation:

\[((R(t=-20)-R(t=25))\times I=1.25\text{\ volts}\]

which when solved for I using the values from Appendix 3 yields:

\[I=1.03\text{ milliamps}.\]
III. A (continued)

An offset is required such that full scale occurs at -20 degrees (C) or:

\[ R(t=-20) \times 1 - V_{os} = 2.5 \text{ volts.} \]

Vref3 is adjusted to 1.05 volts for the proper offset. For convenience, to add a negative offset, the required current is halved and the amplifier given a gain of two. This allows adding offset without upsetting the differential operation of the circuit. As the offset voltage does not get multiplied by the amplifier, the predetermined value is still valid. Vref4 is adjusted for 840 mV resulting in a

![Figure 5 Temperature Sensor](image-url)
III. A (continued)

thermistor current of .565 mA. The output of this circuit is applied to analog input port #1.

The various reference voltages required are developed by the circuit illustrated in Figure 6. They are derived from a multiple resistive divider that is supplied by a constant voltage. A temperature compensated zener diode is used to regulate the voltage. Two capacitors reduce the amount of motor noise that is present on the unregulated supply.
III. HARDWARE (continued)

B. POWER SUPPLIES

The main logic supply (shown in Figure 7) obtains power from the auxiliary battery. This supply is controlled by the vehicle's ignition switch. A diode and large valued capacitor ensure that the supply remains at 5 volts for several milliseconds after power is removed. This allows the processor time to effect an orderly shut-down to retain the memory contents.

![Figure 7 Power Supply - Logic](image-url)
III. B (continued)

A second supply (Figure 8) is sourced directly from the battery and is used to power the processor's internal RAM. This supply is on at all times.

Figure 8 Power Supply - Memory
III. B (continued)

A negative supply (Figure 9) is needed for the analog circuitry. The NAND gates form an astable multivibrator. This AC voltage is applied to the transformer whose secondary is rectified so as to provide a negative voltage with respect to ground. A Zener diode is used to provide regulation for this supply.
III. HARDWARE (continued)

C. POWER INTERFACE

The armature information from the processor circuitry is used to drive the relay coils via a Darlington transistor circuit. As shown in Figure 10, the relay contacts K1-K5 are connected between the motor armature and the various battery taps. Fuses are included to protect the vehicle if a relay contact should weld shut.

The pulse width modulation circuitry is optically isolated to prevent the high voltage spikes in the motor field winding from reaching the processor. The circuit is a high gain DC amplifier with two power transistors paralleled to drive the field winding.

Relays K7, K8 remove power from the field circuitry when the vehicle is parked.

Relay K6 allows the armature relays to function only when field voltage is applied. This prevents an overspeed condition in the event of a failure in the field driver circuitry.
III. HARDWARE (continued)

D. MICROPROCESSOR AND SUPPORT

The microprocessor used in this control system (illustrated in Figure 11) is the ROM-less version of INTEL's MCS-48 series, the 8035. Program memory is contained in Z2, a 1k by 8 EPROM (2758).

The data bus of the processor is connected to latch/decoder/drivers (Z12, Z13) that interfaces to the percent of charge display. A write to external memory command updates the display as the display latch is activated by the WR line of the processor.

The lower nibble of port 2 (bits 0-3) is multiplexed with the address lines (8-11) internal to the 8035. Latch Z7 retains the information output on the port during the memory access cycle of the processor.

The most significant bit of port 2 is the pulse width modulation output for field control. Bit 6 is presently unused. Bits 4 and 5 address the analog multiplexer to select the analog input quantity to be converted by the analog to digital routine. Bit 3 turns off the field voltage if the armature voltage has been turned off, re-
III. D (continued)

ducing battery drain when the motor is turned off. The remaining bits are decoded in a 3 to 8 line encoder and control the armature relays.

Port 1 is used exclusively to create an A/D conversion circuit. It transmits the digital approximation of the analog input to the Digital to Analog converter chip Z3.

Z3 converts this value to an analog voltage which is then compared via Z4 to the corresponding input. When the estimated value becomes too large, the processor is signaled by Z4 using the processor's T0 input.

The reset line of the processor is controlled by the ignition switch. The processor is reset immediately upon the ignition switch being turned off so that as the processor supply is removed, an orderly shutdown of the processor is guaranteed. This protects the contents of the internal RAM which contains the batteries' percent of charge information.
III. D (continued)

The status of the vehicles brakes is sensed by monitoring the voltage applied to the brake lights. This information is filtered and input to the processor via T1.
IV. SOFTWARE

A. PULSE WIDTH MODULATION

The pulse width modulation control of the field voltage is generated utilizing the internal timer generated interrupt of the 8035 microprocessor. The duty cycle is contained in a look up table that is accessed according to the control word address and accelerator position. Upon entering this routine, it is necessary to save the accumulator contents as the timer interrupt is unpredictable. It can occur at any point in the program, including the subroutines.

Figure 12 presents a logical flowchart of the pulse width modulation subroutine. The control word address is loaded from a register common to the main program. Then the actual control word is loaded and all bits except those dedicated to field control are removed. If the field is on, the off time is computed and vice-versa.

If the off time is zero (i.e. full field voltage is required) the timer is reloaded with the on time. The proper time is loaded into the timer, the accumulator restored, the timer restarted, and the processor continues with the main program.
ENTER

- turn off timer

- save accumulator

- load control word

- is field on?

  yes

  - compute off time

  - decrement loop counter

  yes

  off time = 0

  no

  - turn off field

  no

  - compute on time

  - turn on field

  - load timer

  - restore accumulator

  - restart timer

RETURN

Figure 12 Pulse Width Modulation (flowchart)
IV. A (continued)

Note that if the field is on when entering the routine, a loop counter is decremented. As the sum of the off and on times is a constant (3.3ms) a real time clock is formed. This clock is used to determine the integration rate of the current discharge and to set the relay delay time.

