SPEED CONTROL OF DC SHUNT MOTOR FOR ELECTRIC CAR USE

BY

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RESEARCH REPORT

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ABSTRACT

This report describes the speed characteristic and various methods of speed control of DC shunt (separately excited) motors, especially for application in electrical vehicles. The basic behavior of the DC motor is discussed, along with traditional and modern techniques of speed control. As an example, a speed controller for a shunt motor (built and tested by the author) is discussed. Two types of speed controllers for electric cars are discussed, and the performance results for an experimental electric car are presented. Finally, a design for a 24 HP car motor controller using both armature and field control was simulated on a smaller scale in the laboratory.
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In the preparation of this paper, many resources have been used. A number of the diagrams and figures have been taken directly from books and papers, and a number of the descriptions of circuit operation, control systems, etc. have been adapted from the writings of other authors. Since these authors have not been approached for permission to use these materials, I want to apologize to them for seeking this courtesy in advance. In all cases I have tried to give them credit for figures and graphs, and wish to point out that these cases of borrowing from the works of others have been done entirely on my own part and do not reflect policy or action on the part of the Electrical Engineering and Communication Sciences Department or on the University of Central Florida.
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INTRODUCTION

This research looks at the speed control of shunt and separately excited DC motors, and its application in electrical vehicles. Whenever electrical energy is combined with mechanical motion, the impact of solid state electronic control of electric motors is apparent. It is true that many tools, and vehicles were electrically powered prior to the advent of thyristors, power transistors, and sophisticated integrated circuit modules. However, the improvements in precision, flexibility, reliability, and controllability have been so great with the new devices and techniques, that a new and fascinating aspect of technology is occurring.

When both power engineering and electronics were still in their early stages, those with bold imaginations perceived the potential benefits that might result from a merger of two arts. What prevented these two technologies from being combined was the unreliability of then-available electronic devices and components. During the 1930's and 1940's, the electronic control of motors did make some progress as better tubes and components became available for such applications. In particular, thyatrons and ignitrons became popular. It became feasible to electronically control speed of fractional-horsepower machines and, to some extent, larger integral horsepower machines.
Significantly, some of these circuit techniques are clearly recognizable as the predecessors of present day solid state controllers.

These developments lead to the solid state chapter of electronic evolution. Initially, the invention of the transistor sparked a number of application efforts. With the soon to follow development of the power transistors, the direct control of larger electromagnetic devices became possible. Finally, the introduction and quick commercialization of thyristors enabled the precise and efficient control of very large motors.

The present emphasis is on the ever increasing power capability of these solid state components along with the development of drive, logic, and isolation devices. These devices include monolithic gating and timing modules, to say nothing of entire systems on a chip, such as registers, counters, phase locked loops, etc. Other devices include operational amplifiers, regulated power supplies, and the relatively new optoisolators.

In order that the reader may better understand the application of the electronic motor control techniques, the first chapter of this paper will deal with the operation, characteristics, and behavior of electric motors. Chapters Two and Three will discuss the various old and modern speed control techniques and devices being used. This presentation will be particularly useful to those who work with both electronics and electric motors. In Chapter Three there is a representation of an armature controller using transistors,
which the author has built as a prototype circuit in order to implement a field controller for the electric car research project (a project sponsored by the Engineering and Industrial Experiment Station).

The application of the new control techniques using transistors and SCR's for the different types of DC motors, especially shunt and separately excited, in electric vehicle use is discussed in Chapter 4. Two types of solid state controller which have been used in electric cars are discussed in detail. This chapter also includes the conclusions and recommendations for improvement.
CHAPTER I

BASIC CONCEPTS OF DC MOTOR

In this chapter the more specific matters concerning DC motors, like type of winding and operational behavior, are considered.

Direct-current motors are classified according to the type of winding employed, as:

1. series-wound
2. shunt-wound
3. compound wound.

The series-wound motor (Fig. 1.1) is one in which the field coils and armature are connected in series, and the entire current flows through the field coils. The shunt-wound motor (Fig. 1.2) derives its name from the fact that the field coils and the armature are connected in shunt (parallel), and because of this, the field current is only a small portion of the total or line current. The compound-wound motor (Fig. 1.3) incorporates both series-wound and the shunt-wound windings. In other words, it has both the series and the shunt windings.
Fig. 1.1. Diagram of the connections for a series wound DC motor

Fig. 1.2. Diagram of the connections for a shunt wound DC motor

Note: The sources of the diagrams used in this research report are listed in References Cited, page 130.
Operating Characteristics

Series Motors

The load characteristic curves of a series motor are given in Fig. 1.4. A study of the current-torque curves indicates that the torque varies approximately as the square of the armature current. From this, it follows that this type of motor is suitable in load applications where it is necessary to supply a large torque with a moderate increase in current, such as in traction work, crane operation, etc.

The speed of a series motor, as indicated, varies greatly with the change in load. Because of this speed characteristic, and the resultant possibility of dangerously high speed at light loads, this motor is not suitable for belt drive or for use on any load where the torque might drop below 15% of full-load torque.
Fig. 1.4. Operating characteristic curves of a series DC motor

Shunt Motor

From the characteristic curves of a shunt motor (Fig. 1.5) it is noticed that this motor will run at very nearly the same speed at any load within its capacity, and will not slow very much even when greatly overloaded. There is but a slight drop in speed from no load to full load. This drop may vary from 5 to 15% of the full load speed, being dependent on saturation, armature reaction, and brush position.

Because of computation limitations, shunt motors in integral horsepower sizes are not suitable for across the line starting. Shunt motors designed for operation over a given speed range by
field control are not technically shunt motors, in that a stabilizing series field is added to assure stable speed under weak field conditions. When this winding is included, the possibility of armature reaction demagnetizing the weakened shunt field with a change in load is eliminated. Shunt motors without speed control are used to drive machinery that is designed to run continuously at a constant speed.
Compound Motors

The addition of a cumulative series field winding to the shunt field produces a compound motor. The addition of this series field winding gives the motor a characteristic which is a combination of the series and shunt motor.

The speed changes with the load, but it does not change as much as in a series motor, and it usually changes a great deal more than in a shunt motor. Like the series motor, the compound motor has excellent characteristics for starting heavy loads and yet is in no danger of "running away" at light loads when used without a speed controller.

Compound motors are used for loads requiring high starting torque, or for loads subject to torque pulsations. They are not practical for applications requiring adjustable speed by field control. With a weakened shunt field, the series field flux becomes a greater portion of the total flux; hence the changes in load may produce unstable speeds.