The structure of the control word is shown in Figure 13 along with a timing chart of the pulse width modulation routine and an example of the control word table organization. Refer to the program listing (Appendix 1) for a complete listing of the values used in the control table.
a) ACCELERATOR TABLE

<table>
<thead>
<tr>
<th>table address</th>
<th>control word</th>
<th>motor voltages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hex</td>
<td>binary</td>
</tr>
<tr>
<td>00</td>
<td>00</td>
<td>0000 0000</td>
</tr>
<tr>
<td>01</td>
<td>8F</td>
<td>1000 1111</td>
</tr>
<tr>
<td>02</td>
<td>9F</td>
<td>1001 1111</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>D2</td>
<td>1101 0010</td>
</tr>
<tr>
<td>30</td>
<td>D1</td>
<td>1101 0001</td>
</tr>
<tr>
<td>31</td>
<td>D0</td>
<td>1101 0000</td>
</tr>
</tbody>
</table>

b) CONTROL WORD

<table>
<thead>
<tr>
<th>master field switch</th>
<th>armature control 2</th>
<th>armature control 1</th>
<th>armature control 0</th>
<th>field control 3</th>
<th>field control 2</th>
<th>field control 1</th>
<th>field control 0</th>
</tr>
</thead>
</table>

c) FIELD VOLTAGE TIMING

FIGURE 13 MOTOR CONTROL VIA PULSE WIDTH MODULATION
IV. SOFTWARE

B. ANALOG TO DIGITAL CONVERSION

Figure 14 presents the logical flowchart of the Analog to Digital conversion subroutine.

After road testing the control system, it was found necessary to modify the analog to digital routine (A/D) from a successive approximation style to an integrating approximation technique. This greatly reduced the noise influence on the conversion.

The processor functions in conjunction with an 8 bit digital to analog converter (D/A). A digital word is sent by the processor to the D/A converter which in turn outputs an analog signal proportional to the digital input. The output of the D/A is compared (via the comparator) to the incoming signal that has been selected before entering this routine. The output of the comparator is fed back to the processor. If the analog approximation is too small, the digital word sent to the D/A is incremented by 1. In this manner, the analog approximation integrates up to the analog input.
Figure 14 Analog to Digital Conversion
IV. B (continued)

When the approximation exceeds the input value, the comparator signals the processor which than uses the previous approximation as the conversion result. If the analog input is over range, a counter in the routine overflows to indicate this condition. A full scale value is returned in this situation. All data transfer occurs through the accumulator. Worst case conversion time is approximately 12 milliseconds.
IV. SOFTWARE

C. MULTIPLICATION SUBROUTINE

It is well known that when multiplying two eight bit binary numbers, their product can be as large as sixteen bits. In this control system a number of that precision is inconsequential. The errors in the digital to analog converter (8 bit resolution) and the analog buffer circuits define the resolution of the internal mathematics. Therefore, this multiply routine, while using the standard 'shift and add' multiplying technique, allows the lower eight bits of the product to 'fall off', leaving the most significant eight bits as the result. The multiplier is considered to be a positive number between zero and "one" (255/256). As such, the maximum number that can be returned as a product is the multiplicand (i.e. multiplier = "one"). This structure is illustrated in Figure 16.

Figure 16 is the logical flow chart of this unsigned multiply routine.
Figure 15  Multiplication Technique
Figure 16 Multiplication
(flowchart)
IV. SOFTWARE

D. MAIN PROGRAM

Figures 17a to 17c outline the logic flow of the main program. Upon application of power (ignition switch to 'on') the processor is internally reset to address 00 by a power on reset circuit. The program first makes sure that all motor drive signals are set to 'off' to prevent a runaway vehicle. Then, the starting control word and various pointers are initialized.

The main program loop begins by resetting the regeneration flag and the continuous overload flag. Any overload should have been remedied in the previous program loop by the protection routines. If the batteries have been recharged, a switch is activated by the driver and the program resets the charge indication display to 99%.

Motor current is input by first selecting the proper analog channel (00) via the multiplexer and then calling the A/D subroutine. As the A/D converter operates on positive signals only, the software subtracts the positive offset added by the current amplifier circuitry.
Figure 17C Main Program
IV. D (continued)

The polarity of the current is determined to tell the operational mode of the motor; a positive current represents a motoring condition, and a negative current represents the generating mode. Two different paths are followed depending on the polarity:

1. MOTOR - If the motor is drawing more than 400 amps from the batteries, a delay register is decremented to indicate a short term overload has occurred. When this register is decremented to zero, the overload is considered continuous and the overload flag is set. A short term overload would occur when shifting gears or starting the vehicle from a standstill. Setting the flag indicates the current must be reduced to prevent damage to the motor and/or batteries. This type of overload would occur during fast acceleration, climbing a steep grade, or starting in the wrong gear. A continuous overload has been defined as a current greater than 400 amps for a period greater than 3 seconds. Three seconds is an arbitrary time chosen so as to be long enough to prevent nuisance detection of momentary surges in motor current but short enough to prevent motor damage during a legitimate over-load situation.
IV. D (continued)

Since the discharge rate of the batteries is temperature dependent, the thermistor is addressed (01) and the battery temperature is converted to digital format. The temperature factor is multiplied by the current for an adjusted discharge rate which is then multiplied by the display constant before being subtracted from the display. The display constant is discussed in detail in Appendix 2.

2. REGENERATION - The regeneration flag is set to indicate reverse current flow and the magnitude of the current is checked to see if it exceeds 260 amps. A delay system identical to that described in MOTOR above is used here also. Short term overloads would occur initially during down-shifting and continuous overloads would occur when descending a steep grade. The lower current threshold was chosen to prevent warping of the battery plates and rapid generation of hydrogen gas caused by this current has been recommended as the maximum recharge current for two 6 volt batteries operated in parallel.13
IV. D (continued)

The recharge rate of a battery is not greatly affected by temperature so in this loop the thermistor is not addressed. The charge current is multiplied by the charging efficiency of a battery (80%) and then by the display constant before being added to the display.

At this point, both paths rejoin. After the display is updated, the program checks for a continuous overload. If one is present, the accelerator is bypassed and the motor drive is adjusted so as to remove the overload condition. This includes increasing the motor drive to reduce a generating overload or decreasing the motor drive for a motoring overload.

In the absence of continuous overloads, the accelerator is addressed (03) and its position is input. If a short term overload is present, the accelerator is followed only if it is in a direction that would eliminate the overload. As many loops expire before a short term overload becomes a continuous one, it would be possible to greatly increase the motor drive, and
IV. D (continued)

therefore the magnitude of the overcurrent without this test. This check allows advancement only when the current is within the normal operational boundaries (-260 < I < 400).

For a complete absence of overloads, the accelerator is compared to the present control word address. A larger value of the accelerator causes the control address to be incremented, whereas a smaller value causes a decrease of two in the control address. This variation was added after road testing of the vehicle. Single decrementation gave the feeling of a runaway vehicle, as the braking effect of the motor is negligible for a one step change in the control table. The dual step size more closely approximates the feel of a gas powered vehicle.

Once the motor control word is revised, the processor checks for a signal from the brake input if the vehicle is decelerating. If present, a branch occurs for additional testing. This will be discussed later. Assuming the brake is not applied, the new control word is loaded from the table. The three pertinent bits of armature information are checked for equality to the present control bits. If
IV. D (continued)

different, the presently energized armature relay is turned off. Then, if complete motor shutdown is not required, a period of 160 mS is allowed before turning on the new relay. This allows time for the contacts to respond, insuring that no relays are closed simultaneously. A condition of this sort would place a direct short circuit across a bank of batteries with a fault current of thousands of amps. Fuses back up this software protection due to the severity of a failure, however remote.

The program is directed into a delay loop until a total loop time of 254 mS expires. Alternately, the loop may be exited by application of the brake. This allows fast reaction to this input.

When the brake is detected, the control word is additionally decremented to increase the amount of regenerative braking (unless a regenerative overload exists). If the brake is on and the motor is drawing power, then the brake and motor are opposing each other. This situation results in the motor being immediately shut down. A panic stop in which the energy of the vehicle cannot be transferred into
IV. D (continued)

the batteries quick enough (while still maintaining safe current levels) will result in this condition as will bringing the vehicle to a full stop with the clutch engaged.

Upon completion of the braking sequence, the program returns to a delay loop to await the end of the 234 mS delay. The register being decremented as the delay counter is modified by the timer interrupt subroutine which also controls the field voltage.

At the completion of either delay loops, the delay constant is reloaded and the program is repeated.
V. THE TEST VEHICLE

A. DESCRIPTION

The control system was installed in a test vehicle for 'real world' evaluation. The vehicle is a 1967 English Ford, Anglia 105E. Originally powered by a conventional gasoline engine, it has been modified to become an electric vehicle.

The modification involved removing of all gasoline related components (engine, gas tank, etc.). The transmission was retained along with the clutch to provide more torque to the wheels at low vehicle speed and to reduce motor currents on vehicle startup. The rear seat was removed and the resulting area used as a battery compartment. Nine Deka model 9G batteries are stored in this location. Each battery weighs 64 pounds. The rear suspension has been stiffened to support this additional weight. Three batteries and a General Electric 10 horespower starter/generator are mounted in the engine compartment. All lights, accessories, and the control system power requirements are furnished by an auxiliary 12 volt automotive type battery (Sears) located in the trunk. The control system has been fastened to the lower parcel shelf on the passenger side of the vehicle.
V. A. (continued)

The specifications of the completed vehicle are presented in Table 1.
TABLE 1
SPECIFICATIONS OF TEST VEHICLE

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheelbase</td>
<td>90.5 inches</td>
</tr>
<tr>
<td>Body</td>
<td>Monocoque, front engine, rear drive</td>
</tr>
<tr>
<td>Transmission</td>
<td>4 Speed Manual</td>
</tr>
<tr>
<td>Tires</td>
<td>5.20x13 4 ply</td>
</tr>
<tr>
<td>Rear Axle</td>
<td>4.44:1</td>
</tr>
<tr>
<td>Weight (Original)</td>
<td>1645 lbs.</td>
</tr>
<tr>
<td>Weight (Electric)</td>
<td>2350 lbs.</td>
</tr>
<tr>
<td>Motor</td>
<td>10 hp, 30 vdc, Compound Field</td>
</tr>
<tr>
<td>Batteries</td>
<td>9.6 Kwh @ 36 volts</td>
</tr>
</tbody>
</table>
V. THE TEST VEHICLE

B. PERFORMANCE OF THE CONTROL SYSTEM

Even with the modified suspension, the battery weight distribution caused difficulties in handling the vehicle at moderate speeds. For this reason, it was not possible to license the test vehicle for on road use. However, a considerable amount of back road testing was accomplished. Although not as conclusive as long distance driving, these limited test drives produced data that is encouraging. Additional work on the test vehicle will be done in the coming year to provide more complete results.

It is anticipated that when the vehicle is stabilized, fourth gear will be able to be used to obtain higher vehicle speeds. An increased motor current will be required at these higher speeds, so the maximum distance that can be travelled will not change or will possibly decrease. It is again obvious that the weak link in an electric vehicle is the energy source.

One of the major disadvantages of the battery tap technique is the 'jerk' that occurs when the battery tap
is changed. It is especially noticeable in low voltage systems where the tap change is a considerable percentage of the total motor voltage. The intent of the control system described in this thesis was to adjust the field voltage to minimize the severity of the tap change effects. While this was accomplished, the final results were not as smooth as anticipated. The torque of the motor is reduced as the field is reduced so that the vehicle does not accelerate at the same rate as when the armature voltage is stepped. Hence a smooth transition does not occur. Also noticeable was the 150 mS delay used to allow the relays time to settle. As the control system presently uses the smallest voltage tap size that is available, the alternative is a PWM armature control. Unfortunately, this would greatly increase the cost of the system.

The acceleration time was slightly longer than anticipated. (Table 2) This time is controlled by the over-current delay time allowed by the program. Increasing the delay time would decrease the acceleration time at the expense of battery and motor life. A better solution (although not
V. B (continued)

as easy) would be to reduce the rolling resistance of the vehicle. This could best be done with a vehicle specifically built for electric propulsion.