Compound motors are commonly employed for elevators, air compressors, ice machines, certain kinds of hoisting and conveying machinery, printing presses, paper cutters, pumps, and other machinery where the load fluctuates suddenly or periodically, and where constant speed is not essential. They are usually designed so that there will be a drop in speed of about 20% between no load and full load. Compound motors may be wound for greater or less speed change to meet special conditions and are usually wired for
across the line starting in sizes up to 5 HP (3.73 Kw). Compari-
sons of the speed-torque characteristic curves of series, shunt, 
and compound DC motors are given in Fig. 1.6.

In the remainder of this report the shunt connection of DC 
motor is discussed. It is focused on the speed control of shunt 
motor (separately excited) in various techniques and its applica-
tion in electrical vehicles.¹

The remainder of this chapter is devoted to the theory 
of the shunt motor in order to gain insight into the concept of 
speed control of shunt motors in the succeeding chapters.

The shunt motor (separately excited) is operated in drive 
systems with the main or shunt field supplied with field current 
independently of the armature. The field current may be kept con-
stant or adjusted to supplement the speed range. A sketch showing 
the cross section of a shunt motor is given in Fig. 1.7a. All of 
the possible windings are shown, although some may not be used in 
every application. The shunt field winding establishes the basic 
magnetic field in the air gap under the poles, which reacts with 
the armature current to produce torque, and with the moving arma-
ture conductors to produce the generated armature voltage. The 
series field winding, used in some motors, acts to increase the 
speed drop when connected additively to the shunt field, and to de-
crease the drop for the opposite connection. The interpole winding 
in the cross field axis acts to assist commutation. Finally, the 
pole face windings act to reduce the armature inductance and to
Fig. 1.6. Speed torque characteristic curves for compound, shunt, and series DC motors of equal size prevent the armature current from distorting the magnetic field produced by the shunt field winding. The windings are connected as shown in Fig. 1.7b.

The steady state operation of the motor is governed by three equations. The total armature circuit voltage is

\[ V_m = V_a + I_a R_a \quad \text{where} \]

\[ V_m = \text{armature circuit voltage} \]

\[ V_a = \text{armature voltage} \]

\[ I_a = \text{armature current} \]

\[ R_a = \text{armature circuit resistance} \]
The generated armature voltage is given by
\[ V_a = K \phi_f N \]  
where
\[ \phi_f = \text{magnetic field flux} \]
\[ N = \text{motor speed} \]
and, the internal torque is
\[ T = K_t \phi_f I_a \]  
(1.3)
The torque constant \( K_t \) and armature voltage constant \( K \) are equal in a consistent set unit (mks). The simultaneous solution of the three equations yields for the speed
\[ N = \frac{V_m - T (R_a / K_t \phi_f)}{(K_a \phi_f)} \]  
(1.4)
The second term of the numerator of Equation 1.4 is usually small, say five percent of the first term, \( V_m^2 \).

In the next chapter the various techniques of speed control based on Equation 1.4 will be discussed.
CHAPTER II

SPEED BEHAVIOR AND BRAKING OF SHUNT DC MOTORS

The speed control characteristics of the DC shunt motor are particularly important since they are often the basis for comparison with other types of motors. Speed can be controlled by two different methods: old methods, using resistors and contactors, and new methods using solid state electronics, transistors, thyristors, etc. Each method is described in detail. Methods of braking are also described in later part of the chapter.

The speed of any DC motor (shunt, series, or compound) can be altered by a change in any of the variables in the fundamental speed equation (1.4).

Four methods of controlling the speed of DC motor will be discussed in the early part of this chapter. After discussion of these four methods, various designs of automatic controllers that incorporate the functions of starting, reversing, controlling speed, and braking are considered. The four methods are:

1. Changing the field flux, $\phi$, by means of a variable series or shunt rheostat. This method is known as "field control: (Fig. 2.1).

2. Changing the voltage $V_a$ across the armature by using a
variable resistance in series with the armature. This method is called "armature resistance control" (Fig. 2.1).

3. Changing the voltage across the armature, and the current $I_a$ in the armature, by a combination of two variable resistance in parallel and in series with the armature. This method is called "series and shunt armature resistance control" (Fig. 2.2).

4. Using a controlled source of variable DC voltage to change the voltage $V_a$ across the armature of a separately excited motor. This method is known as "armature voltage control" (Fig. 2.3).

Field Control

When the rated or line voltage is applied to the armature of a DC motor ($V_a = V_1$) and the field flux is manually or automatically varied by means of a field rheostat in series or in parallel with the field excitation winding, the method of speed control is called "field control". As shown in (Fig. 2.1), when the motor is started and the variable armature resistance is shorted out (at point a) so that $V_a$ equals $V_1$, control of the speed may be achieved by varying the field rheostat from point a' (no added field resistance or full field current) to point b' (maximum field resistance or minimum field current).

The speed achieved with the full armature voltage and full field current (no added field resistance) is called the basic speed
of the motor. Increasing the field resistance, therefore, will decrease the field current and field flux in the fundamental speed equation, causing the speed to rise. Field control can therefore produce only speeds above the basic speed.

Field control as a method to obtain speeds above basic speed has the following advantages over other speed-control methods: (1) field control is relatively inexpensive and simple to accomplish, both manually and automatically; (2) it is relatively efficient in terms of motor performance, since the field circuit loss is only 3 to 5 percent of the total power drawn by the motor; (3) within limits, field control does not affect speed regulation in the cases of shunt, compound, and series motors; and (4) it provides relatively smooth, stepless control of speed.

The third advantage, however, carries with it a warning that this method of speed control is achieved by weakening the field flux within limits. If the field is weakened considerably or interrupted completely, dangerously high speeds are produced.

With a weak field and a high armature current, the DC shunt motor is particularly susceptible to the effects of armature reaction instability and may run away in the same manner as a differential compound motor. It is precisely for this reason, moreover, that DC motors are started with full field current. With a high speed and high armature current, moreover, commutation difficulties are increased, as the high armature currents are reversed more rapidly and serious damage to the commutator may be produced in arcing. It is
customary to set a maximum permissible limit on the overspeed when using field control as a method of speed control. Usually this is 1.5 times the basic speed. Thus, disadvantages of this method are (1) inability to obtain speed below the basic speed, (2) instability at high speeds because of armature reaction, (3) commutation difficulties and possible commutation damage at high speeds.