The final data for the test vehicle is shown in Table 2. These values are the average of data taken under various conditions and revisions of the test vehicle. During these tests, the vehicle was carrying a single passenger on an average trip length of 1.1 miles. The longest distance travelled without a stop was .2 miles. Two complete stops were made on each trip.
TABLE 2
PERFORMANCE OF TEST VEHICLE

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top speed</td>
<td>33mph (in 3rd gear)</td>
</tr>
<tr>
<td>Time to top speed (from standstill)</td>
<td>14 seconds</td>
</tr>
<tr>
<td>Distance at top speed</td>
<td>31 miles*</td>
</tr>
<tr>
<td>Decelleration time (from top speed to end of regeneration)</td>
<td>6 seconds</td>
</tr>
<tr>
<td>Motor current (level road, top speed)</td>
<td>310 amps</td>
</tr>
</tbody>
</table>

* Calculated from % of charge display by driving at constant speed over a known distance.
VI. SUMMARY

The control system described in this thesis is a low cost ($300) system designed to control the speed of an electric vehicle by adjusting the speed of a compound wound DC motor. Since it uses a microprocessor, it is readily adaptable to a variety of motor voltages and motor control techniques by modifying an internal firmware accelerator map. It is this map that determines the vehicle's speed.

The method developed in this system is a combination of battery tapping for control of the armature voltage, and pulse width modulation field control generated by the processor. Overcurrent protection was included to prolong battery and motor life. Regeneration is automatic upon release of the accelerator and has two levels. The first is a light regeneration simulating the braking effect of a gasoline engine. The second level is executed when the brakes are applied. Here, the goal is to return as much energy from the vehicle as can be safely delivered to the batteries. Over current protection is provided on regeneration to prevent battery damage.
VI. SUMMARY (continued)

A display of the remaining charge in the vehicle's batteries has a continually powered memory to retain this information when the vehicle is parked. This display is also temperature compensated to model the characteristics of a lead acid battery over varying temperatures.

The control system was installed in a test vehicle where it was debugged and evaluated. The results were favorable but suffered from mechanical limitations of the test vehicle.
APPENDIX 1 PROGRAM LISTING

IISIS-II MCS-4®/UPI-41 MACRO ASSEMBLER, V3.0

LOC OBJ LINE SOURCE STATEMENT
1     0BJ     1     0RJISION 3
2     0BJ     2     0SEPTEMBER 20, 1979
3     0BJ     3     IPWM CONTROL FROM 37.5% TO 100%
4     0BJ     4     ITO INCREASE TOP SPEED PAST 30 MPH
5     0BJ     5     ICHANGE LOOP DELAY CONSTANT
6     0BJ     6     IALTER ACCELERATOR TABLE
7     0BJ     7     ICHANGE TIMER ROUTINE FOR 24 BIT PWM
8     0BJ     8     IREVISION 2
9     0BJ     9     IJULY 31, 1979
10     0BJ    10     ICHANGE ADD TO INCREMENTAL TYPE
11     0BJ    11     ITO REDUCE NOISE INFLUENCE
12     0BJ    12     IMODIFY ACCELERATOR TABLE
13     0BJ    13    (IF ADD IDLE AT 12 VOLTS UNLESS BRAKE APPLIED
14     0BJ    14     IDECREMENT BY 2 FOR FASTER DECELERATION
15     0BJ    15     IREVISION 1
16     0BJ    16     IJULY 19, 1979
17     0BJ    17     IRESULT OF 1ST ROAD TEST
18     0BJ    18     IADDS INITIALIZING OF CONTROL WORD
19     0BJ    19     ITO A Ø CONDITION AND IGNORES MOMENTARY
20     0BJ    20     IOVERLOAD IF ACCELERATOR+GOAL
21     0BJ    21     ;
22     0BJ    22     IMAY 5, 1979
23     0BJ    23     ;
24     0BJ    24     IELECTRIC VEHICLE CONTROLLER
25     0BJ    25     ;
26     0BJ    26     ICONTROLS FIELD VOLTAGE BY PWM FROM 50% TO 100%
27     0BJ    27     ICONTROLS ARMATURE VOLTAGE BY BATTERY TAP RELAYS
28     0BJ    28     IIN STEPS FROM 12-18-24-30-36 VOLTS
29     0BJ    29     IDISPLAYS THE REMAINING CHARGE IN BATTERY BANK
30     0BJ    30     IWHERE THE DISCHARGE RATE IS CALCULATED
31     0BJ    31     IFROM THE ACTUAL BATTERY CURRENTS AND
32     0BJ    32     ISCALED BY 1/T WHERE T=BATTERY TEMPERATURE
33     0BJ    33     ITHE BATTERY CAPACITY IS ASSUMED TO BE
34     0BJ    34     I120 MINUTES AT 150 AMPS AT 80 F
35     0BJ    35     ISIGNALS AN OVERCURRENT OF +400 AMPS
36     0BJ    36     IAND IF PRESENT FOR GREATER THAN 2
37     0BJ    37     ISECONDS REDUCES THE MOTOR DRIVE
38     0BJ    38     ISIGNALS AN OVERCURRENT OF -265 AMPS
39     0BJ    39     IAND IF PRESENT FOR GREATER THAN 2
40     0BJ    40     ISECONDS INCREASES MOTOR DRIVE
41     0BJ    41     IUPTON BRAKING, ALLOWS REGENERATION TO OCCUR
42     0BJ    42     IWTHIN CURRENT LIMITS AND TURNS OFF
43     0BJ    43     IMOTOR WHEN MOTOR STARTS TO OPPOSE
44     0BJ    44     IBrake as in a FAST STOP
45     0BJ    45     ;
46     0BJ    46     IPROGRAMMED BY RON MOFFATT IN SPRING '79
47     0BJ    47     IAS PART OF THE MASTERS REQUIREMENTS
48     0BJ    48     IOF ROCHESTER INSTITUTE OF TECHNOLOGY
49     0BJ    49     ;
50     0BJ    50     ;
51     0BJ    51     ;
52     0BJ    52     ;
53     0BJ    53     ;
54     0BJ    54     ;
55     0BJ    55     IMAIN PROGRAM
56     0BJ    56     ;
57     0BJ    57     ;
58     0BJ    58     ;
59     0BJ    59     IP2 FORM=FXIISAAA
60     0BJ    60     IWHERE-
61     0BJ    61     IF=FIELD PWM WAVEFORM
62     0BJ    62     IX=EXTRA I/O
63     0BJ    63     I1=ANALOG INPUT ADDRESS
64     0BJ    64     IS=FIELD SWITCH
65     0BJ    65     IA=ARMATURE CONTROL
66     0BJ    66     ;
67     0BJ    67     ;
68     0BJ    68     ;
69     0BJ    69     LINE1: JMP START IRESET VECTOR
70     0BJ    70     ;
71     0BJ    71     ;
72     0BJ    72     ORG 0007H
73     0BJ    73     ITIMER INTERRUPT CAUSES PROCESSOR
74     0BJ    74     TO EXECUTE ADDRESS 07
75     0BJ    75     JMP TIMER ITIMER VECTOR
76     0BJ    76     ;
77     0BJ    77     ;
<table>
<thead>
<tr>
<th>LOC</th>
<th>OBJ</th>
<th>LINE</th>
<th>SOURCE STATEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0004 27</td>
<td>START:</td>
<td>CLR A</td>
<td>INITIALIZE OUTPUT TABLE ADDRESS</td>
</tr>
<tr>
<td>0004 A9</td>
<td>MOV R6:A</td>
<td>TO 30H</td>
<td></td>
</tr>
<tr>
<td>000B 3A</td>
<td>OUTL P2:A</td>
<td>INITIALIZE CONTROL CIRCUITRY</td>
<td></td>
</tr>
<tr>
<td>000C D5</td>
<td>SEL R8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>000D 8A2</td>
<td>MOV R2:#02</td>
<td>SET FIELD STATUS TO OFF</td>
<td></td>
</tr>
<tr>
<td>000F 62</td>
<td>MOV T:A</td>
<td>END OF INITIALIZATION</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0010 85</td>
<td>CLR F0</td>
<td>CLEAR REGEN FLAG</td>
<td></td>
</tr>
<tr>
<td>0011 45</td>
<td>CLR F1</td>
<td>CLEAR OVERLOAD FLAG</td>
<td></td>
</tr>
<tr>
<td>0014 49</td>
<td>MOV R1:A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0015 C5</td>
<td>MOV R8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0016 49</td>
<td>MOV R1:A</td>
<td>Restore pointer in both banks</td>
<td></td>
</tr>
<tr>
<td>0017 FA1F</td>
<td>JN I NOCRC</td>
<td>INITIALIZE DISPLAY</td>
<td></td>
</tr>
<tr>
<td>0019 BFCF</td>
<td>MOV R4:#0FFH</td>
<td>FILL LSB</td>
<td></td>
</tr>
<tr>
<td>0018 30DF</td>
<td>MOV R5:#09FH</td>
<td>AND FILL MSB AND SET LSD=9</td>
<td></td>
</tr>
<tr>
<td>001D 01E9</td>
<td>MOV R6:#19H</td>
<td>ISET MSB=9</td>
<td></td>
</tr>
<tr>
<td>001F 25</td>
<td>NOCRC:</td>
<td>EN TCKTI ENABLED TIMER INTERRUPT</td>
<td></td>
</tr>
<tr>
<td>0020 55</td>
<td>STRT T</td>
<td>START TIMER</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>101</td>
<td></td>
<td></td>
</tr>
<tr>
<td>102</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0021 9ACF</td>
<td>IN:</td>
<td>ANL P2:#0CFH</td>
<td>OUTPUT SHUNT ADDRESS</td>
</tr>
<tr>
<td>0022 3450</td>
<td>CALL A2D</td>
<td>INPUT CURRENT</td>
<td></td>
</tr>
<tr>
<td>0025 03A0</td>
<td>ADD A:#00H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0027 A1</td>
<td>MOV R1:A</td>
<td>SUBTRACT 300 AMPS AND STORE</td>
<td></td>
</tr>
<tr>
<td>0029 E657</td>
<td>JNC REGEN</td>
<td>IF I&lt;0 SYSTEM REGENERATING</td>
<td></td>
</tr>
<tr>
<td>002A 9380</td>
<td>ADD A:#00H</td>
<td>CHECK IF MOTOR IS DRAWING</td>
<td></td>
</tr>
<tr>
<td>002C 6A1</td>
<td>JNC</td>
<td>ISET I&lt;0</td>
<td></td>
</tr>
<tr>
<td>002E EF33</td>
<td>MOV R5: #0FFH</td>
<td>FILL LSB</td>
<td></td>
</tr>
<tr>
<td>0030 E5</td>
<td>DJNZ R7: TEMP</td>
<td>ELSE DECCREMENT DELAY REG</td>
<td></td>
</tr>
<tr>
<td>0031 BF3D</td>
<td>MOV R7: #00DH</td>
<td>IRESET DELAY LOOP</td>
<td></td>
</tr>
<tr>
<td>113</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>114</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>115</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0033 3410</td>
<td>TEMP:</td>
<td>ORL P2:#010H</td>
<td>ADDRESS THERMISTOR</td>
</tr>
<tr>
<td>0035 19</td>
<td>INC R1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0036 3450</td>
<td>CALL A2D</td>
<td>INPUT TEMPERATURE</td>
<td></td>
</tr>
<tr>
<td>0038 AB</td>
<td>MOV R3:A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0039 C9</td>
<td>DEC R1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>003A 3441</td>
<td>CALL MULTP</td>
<td>ICALCULATE I X T</td>
<td></td>
</tr>
<tr>
<td>003C 67A</td>
<td>JS DISPLAY</td>
<td>IIF PRODUCT=0, DISPLAY ON</td>
<td></td>
</tr>
<tr>
<td>003E A1</td>
<td>MOV R1:A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>003F BB5</td>
<td>MOV R3:#0CFH</td>
<td>IRESET BY DISP CONSTANT</td>
<td></td>
</tr>
<tr>
<td>0041 3441</td>
<td>CALL MULTP</td>
<td>IOF .81</td>
<td></td>
</tr>
<tr>
<td>0042 67A</td>
<td>JS DISPLAY</td>
<td>IIF PRODUCT=0, DISPLAY</td>
<td></td>
</tr>
<tr>
<td>0044 37</td>
<td>CPL A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0046 17</td>
<td>INC A</td>
<td>ELSE SUBTRACT FROM XCHRG</td>
<td></td>
</tr>
<tr>
<td>0047 6C</td>
<td>ADD A:#R4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0048 AC</td>
<td>MOV R4:A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0049 F67A</td>
<td>JC DISPLAY</td>
<td>IIF CARRY FORM LSB DISPLAY</td>
<td></td>
</tr>
<tr>
<td>004B FD</td>
<td>MOV A:#RS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004C 03FF</td>
<td>ADD A:#0FFH</td>
<td>ELSE BORROW FROM MSB/DIS</td>
<td></td>
</tr>
<tr>
<td>004E AD</td>
<td>MOV R5:A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004F F67A</td>
<td>JC DISPLAY</td>
<td>IIF CARRY DISPLAY</td>
<td></td>
</tr>
<tr>
<td>0051 S39F</td>
<td>ANL A:#0FFH</td>
<td>ELSE RS WAS 0, NOW FF</td>
<td></td>
</tr>
<tr>
<td>0053 AD</td>
<td>MOV R5:A</td>
<td>ISET LSD T0 9</td>
<td></td>
</tr>
<tr>
<td>0054 CE</td>
<td>DEC R6</td>
<td>IAND DECIMUM MSD OF DISPLAY</td>
<td></td>
</tr>
<tr>
<td>0055 847A</td>
<td>JMP DISPLAY</td>
<td>THEN DISPLAY</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>141</td>
<td></td>
<td></td>
</tr>
<tr>
<td>142</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0057 95</td>
<td>REGEN:</td>
<td>CPL F0</td>
<td></td>
</tr>
<tr>
<td>0058 37</td>
<td>CPL A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0059 17</td>
<td>INC A</td>
<td>ISET REGEN FLAG</td>
<td></td>
</tr>
<tr>
<td>005A A1</td>
<td>MOV R1:A</td>
<td>ISTORE MAGNITUDE IF CURRENT</td>
<td></td>
</tr>
</tbody>
</table>
## APPENDIX 1 (continued)