![Diagram of Field and Armature Resistance Control](image1)

**Fig. 2.1.** Field and armature resistance control

![Diagram of Series and Shunt Armature Resistance Control](image2)

**Fig. 2.2.** Series and shunt armature resistance control

![Diagram of Armature Voltage Control](image3)

**Fig. 2.3.** Armature voltage control
Armature Resistance Control

When the field rheostat is set so that normal field excitation (in the saturation region) is produced, and the voltage across the armature is reduced, by means of a variable resistance in series with the armature, the method of speed control is called "armature resistance control". As shown in Fig. 2.1, the field rheostat is adjusted to provide normal excitation, and the series armature resistance is adjusted so that the armature voltage, \( V_a \), is varied below the line voltage, \( V_1 \). Control of speed is obtained by varying the resistance in series with the armature. Increasing the series armature resistance reduces the voltage across the armature (at any given load) in the fundamental speed equation, (1.4) causing the speed to drop. Therefore armature resistance control can produce only speeds below the basic speed.

The armature current is a function of the load. At any setting of the series armature resistance, an increase in load will produce an increased voltage drop across the series connected armature resistor, which produces a drop in speed. For any no-load speed setting below the basic speed, armature resistance control will produce a sharp drop in speed with the application of load, resulting in poor speed regulation. The current flowing through the series-connected armature resistance will produce an appreciable power loss \( (I_a^2R_s) \), which reduces the overall motor efficiency. This power loss does not produce heat within the motor, but it does require a large continuously rated, externally connected, variable resistor capable
of carrying the rated armature current. This variable resistor may be used both for motor starting and for speed control.

The disadvantages of armature resistance control are (1) the relatively high cost of large, continuously rated, variable resistors capable of dissipating large amounts of power (particularly in higher horse power ratings), (2) poor speed regulation for any no load speed setting, (3) low efficiency resulting in high operating cost, (4) difficulty in obtaining stepless control of speed in higher power ratings. The combination of armature and field resistance control of a shunt motor, shown in Fig. 2.1, provides a reasonably effective and relatively inexpensive means of providing speeds both above and below the basic speed in the case of smaller DC motors. In the larger horsepower ratings, where extremely low speeds may be required for "inching" or "jogging" control, a fairly high resistance is required in the armature circuit of relatively high power rating. Such a resistance produces inefficient operation and is relatively expensive. This difficulty is overcome by series and shunt armature resistance control.

**Series and Shunt Armature Resistance Control**

The schematic diagram of a rheostatic speed control using combined resistances both in series and in parallel is shown in Fig. 2.2. $R_{sh}$ is a variable resistor shunting the armature, and $R_s$ is a variable resistor in series with the armature. The former acts as a diverter, tending to reduce the armature current as its
(R_{sh}) resistance is reduced. The latter, R_s, acts in the same manner as in the simple armature resistance control described in the preceding section. Thus, in the fundamental speed equation,

\[ N = k \frac{V_a - I_a R_a}{\phi}, \]

for a constant field flux, at any given load, an increase in R_s will produce a decrease in V_a and a drop in speed. An increase in R_{sh} will produce an increase in the I_a R_a drop and also a drop in speed. The speed may be raised, therefore, by decreasing both R_s and R_{sh} (the latter within limits). As in the case of field control, there is a maximum permissible limit to the shunting effect produced by R_{sh} at higher speed. If R_{sh} approaches a short circuit across the armature, extreme torque instability occurs as a result of tendency toward high speeds and increased loads. The net effect of the shunt resistor, R_{sh}, is to make the operating speed less susceptible to changes in load torque and, as a result, improve the speed regulation of the motor over that which might be obtainable using only resistance control. However, a reduction in shunting resistance produces a proportionate reduction in developed torque.

Shunting resistors across the armature are used with armature resistance control, therefore, where it is desirable to maintain approximately the same operating speed and where the load torque may tend to vary. Fig. 2.2 also shows the basic switching circuit for starting and running with series and shunt armature resistance control, as well as the switching sequence used with these contactors. On starting, only contactor 2A is closed. This provides the maximum protective resistance in series with the armature, as
well as controlled current in the armature, in order to develop the necessary starting torque. The motor is accelerated in progressive steps by (1) opening n.c. 2A, (2) closing n.o. 3A, and (3) closing n.o. 4A. At time \( t_1 \) shown in the sequence diagram, therefore, all contacts are in their operating position and the motor is running as a shunt motor.

Progressive decreases in speed with reasonably good speed regulation may now be obtained by opening (deenergizing) 4A at time \( t_2 \), followed by 3A, at time \( t_3 \), deenergizing 2A (1A is open and energized) to provide combined series-shunt armature resistance at time \( t_5 \). Thus, in the last case, running with all the contacts as shown in the figure provides the lowest running speed, with better speed than provided by increasing the series armature resistance.

The advantages of this method are (1) improved speed regulation (better than with armature resistance control), (2) possible use of the armature shunting resistor for dynamic braking.

The disadvantages are (1) reduced operating torque with increased diversion of armature current, (2) reduced efficiency because of power losses in the series and shunt resistors.

**Armature Voltage Control**

In the case of motors of higher horsepower, efficiency, torque, good speed regulation, and smooth stepless speed control are all extremely important considerations. Heavy loads with high inertia require smooth acceleration over a wide speed range. All
these criteria may be achieved by using a variable DC voltage from a source of sufficient capacity to supply the required armature voltage and current to a DC motor. The field is always separately excited from a constant-current or constant-voltage source, as shown in Fig. 2.3. This method also eliminates the need for series armature starting resistance. If the armature voltage supplied from the variable DC source is zero, the motor develops zero torque \( T=k\phi I_a \) and is at a standstill. If the armature voltage is increased slightly, in accordance with, \( N = k(V_a-I_aR_a)/\phi \), the motor starts and turns at a low speed with a minimum of acceleration. The armature current is limited because of the low voltage across the armature. Reducing the armature voltage to zero, and reversing the polarity of the variable voltage source, will stop and reverse the motor in accordance with the left-hand motor rule. For DC motors of fractional and relatively low horsepower rating, the variable DC voltage source may be a semiconductor (SCR) amplifier, operating from a three-phase or single-phase AC supply. Motors of moderate rating, up to 100 HP, may be armature-voltage controlled using rotary amplifiers such as Rototrol, Regulex, or smaller amplidyynes. In addition, static amplifiers such as magnetic amplifiers may be used as the adjustable DC voltage source. Large DC motors, above 100 HP, are controlled in this manner by means of rotary amplifiers such as the amplidyne or the Ward-Leonard control system.
In summary all four methods of speed control of shunt DC motor are shown in Fig. 2.4.

**Field resistor control**

\[ S = \frac{E_o}{K\Phi} = \frac{V_o - I_a R_s}{R_s + R_{shR}} \]
\[ \omega = \frac{E_o}{k\phi} = \frac{V_o - I_a R_s}{k\phi} \]

\( \phi \) or \( \phi \) changes along saturation curve as \( R_{shR} \) changes

\[ I_s = I_a - I_{sh}, I_{sh} = \frac{V_o}{R_{sh}} \]

Increasing \( R_{shR} \) increases speed

- Decreasing torque, constant power as speed increases

**Shunt field and series armature res. control**

\[ S = \frac{E_o}{K\Phi} = \frac{V_o - I_a (R_s + R_{ser})}{R_s + R_{ser} + R_{shR}} \]
\[ \omega = \frac{E_o}{k\phi} = \frac{V_o - I_a (R_s + R_{ser})}{k\phi} \]

\( \phi \) or \( \phi \) changes as in circuit 1

\[ I_s = I_a, I_{sh} = \frac{V_o}{R_{sh} + R_{shR}} \]

Increasing \( R_{shR} \) increases speed

Increasing \( R_{ser} \) reduces speed

**Series and shunt armature res. control**

\[ S = \frac{E_o}{K\Phi} = \frac{V_o - I_{sh} R_{ser} - I_a R_s}{R_s + R_{shR}} \]
\[ \omega = \frac{E_o}{k\phi} = \frac{V_o - I_{sh} R_{ser} - I_a R_s}{k\phi} \]

\( \phi \) or \( \phi \) fixed point on saturation curve

\[ I_{ser} = I_a - I_{sh}, I_{sh} = \frac{V_o}{R_{sh}}, I_a = I_{ser} - \left[ \frac{V_o - I_{sh} R_{ser}}{R_{shR}} \right] \]

Increasing \( R_{ser} \) reduces speed

Decreasing \( R_{shR} \) reduces speed

**Line voltage control**

\[ S = \frac{E_o}{K\Phi} = \frac{V_{adj} - I_a R_s}{K\Phi} \]
\[ \omega = \frac{E_o}{k\phi} = \frac{V_{adj} - I_a R_s}{k\phi} \]

\( \phi \) or \( \phi \) may be fixed or separately adjustable on saturation curve

\[ I_s = I_a, I_{sh} = \frac{V_{adj}}{R_{sh}} \]

Increasing \( V_{adj} \) increases speed

Increasing \( V_{sh} \) reduces speed

- Constant torque, power increases with speed

**Fig. 2.4. Shunt motor speed control (3)**
Reversing DC Motors

It is possible to reverse the direction of rotation of any DC motor by reversing the direction of either its field flux or its armature currents, in accordance with the left-hand motor rule. Reversing both the field flux and the armature current simultaneously, by reversing the line connections, produces torque in the same direction, and the direction of rotation is unchanged. Thus, a DC series, shunt, or compound motor may be reversed by (1) reversing the direction of current in its armature circuit (including the interpole and compensating winding), or (2) reversing the direction of its shunt and/or series fields only, the direction of armature current, compensating winding, and interpole flux remaining the same. The most popular method of reversal is to reverse the armature connections, despite the fact that heavier currents are interrupted. There are two disadvantages associated with field reversal: (1) opening the field for reversal purposes may cause dangerous runaway, instability, and exceedingly high armature currents; (2) the field is more highly inductive than the armature; opening a highly inductive circuit will produce more severe arcing and voltage break-down than in interruption of the armature circuit.

It is usually customary to "brake" a motor prior to reversing so that during the period that a motor slows down (prior to reversal) its armature is drawing little or no current from the line.

An electrically reversible motor is defined by the ASA as one which can be reversed by changing the external connections, even
when the motor is running. All DC motors fall into this category. Thus, if the motor armature connections to the supply are reversed, a form of braking known as "plugging" occurs automatically. Plugging is the principle of applying power to a motor in such a direction that it attempts to reverse. Since it obviously must stop, or pass through a standstill condition, before it can reverse, it is possible to stop or "brake" a motor by plugging.

Motors may be reversed manually, using cam-operated or drum switches, or automatically, by means of relays and contacts. The basic circuit for shunt-motor reversal is shown in Fig. 2.5. A set of M contacts is used to energize the field circuit and (if automatic starting is used) a control circuit. Closing the F of forward contacts will produce one direction of rotation.

Closing the R contacts will produce the reverse direction of rotation and armature current. As may be seen from Fig. 2.5. Closing both the F and R contacts simultaneously will produce a short circuit directly across the line. In the case of manual switching, this is hardly likely because, in moving from forward to reverse, a transition (open) occurs in which the F contacts are opened and the R contacts are closed. In this case of automatic reversal, it is necessary to use electric and mechanical relay interlocks to prevent both sets of contacts from being energized simultaneously.
Fig. 2.5. Basic circuit for manual or automatic reversing of shunt DC motor

A controller for the automatic starting and reversal of a shunt motor using electric and mechanical interlocks of contacts and relays is shown in Fig. 2.6. The configuration of the armature and field circuit is essentially the same as shown in Fig. 2.5 with the addition of dashpot (or other suitable) time-delay relays 1A, 2A, and 3A. The unique features of this controller are in the control circuit. For the operating discussion see reference 4.

**Plugging Braking**

When a motor armature is running in a specific direction and its armature applied voltage polarity is reversed, at that instant the counter emf is in phase (of the same polarity) with the applied voltage. The total applied voltage across the unprotected armature then is practically twice the voltage that may occur at the moment of starting, without any protective resistance in series with the armature. The maximum possible current (usually 1.5 times rated) on starting is the same as that which should flow at the instant
Fig. 2.6. Controller for automatic reversal of a DC shunt motor

(a) Complete schematic using electrical and mechanical interlocks

(b) Alternate control circuit using mechanical interlocks only.
that plugging is initiated. Therefore, for proper plugging, addition-
al series armature resistance, over and above the starting series
armature resistance, should be introduced, in order to limit the
armature current to a safe value. Thus, while the normal starting
resistance in Fig. 2.6a may serve to limit the current as the speed
decreases and reverses, it does not provide sufficient resistance
for plugging at the time when such resistance is most required, i.e.,
at the moment when the polarity reversal occurs (since it takes
time for the contacts to drop out)\(^4\).

**Dynamic Braking**

When the armature of a motor is disconnected from its supply, it will come to a stop eventually, despite the inertia of its load, because energy is no longer provided to the armature and mechanical losses are present. If the field excitation of a DC motor is main-
tained at the time that the armature is disconnected from the supply, the moving armature conductors will have a voltage induced in them and the deenergized armature will act as a separately-excited generator. The prime mover of the armature is the inertia of the motor rotor and its connected load.