### 16IS-II MCS-48/UPC-41 MACRO ASSEMBLER: V3.0

<table>
<thead>
<tr>
<th>LOC</th>
<th>OBJ</th>
<th>LINE</th>
<th>SOURCE STATEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>006F</td>
<td>03A0</td>
<td>147</td>
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APPENDIX 1 (continued)

PAGE 4

LC OBJ LINE SOURCE STATEMENT

d34F F3 214 ARM: MOV A,R0 LOAD CONTROL WORD
e05E F3 215 MOV P3 A,0A FROM TABLE ON P3
b85F 5F0 216 ANL A,0FH REMOVE FIELD
e053 47 217 SWAP A
w084 0B 218 MOV R3,A
w085 0A 219 IN A,R2 READ PORT 2
w086 5F0 220 ANL A,0FH REMOVE ALL BUT ARMATURE
e086 0B 221 XRL A,R3 IDoes present ARMATURE
w097 D5 222 SEL RB1 AGREE WITH COAL?
e0BA C6D1 223 JZ WAIT IF SO DONE
e0BC 0A 224 RELAY: IN A,R2 HELSE
e0BD 5F0 225 ANL A,0FH TURN OFF RELAYS
w0BF 3A 226 OUTL P2,A ISO TWO CANNOT BE ON
w0C0 FF 227 MOV A,R7 LOAD PRESENT LOOP COUNT
e0C1 63CE 228 ADD A,0CEH CALCULATE 16MS DELAY
e0C3 A1 229 MOV B,R1,A FOR SETTLE TIME
e0C4 F8 230 MOV A,R3 ICHECK IF ANY RELAY
w0C5 C6D1 231 JZ WAIT IF TO BE TURNED ON
w0C7 FF 232 DELAY: MOV A,R7 IF SO THEN
w0C8 1D1 233 XRL A,R1, WAIT FOR RELAYS
w0C9 96C7 234 JNZ DELAY INTO SETTLE
w0CB C5 235 SEL RB0
w0CD 0A 236 IN A,R2
w0CD 5F0 237 ANL A,0FH PLACE NEW CONTROL
e0CF 4B 238 ORL A,R3 WORD ON P2
e0D0 3A 239 OUTL P2,A

240:

w0D1 D5 241 243 WAIT: SEL RB1
w0D2 5E3 244 246 JT1 BRAKE: IS BRAKE ON?
e0D4 FF 245 247 MOV A,R7 INO
w0D5 96D1 246 248 JNZ WAIT: WAIT FOR DELAY
w0D7 BF49 247 249 MOV R7,#049H IRELOAD LOOP DELAY
w0D9 0410 248 249 JMP LOOP END OF PROGRAM
w0DB 66AC 250 252 RETR: JF# SPLED: IF CURRENT TOO -
251 ICREASE MOTOR DRIVE
w0DC C8 252 254 DEC R8: DEC R8: IF CURRENT TOO +
253 255 DEC R8: IDEBUG FOR FAST RESPONSE
w0DF 2427 254 256 CALL LIMIT: DECREASE MOTOR DRIVE
255 257 JNT1 ARM: DETEECT ARMATURE ON OUTPUT
w0E3 2401 256 257 BRAKE: JMP BREAK IF ARMATURE
w0E5 C5 258 259 BREAK: SEL R80 INDECELERATE FAST
w0E6 F8 259 260 MOV A,R0
w0E8 07 260 261 DEC A
w0E9 07 261 262 DEC A
w0EB 37 262 263 CPL A ICHECK IF R80
w0ED F216 263 264 JBP STILNO INO THEN OR ELSE
w0EE 8900 264 265 STOPP: MOV R8,#00H SET CONTROL TO 0
w0FA 0A 265 266 IN A,R2
w0FD 5F0 266 267 ANL A,0FH TURN OFF MOTOR
w10D 3A 267 268 OUTL P2,A ARMATURE AND FIELD
269:

270:

271:

272 WATE: SEL RB1 THIS DELAY LOOP DOES
273 MOV A,R7
274 JNZ WATE: IF STATUS BUT CAN ONLY
275 MOV R7,#049H IBE ENTERED IF
276 JMP LOOP IBRAKE WAS ON
277 STILNO: JF# HELPMINSYSEM GENERATING
278 JMP STOPP: NO3 THEN SHUTDOWN
279 HELPIN: MOV B,R1,A
280 MOV A,R7
281 IRL A,#0DH
282 JNZ WATE: IF OVERCHARGE DO NOTHING
283 JF1 WATE: IF OVERLOAD DO NOTHING
284 MOV A,R1
285 CPL A IELSE LOAD
286 MOV R8,A INEW OUTPUT CODE
287 JMP WATE IAND WAIT FOR LOOP
288:
APPENDIX 1 (continued)

LOC 0EJ - LINE - SOURCE STATEMENT

289 1
290 ISUBROUTINES FOLLOW
291 1
292 1
293 1

.117 F3
294 LIMIT: MOV A,R0 IES $R0<1F?
.012D F136
295 JB7 NEG IES R0 < 0?
.012A 06JC
296 JZ ZERO IES R0 = 0 OR 1
.011C 07
297 DEC A
.012D 06JC
298 JZ ZERO
.011F 17
299 INC A
.0150 03E1
300 ADD A,#$E1 IES R0>1F
.013C 37
301 CPL A
.0133 F139
302 JB7 FS
.0135 83
303 RET IIF SAFE RETURN
.0136 0300
304 NEG: MOV R0,00
.0139 93
305 RET IIF 0 SET TO 0
.0139 B11F
306 FS: MOV R0,#01FH IIF TOO LARGE
.013B 83
307 RETRN: RET IIF TO FULL SCALE
.013C 763B
308 ZERO: JFI RETURN IIF = 0 AND OVERLOAD, OK
.013E B992
309 MOV R0,#0CH IELSE SET TO IDLE
.0140 93
310 RET
311 1
312 1
313 IMULTIPLY ROUTINE
314 1
315 MULTIPLIER IN R3
316 MULTIPLICAND IN R4
317 RESULT IN ACCUMULATOR
.0141 BA08
318 MULT: MOV R2,#03H INITIALIZE COUNTER
.0143 97
319 CLR C
.0144 27
320 CLR A
.0145 67
321 MULT2: RRC A ROTATE RESULT RIGHT
.0146 2B
322 XCH A,R3
.0147 67
323 RRC A
.0148 2B
324 XCH A,R3 ROTATE MULTIPLIER RIGHT
.0149 E64C
325 JNC MULTI IIF MSB WAS 1
.014A 61
326 ADD A,#1 ADD MULTIPLICAND TO RESULT
.014C EA45
327 MULT2: DJNZ R2,#MULT2 IELSE DECREMENT LOOP
.014E 07
328 RRC A IIF 0 MULTIPLY COMPLETE
.014F 33
329 RET
330 1
331 ANALOG TO DIGITAL ROUTINE
332 18 BITS WIDE
333 RESULT IN ACCUMULATOR
334 INCREMENTS UNTIL CORRECT
335 VALUE IS OUTPUT
.0150 27
336 A2D: CLR A INITIALIZE TRIAL
.0151 39
337 NEXT: OUTL P1,A TRY NEW APPROX.
.0152 17
338 INC A READY NEXT TRY
.0153 00
339 NOP
.0154 00
340 NOP
.0155 00
341 NOP
.0156 00
342 NOP
.0157 265B
343 JNT0 TEST IIF TOO SMALL CHECK FOR OVERFLOW
.0159 07
344 DEC A IELSE BACKTRACK
.015A 33
345 RET IIF NO OVERFLOW TRY NEXT
.015B 9651
346 TEST: JNZ NEXT IELSE SET ANSWER TO FF
.015D 07
347 DEC A IELSE SET ANSWER TO FF
.015E 03
348 RET IIF AND RETURN
349 1

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### APPENDIX 1 (continued)

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<td>DB 0DH FIELD=34.5;ACC=17</td>
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</tr>
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<td>DB 0DH FIELD=31.5;ACC=19</td>
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<td>416</td>
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</tr>
<tr>
<td>417</td>
<td>DB 0DH FIELD=28.5;ACC=21</td>
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<td>418</td>
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</tr>
<tr>
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</tr>
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<td>DB 0DH FIELD=24.0;ACC=24</td>
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<tr>
<td>421</td>
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</tr>
<tr>
<td>423</td>
<td>DB 0DH FIELD=19.5;ACC=27</td>
</tr>
<tr>
<td>424</td>
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</tr>
<tr>
<td>425</td>
<td>DB 0DH FIELD=16.5;ACC=29</td>
</tr>
<tr>
<td>426</td>
<td>DB 0DH FIELD=15.0;ACC=30</td>
</tr>
<tr>
<td>427</td>
<td>DB 0DH FIELD=13.5;ACC=31</td>
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APPENDIX 2
CALCULATION OF DISPLAY CONSTANT

The percent of remaining charge display is directly related to the capacity of the vehicle's battery and the rate at which it is discharged. The display constant is chosen such that the display will decrement from 99% to 0 as the batteries are depleted from a fully charged condition.

For the vehicle tested, the batteries have a rating of 275 amp hours at a discharge rate of 150 amps. This specification is given for a battery temperature of 25 C. For the control system to calculate the number of amp hours removed from the batteries, it is necessary to integrate the motor current. This requires a time base.

The loop time of the main program is determined by the timer interrupt routine and the main loop counter. To allow time for the armature relays to settle, the program was set to execute the main loop every 234 mS. This loop

Since this time was established, 50 mS was removed from the relay settling time to lessen the pause caused when all relays were off. The display constant was not readjusted as the loop time was not changed. It is anticipated that this time can be reduced by 50 mS also and the display constant modified to reflect this change.
time is used as the system clock.