If an electric load in the form of a resistor is connected across the deenergized armature of a DC motor, the motor will be brought to a stop very rapidly, since the inertia of the motor arma-
ture (as prime mover) must supply both electric and rotational
losses. This form of braking in which the motor armature (only) is
deenergized, connected across a resistor, and permitted to dissipate
its rotational energy as a generator, is "dynamic braking".

Because a resistor is required in series with the armature of
a DC motor for purposes of motor starting, it is customary to use a
portion of this resistor as a braking resistor to dissipate the
generated energy of the motor when its armature is disconnected from
the supply. Dynamic braking of a nonreversing shunt motor is shown
in Fig. 2.7. A quick-acting braking relay, B, energized when the
motor is started, maintains the necessary connection through its
n.c. contact B from the starting resistor to the armature. For
controller operation see reference 4.

As in the case of plugging braking, it is sometimes desired
to operate a motor using a sequence which calls first for braking
and then for rapid reversal of the motor. Dynamic braking may be
used to bring the motor to a standstill before the reverse polarity
(plugging) is applied. A typical controller employing dynamic
braking and reversing, or dynamic braking to a quick stop, is
shown in Fig. 2.8.

Regenerative Braking

A third type of electric braking, in addition to plugging and
dynamic braking is "regenerative braking". The term "regeneration"
implies energy return (or generating energy back) to the supply.
Regenerative braking stems quite naturally from dynamic braking,
Fig. 2.7. Dynamic braking of a nonreversing shunt motor using the starting resistance as a braking resistor.
Fig. 2.8. Dynamic braking of a reversing shunt motor using starting resistance as a braking resistor
since it would appear quite logical not to waste or dissipate the rotational energy of a large motor (operating as a generator during dynamic braking) by dissipation in a resistor, but to return that energy to the supply instead.

Any generator is loaded when it is paralleled and supplying energy to a bus. The greater the amount of energy supplied to the bus, the greater the prime-mover energy required to sustain the generator. In the case of a motor rotating at fairly high speed, whenever the load tends to drive the motor in the same direction and full field excitation is applied, there is a strong possibility that the induced voltage may exceed the line voltage. If the nature of the motor load is such that it tends to drive the motor (as in descending elevator, for example), the motor speed will increase and the generated voltage will tend to exceed the line voltage considerably. Motor loads for electric locomotives, trolleys, bases, elevators, cranes, and hoists will have sufficient potential energy (at top of a hill in the case of fraction, or heavy load about to descend in the case of lifting devices) to drive their motor shafts at extremely high speeds. The speed of these motors may be reduced considerably, with practically little waste of energy requiring no mechanical or friction braking, by using regenerative braking. The power returned to the lines may be used for other motors, devices, or equipment served by the bus. In contrast to the internal combustion engine in an automobile, which dissipates its braking energy in brake linings, the electric car offers high
energy-conservation possibilities. On fairly flat surfaces, energy is theoretically required only during acceleration. Similarly, energy is only required in uphill travel. During periods of deceleration and downhill travel, regenerative braking maintains safe speeds and returns energy to the electric-car batteries. Thus, the only energy required for travel is that consumed by losses inherent in the mechanical and electrical design.

The principal of regenerative braking is very simple. A DC dynamo acts as a motor when its armature is connected to a supply and when the dynamo develops a counter emf that is less than the terminal voltage. The motor will run at a speed determined by its excitation and counter emf \( N = K E/\phi \) as long as it is drawing current from the line (motor action). If, however, the dynamo excitation is increased and it is driven by a prime-mover at a higher speed, the dynamo will send current into the line and acts as a generator. The load on its prime mover as a result of generator action will reduce the prime-mover speed and will cause the dynamo to resume motor action when its counter emf and speed return to a value such that current is delivered by the line to the dynamo. In regenerative braking, therefore, it is not even necessary to disconnect the motor from the line. All that is required is that the motor speed and the field excitation be increased sufficiently to reverse the armature current and produce generator action.
Schematic diagrams of the switching circuits for plugging, dynamic, and regenerative braking are shown in Fig. 2.9 for purposes of a comparison as well as reference. In each of the figures, the motor is accelerated to its rated speed by closing acceleration contacts A. At the end of a specific time, contacts $A_R$ are closed, shorting out the protective series armature resistance. When it is desired to brake the motor, all A contacts are deenergized and all B contacts are energized. In the case of braking by plugging, shown in Fig. 2.9a, the armature polarity is reversed through protective resistor $R$ and the full field flux is applied. In the case of dynamic braking, shown in Fig. 2.9b, the armature is disconnected from the line when the A contacts open, and is connected across a portion of the starting resistance when the B contacts close. Both plugging and dynamic braking will bring the motor to a stop (at which point the B contacts should be opened).

In the case of regenerative braking, shown in Fig. 2.9c, braking occurs automatically whenever the speed of the motor armature is high and the load drives the motor as a generator. Contact B, a reverse current relay, closes to increase the field excitation and braking action during this period.

Regenerative braking will not bring the motor to a stop but serves only to reduce its speed (1) without the necessity for mechanical brakes, and (2) with little energy loss.

The discussion of resistive DC motor control is terminated at this point, and in chapter three the electronic DC motor control...
which doesn't dissipate the energy as much as resistive control will be discussed in detail.

Fig. 2.9. Plugging, dynamic, and regenerative braking of a shunt motor; in schematic form for manual or automatic control (control circuits not shown)
CHAPTER III

ELECTRONIC CONTROLS FOR DC MOTORS

Electronic power control for electric motors probably started in 1930 with a simple power triode or thyroton system. However, electronic control has only relatively recently taken off since the advent of semiconductors. It is probably true that present technology is sufficiently advanced to solve practically any power control problem, the only real limitation being cost. Until recent years capital cost was of greater importance than such things as ease of maintenance, reliability, and efficiency. However, since electronic power control circuits are highly efficient, there is likely to be a gradual increase in the use of solid-state devices in all areas of power control.

The thyristor and transistor are not the ideal power control devices, but they go a long way towards providing ideal control systems. There follows a description of the solid-state devices that are widely used in power control circuits. There are three types of device suitable for wide scale use in motor and other power control systems, namely:

The Thyristor
The Triac
The Transistor
The Thyristor is the most commonly used in applications ranging from simple electric drill speed controllers to complex high power inverters, and will be discussed in detail. The Triac is in fairly wide use, but it is limited in use to the control of AC systems and is, therefore, not so versatile as the thyristor and the transistor. The Triac is essentially two thyristors connected in reverse parallel. The transistor as described later is the most promising of semiconductor current control devices. Providing the present limitations of the power handling capabilities of the transistor are overcome, this device will probably supersede all other semiconductor devices for power control applications.

Power Control Devices

The Thyristor

The term thyristor is the generic name for semiconductor-devices that have characteristics similar to those of thyratron tubes. Basically, this group includes bistable semiconductor devices that have three or more junctions (i.e., four or more semiconductor layers) and that can be switched between conducting states (from OFF to ON or from ON to OFF) within at least one quadrant of the principal voltage current characteristic. There are several different types of thyristors, which differ primarily in the number of electrode terminals and in their operating characteristics in the third quadrant of the voltage current characteristic, as shown in Table I. Reverse-blocking triode thyristors, commonly called
silicon controlled rectifiers (SCR's), and bidirectional triode thyristors, usually referred to as triacs, are the most popular types.

TABLE 1
DIFFERENT TYPES OF THYRISTORS

<table>
<thead>
<tr>
<th>No. of terminals</th>
<th>Third-Quadrant Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Blocking</td>
</tr>
<tr>
<td>2</td>
<td>Reverse blocking diode thyristor</td>
</tr>
<tr>
<td>3</td>
<td>Reverse blocking triode thyristor</td>
</tr>
</tbody>
</table>

The development of the thyristor or silicon-controlled rectifier (SCR) for low and medium power applications in the 1950s has created unlimited possibilities for DC motor control from an AC supply by electronic methods. The small size, high reliability, and relatively efficient SCR has begun to dominate the latter half of the twentieth century for controlling both DC and AC small and medium sized motors from and AC source. As of this time, SCRs up to 400 A (rms) with voltage ratings (peak forward and reverse blocking) up to 1200 V are available. Above 100 HP at 115 DC and 200 HP at
230 V DC some other types of systems such as mercury-arc rectifiers, magnetic amplifiers, rotary convertors, and motor generator sets to convert and supply the direct current required for extremely large DC motors, can be used. An SCR is basically a four layer p-n-p-n device that has three electrodes (a cathode, an anode, and a control gate). Fig. 3.1 shows the junction diagram principal and schematic symbol for an SCR. An analysis of the voltage-current characteristics of SCRs and of the charge-carrier interactions that make possible the switching transitions indicated by those characteristics provides useful information concerning the operation and possible applications of this device. In many drives the AC motor-DC generator set is replaced by a thyristor circuit which utilizes SCRs to rectify the voltage from a constant-voltage AC source and to control the armature current of the DC shunt or separately excited motor.

Fig. 3.1. (a) junction diagram, (b) principle voltage current characteristic, (c) schematic symbol for an SCR thyristor.
Fractional and low-integral horsepower motors are usually supplied from single-phase sources, while larger motors are supplied from three phase sources. The thyristor, ideally has infinite resistance for both directions unless the proper bias is applied to the gate terminal, which causes the thyristor to conduct in the forward direction even after the bias is removed. Fig. 3.2 and 3.3 illustrated the use of half-wave and full-wave circuit in simple single-phase arrangements. The field circuit in either may be supplied through a half-wave or a full-wave rectifier. The simpler circuit in Fig. 3.2 requires only one thyristor, which of course can conduct current only in alternate half-cycles. The portion of half-cycle (from about 0 to 180°) over which the thyristor conducts is controlled by adjusting the firing angle with the application of the proper value of the voltage to the gate terminal G from an auxiliary circuit not shown in Fig. 3.2. Since the single thyristor passes only one phase of current per cycle which has a duration of 180° or less, there are sizable dips in the armature. Less ripple results from full-wave arrangement in Fig. 3.3 in which the bridge circuit comprised of thyristor I and II and diodes III and IV accomplishes rectification during both halves of each cycle. The firing angle of the thyristors determines the amount of direct current supplied to the motor armature.
Fig. 3.2. Single-phase SCR drives, half-wave

Fig. 3.3. Single-phase SCR drives, full-wave

Fig. 3.4. Three-phase SCR drive
Diodes IV, V, and VI provide the return path for the three phase currents. During the dips in the voltage the energy stored in the armature inductance produces a component of current through the path provided by the free wheeling diode connected across the armature. While three phase is more complex, it makes less ripple in that it passes six pulses per cycle. The current ripple increases heating of the armature, and more difficult commutation particularly at light load and high speed, when the pulses are of shorter duration.

Schematics for half-wave and full-wave control of shunt-wound motors are shown in Fig. 3.5 and 3.6. SCRs are also used to control DC motors supplied from DC sources. The advantage of the SCR arrangement, where DC sources are available, is due to the much smaller power consumption of SCRs than that of the resistors that are normally required to control motor speed in the straight DC devices. A method for controlling a shunt motor supplied from a DC source is shown in Fig. 3.7. The DC source arrangement requires a means for turning off the thyristor when the current pulse has attained the desired duration. This is done by means of a commutation circuit which incorporates a capacitor and an auxiliary thyristor. Problems associated with the commutator and brushes impose limits on the size of conventional DC machines. A serious problem is that of commutator deformation caused by centrifugal forces and by local heating resulting in improper brush contact. Another disadvantage is the normal maintenance requirement of commutation and brushes.
Fig. 3.5. Half-wave control of shunt-wound motor

Fig. 3.6. Full-wave control of shunt-wound motor
Fig. 3.7. SCR drive from a DC source for a DC shunt (separately excited) motor
The Triac

The triac is a device which behaves like two thyristors connected back to back as shown in Fig. 3.8. The characteristics of the triac are very similar to the thyristor, as shown in the anode voltage current curve of Fig. 3.9. Either positive or negative pulses on the gate will trigger the triac in either direction. The triac is designed specifically for AC power control, using phase control techniques. A typical circuit is shown in Fig. 3.10, and appropriate waveforms in Fig. 3.11. The triac is in fairly wide use, but it is limited in use to the control of AC systems and is, therefore, not so versatile as the thyristor and the transistor.

For an example, a schematic diagram which is used for controlling a small DC motor is shown in Fig. 3.12.