From earlier discussion of the system hardware, an offset voltage has been added to the analog representation of the motor current. This must be subtracted from the digital approximation of the motor current. This must be subtracted from the digital approximation before it is used in any calculations. The amount of offset added was the equivalent of 300 amps. The total current span of the control system is 800 amps. With this information, it is possible to calculate the corresponding digital offset from the equation:

\[
\text{DIGITAL OFFSET} = \frac{\text{ANALOG OFFSET} \times \text{DIGITAL FULL SCALE}}{\text{ANALOG FULLSCALE}}
\]

inserting values:

\[
\text{DIGITAL OFFSET} = \frac{300 \times 255}{800} = 95 \text{ bits}
\]

Now, the digital word that represents 500 amps after the signal is debiased can be expressed as:

\[
\text{DIGITAL SPAN} = \text{DIGITAL FULL SCALE} - \text{DIGITAL OFFSET}
\]

Again, inserting values:

\[
\text{DIGITAL SPAN} = 255 - 96 = 159 \text{ bits}
\]
Summarizing, the digital representation of 500 amps of motor current is 159.

Since the batteries are rated at 150 amps of discharge, it is desirable to establish the digital representation of this current so as to properly scale the charge display. This is done using the equation:

digital value of 150 amps = \( \frac{150}{500} \) x digital value of 500 amps

which when solved results in:

digital value of 150 amps = 48

The temperature compensation scheme multiplies the discharge current by \( \frac{1}{2} \) at 25 C. Hence, the representation of 150 amps at 25 C within the processor is a digital word with the value of 24.

Now, from the battery rating, the loop time, and the digital representation of the battery rating current, it is possible to calculate the number of loops the program must complete, and the number of counts that must be subtracted from the display for it to go from 99% to 0. First to cal-
APPENDIX 2 (continued)

calculate the number of program loops:

Number of loops = battery rating in seconds/loop time
in seconds

\[ \text{Number of loops} = \frac{110 \times 60}{0.234} = 28205 \]

Next calculating the number of counts:

Number of counts = number of loops \times \text{counts per loop}

\[ \text{Number of counts} = 28205 \times 24 = 676920 \]

The top two nibbles of the display register are in BCD
format for easy decoding into seven segment display format.
These two BCD display nibbles represent a factor of one hundred. Therefore, a buffer register is required to hold
6769 bits before the display is decremented.

To extend the life of the batteries, it is preferable
not to completely discharge them. A margin of 25% is used
in the remaining calculations. This decreases the size of
the buffer register to:

\[ \frac{3}{4} \times 6769 = 5077 \text{ counts} \]

It would be very convenient if this buffer size was a power
of two.
The display constant can be defined then as the number that when multiplied times the current, results in a display register whose size is a power of two. In equation form:

\[
\text{display constant} = \frac{\text{closest power of 2}}{\text{present register size}} = \frac{4096}{5077} = .81
\]

Reviewing the significance of this development, a constant has been extracted so that the percent of remaining charge display will accurately reflect the amount of energy remaining in the vehicle batteries.

The charge constant development is similar, requiring use of the discharge constant, the charging efficiency of a battery, and the temperature correction. First, as the battery's charge characteristics are not appreciably affected by temperature, it is not necessary to scale the current during regeneration. Hence the digital word is multiplied by .5 (the 25 C scale factor).

Next, the charging efficiency is required. Although
normal charging efficiencies are 80%, tests have been conducted which show that regeneration charging efficiencies can exceed 100%.\textsuperscript{16} A compromise value of 90% was chosen for this system. Finally, the recharge constant can be computed as:

recharge display constant = display constant x charge efficiency x temperature correction
\[ = 0.81 \times 0.9 \times 0.5 \]
\[ = 0.36 \]

This then is the process from which the two display constants were chosen.
APPENDIX 3

TEMPERATURE CORRECTION OF BATTERY DISCHARGE RATE

The discharge characteristics of a lead acid battery are affected greatly by a change in the battery temperature. As the battery's temperature decreases, the amount of energy the battery can supply decreases. If $25^\circ C$ is considered as the normalized temperature at which a battery is rated, then at a temperature of $-20^\circ C$ the capability of the battery is reduced to 40% of its nominal rating. Within this temperature span, the capacity versus temperature characteristics of a battery can be approximated as a linear function.

In an electric vehicle, the current drawn from the batteries is large enough to cause significant internal heating in the batteries. Usually this generated heat is a limitation to the vehicle since the batteries have a maximum operating temperature of only $50^\circ C$. In cold weather however, this internal heating is beneficial. As the battery 'warms' itself up, its discharge capability increases.

Because of this internal heating, the temperature
APPENDIX 3 (continued)

sensor, unless suspended in the electrolyte, will measure a temperature lower than the actual battery temperature. The control system was designed to correct the battery discharge based on a 50% battery capacity at a -20 C case temperature. This allows for a temperature gradient of approximately 5 C from the case to the center of the battery.

Due to its availability, a negative temperature coefficient (NTC) thermistor was used as the sensing element. Table A3-1 lists the variation of the thermistor's resistance with temperature. From the table it can be seen that the resistance variation is not linear with temperature change. This can be corrected for by parallel-ing a fixed resistor with the thermistor.

For protection, a 3.3 Kohm resistor was placed in series with the thermistor. Since the thermistor mounts directly on a battery's case, there exists the possibility that battery acid may be spilled on it. The series resistance insures that the control system will not be damaged if spilled acid forms a conducting path between the batteries and the thermistor.
APPENDIX 3 (continued)

The temperature characteristics of the thermistor and series/parallel resistors is shown in Table A3-1. Refer to Figure 5 for the schematic of this network.

TABLE A3-1  THERMISTOR RESPONSE

<table>
<thead>
<tr>
<th>Temperature C</th>
<th>Thermistor resistance in K ohms</th>
<th>Network resistance in K ohms</th>
<th>Resulting normalized capacity</th>
</tr>
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<tbody>
<tr>
<td>25</td>
<td>1.00</td>
<td>2.25</td>
<td>1.00</td>
</tr>
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<td>1.25</td>
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<td>.92</td>
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<td>1.57</td>
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<td>.71</td>
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</tr>
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<tr>
<td>-20</td>
<td>9.71</td>
<td>3.45</td>
<td>.50</td>
</tr>
</tbody>
</table>
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