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The diagrams are as follows:

**Fig. 3.8.** Function diagram and schematic symbol for a triac

**Fig. 3.9.** Principle voltage current characteristic for a triac
Fig. 3.10. Basic triac circuit for controlling AC supplies with or without transformer

Fig. 3.11. Voltage waveforms in Fig. 3.10
Fig. 3.12. Speed control of a small DC motor using triacs (Texas Instruments Ltd.)
The Transistor

The transistor is a device which only passes current when a base current is applied, and ceases to do so when the base current is removed. Connections and currents are shown in Fig. 3.13 and the typical collector-emitter characteristics for various values of base current are shown in Fig. 3.14. For most control power work, the transistor is used as a switch. Because of the current gain of transistor (typically > 10) a relatively small base current will control a large collector current. The transistor is inherently more reliable in its switching than the thyristor, since no collector current can flow if there is no base current. The transistor is therefore unlikely to turn on when not required. Although the transistor is a more reliable switch, it is somewhat less rugged than the thyristor. Its main problem is its limitation on peak currents. If the collector current exceeds a figure equal to base current times the current gain ($\beta I_h$), the transistor forward volts drop will rise considerably, and hence will drastically increase its power dissipation. In one other respect the transistor is not as rugged as the thyristor. This is when switching inductive loads. When a transistor, with an inductive load connected to its collector, is turned off, the collapse of flux in the inductive causes the voltage across it to increase. This voltage appears across the transistor, and has the effect of forcing current through it, against the turn-off action. This increases the dissipation in relatively small areas in the transistor and causes localized hot
Fig. 3.13. NPN and PNP transistor symbols and currents

Fig. 3.14. Collector V/I characteristic of transistor with collector load
spots. If allowed to exceed certain values, this increased dissipation can destroy the transistor. Manufacturers have produced curves of safe working areas for their transistors during switching. This effect is called secondary breakdown.

A typical example of a power control application for transistors is next described. The waveforms of Fig. 3.15 indicates that diagonal pairs of transistors are switched on together, causing the voltage across the load to reverse each time the pairs are changed. This circuit provides an alternating square wave output from a DC supply and is called an inverter. By adding another two transistors and switching them all in the right sequence, a three-phase inverter can be easily obtained. There are commercially available AC variable-frequency motor control systems that use transistors in this type of circuit. The diodes across each transistor enable inductive currents to be switched without damaging the transistors. Inductive current can flow through the diodes when the transistors turn off. The diodes also clamp the load voltage to that of the supply.

As an example of the use of transistors in the speed control of a DC motor, the author has built a controller (designed by Motorola Semiconductor Products) for the shunt, separately excited permanent magnet motor. This circuit was a prototype of the field controller. It was modified in order to match the armature chopper circuit (separately excited motor) for the Electric Car project. The circuit behavior and original speed-torque characteristics which have been tested by Motorola Inc. are next described in detail.
Fig. 3.15. Basic transistor bridge inverter circuit and associated output waveform
Feedback Speed-Control Circuit for Shunt and Permanent-Magnet Motors

The feedback arrangement depicted in the schematic diagram of Fig. 3.16 is a design by Motorola Semiconductor Products, Inc. This circuit is speed controller for permanent-magnet motors. It is also applicable to shunt motors, in which case it would be preferable to excite the field from a constant-current source. The speed-torque characteristics are shown in Fig. 3.17. This is an "on-off" system in which operating current is parcelled out to the motor armature in such a way as to maintain a near constant speed. It bears a resemblance to pulse-width modulation but is not ordinarily so designated because both the on time and the current vary. It shares the salient feature of pulse-width modulation, however, in that motor current is either on or off; there is no power dissipation from intermediate current values, as in rheostatic control. The average value of armature current is the controlled parameter, and this is a function of the average duty cycle.

The second parameter is not directly motor speed; rather it is the voltage drop across the base-emitter junction of power-output transistor Q5. This quantity, $V_{BE}$, varies with the motor current. For example, if increased mechanical load is applied to the motor, it tends to slow down and this decreases its counter emf so that it can consume more torque-producing current. Voltage drop $V_{BE}$ in Q5 then becomes greater because of higher collector current. The
sense transistor is \( Q_6 \), and DC voltage that represents motor speed is developed at point "A". This voltage is applied to the input of a Schmitt-trigger circuit that includes transistors \( Q_1 \) and \( Q_2 \). A "comparison" voltage derived from the SPEED-ADJUST control, \( R \), is also applied to this input. The conduction state of transistor \( Q_2 \) is therefore governed by the net DC voltage sampled by the base of input transistor \( Q_1 \). Transistor \( Q_3 \) is a simple DC amplifier stage for more effective actuation of drive transistor \( Q_4 \). Transistor \( Q_5 \) is the power-output stage which actually "meters" current to the motor armature.

The final essential element is the free-wheeling diode, \( D_3 \). This diode provides a path for armature current during intervals when transistor \( Q_5 \) is in its off state. The source of this current is the energy stored in the magnetic field of the motor. A more-constant torque results from this current path through \( D_3 \). Without \( D_3 \), this stored energy would manifest itself as a destructive voltage spike. As already pointed out, an increased motor load results in a higher base-emitter voltage, \( V_{BE} \), in power-output transistor \( Q_5 \). This voltage is sampled by feedback sense stage \( Q_6 \), and a DC voltage that is proportional to the average \( V_{BE} \) in \( Q_5 \) is developed across capacitor \( C_4 \). When a higher voltage is thus developed across capacitor \( C_4 \), it causes input stage \( Q_1 \) of the schmitt trigger to shorten its conduction intervals. The resultant increase in on time for stage \( Q_2 \), and for all subsequent stages through \( Q_5 \), causes a higher average current to be delivered to motor armature, thereby restoring
much of the depleted speed. The opposite reactions take place when the load on the motor is relaxed.

The circuit of Fig. 3 involves positive feedback. (An increase in armature current begets a future increase.) However, the feedback factor is not sufficient to cause any instability. The motor itself tends to discourage a cumulative build up to either a "hung-up" or an oscillatory condition because as each increment of additional current produces increased speed, the counter emf is increased, thereby inhibiting development of runaway current.

It will be observed that the Schmitt-trigger voltage divider, made up of $R_5$, $R_8$, $R_9$, and $R_{11}$ connects across the 12-volt power source. Because of this, if the voltage from the power source becomes higher, transistor $Q_2$ will be biased on for a shorter time, thereby tending to prevent increased average current from being delivered to the motor. Although this compensating action is not perfect, it makes motor speed much less dependent upon supply voltage than would otherwise be the case.

Because of varying characteristics in motors and wide tolerances in transistor parameters, the optimum value for resistance $R_{15}$ will generally require trial-and-error determination. As was said at the end of the last section, this circuit was modified in order to build a field controller for the separately excited shunt motor (20.8 HP) to match an armature chopper circuit in the electric car project. A picture of the circuit and its waveform is shown in Fig. 3.18 and Fig. 3.19.
Fig. 3.16. DC motor speed-control circuit utilizing current feedback
(a) "Natural" characteristics when motor is powered from a tapped battery or a voltage regulated power supply.

(b) Speed-torque characteristic upon the same motor is controlled by feedback circuit in Fig. 3.16. Courtesy of Motorola Semiconductor Products, Inc.

Fig. 3.17. Speed-torque characteristics of DC permanent magnet motor.
(a) Low average current

Vertical: 5V/div.
Horizontal: 1 msec/div.

Fig. 3.18a. Output waveform of pulse modulator with 2Ω load resistor
(b) High average current

Vertical: 5V/div.
Horizontal: 2 msec/div.

Fig. 3.18b. Output waveform of pulse modulator with 2Ω load resistor
Fig. 3.19a. Three-quarter view of feed back speed control circuit
Fig. 3.19b. Top view of feed back speed control circuit
The independent speed and torque control of a shunt motor (and the permanent magnet motor as well) are discussed next. The electromagnetic torque developed in the armature is almost directly proportional to armature current. Therefore, limiting the armature current also defines the maximum torque that can be developed. This follows from the equation for torque $T$, where $T = K I_a \phi$. In this relationship, $K$ is constant, and is a function of design parameters of a given motor, such as a number of poles, the characteristics of the magnetic material, the dimensions of the air gap, etc. Since field strength $\phi$ is, or can be constant, it follows that torque is directly controllable by means of armature current. The control of speed is generally assumed to be derived from torque control and the two performance parameters may appear to be interdependent.

However, the speed of a shunt motor (or permanent-magnet motor) is fairly constant with respect to the torque extracted from the shaft. Moreover, the speed of these motors can actually be controlled by armature voltage while holding armature current constant. What is needed is a controller that will produce abrupt current limiting, as is attainable from laboratory power supplies that have current-limiting controls.

The speed-torque characteristics of a shunt motor with an SCR control unit which allows independent adjustment of speed and torque is shown in Fig. 3.20. These curves also show the way in which
independent adjustment of speed and torque can be attained.

The torque adjustment has a number of uses. With essentially light load, if the load demand exceeds the torque adjustment setting, the motor will slow down drastically, or stop. This prevents overloading the horsepower rating of the motor. Similarly, the motor will not overexert itself when presented with loads requiring higher starting torques than those allowed by the setting of the torque potentiometer. When a drive motor attempts to overcome a "jam-up" in the driven-machinery those features which were described above are valuable.

The torque-control feature can be used for "softening" the starting interval and for controlling acceleration to a preset speed when essentially inertial loads are used.

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Fig. 3.20. Curves showing independent speed and torque control of a shunt motor
The Torque Control of DC Motor
by Use of Current Feedback

As already shown, speed is not the only motor operating parameter amenable to electronic control. Others are starting, stopping, positioning, torque, horsepower. Another interesting and useful control technique is shown in Fig. 3.21. The torque of a DC shunt or a permanent-magnet type is controlled independently of speed. This is done by feed-back current. The torque command voltage is, in essence, an adjustable reference source. For any given value of torque-command voltage, the current in the armature of the motor is maintained at a constant value. Since the torque is proportional to armature current, it also is "programmed" by the torque-command voltage.

The motor is by its nature a current-to-torque transducer. The power converter is, because of the current feed-back loop, a voltage-to-current converter. Therefore, the overall arrangement produces torque in response to input voltage. Although speed depends on the applied mechanical load, it will be recalled that the speed regulation of shunt motor justifies the classification of this type as constant-speed machine. It should be mentioned that the motor employed in such a torque-control system will actually display poorer speed regulation than it normally would without without control. This is because any current regulating process degrades the voltage regulation across the load through which the current is stabilized. Inasmuch as motor speed is proportional to armature
voltage, it follows that the speed in such a system will tend to be an undisciplined performance parameter. However, this is generally not of detrimental consequence in many torque-control applications such as winders, un-winders, tension mechanisms, etc.

A simplified schematic diagram of a power-conversion bridge suitable for the torque-control technique is shown in Fig. 3.22. The bridge is unidirectional in the sense that current always flows in the same direction through the motor. For the waveforms plot see reference 10.

![Simplified schematic diagram of a power-conversion bridge](image)

**Fig. 3.21.** Torque control of a DC shunt or permanent-magnet motor
Another type of speed control is accomplished by a tachometer feed-back system. A speed-control system cannot be more accurate than the method used for the actual sensing of motor speed. Although there is close correlation between impressed armature voltage and speed, and between counter emf and speed, there are applications where more precise speed sensing is needed. This is attained by coupling a DC generator, or tachometer, to the motor shaft. Thus a DC voltage representing speed is produced. This voltage can represent speed quite accurately and is not influenced by armature reaction, current, or temperature within the motor itself. Also the polarity of the tachometer voltage changes with the direction of rotation. This is a fortuitous convenience in bidirectional systems. The tachometer signal is usually fed back to the input of the system, where it is compared with a variable reference, or
speed-command, voltage. The comparison produces an error voltage of the polarity required to extinguish itself by correcting the motor speed. And, as long as the speed-command voltage is held constant, the motor speed will be maintained constant despite variations in mechanical load or in other motor operating factors.

A block diagram of a speed-control system using tachometer feedback is shown in Fig. 3.23. It will be observed that there are other feedback loops as well. These are for the purposes of linearizing overall response, increasing bandwidth, and limiting current.

The tachometer feedback loop embraces all the amplifier stages and therefore is instrumental in determining motor speed. The system shown is intended for use with either a permanent-magnet motor or a shunt motor. With a shunt motor, the high end of the speed range can be extended by reducing field current. However, the available torque will then be less for these higher speeds. If the motor size and the nature of the load are such that a safe temperature rise can be maintained in the motor, the tachometer speed-control method of Fig. 3.23 will work with any type of DC motor $^{10}$.

In the next chapter the application of the DC motor, and the various types of controllers used for the electric car is discussed.
Fig. 3.23. Speed-control system using tachometer feedback
CHAPTER IV

VARIOUS TECHNIQUES OF SPEED CONTROL FOR ELECTRIC VEHICLES

The basic function of the controller in an electric car is to regulate the voltages delivered to the drive motor by proper conditioning of the voltage available from the power source. While this is the basic function, other secondary functions, such as regenerative braking and current limitation, may be incorporated in the control system. Several different methods for accomplishing this regulation are in use today, and the particular one to be employed will depend upon the type of drive motor used, car driving pattern, cost, and other system parameters.

Before discussing the various control methods, the different types of drive motors which are used in electrical vehicles will be considered.

There are basically three types of DC motors in use in electrical vehicles today: the separately excited, series-wound, and compound-wound motors. The separately excited motor is one in which the field windings are excited by a voltage independent of that applied to the armature. This is in contrast to a shunt-wound motor, in which the field windings are connected in parallel with
the armature and thus the field and armature receive the same voltage. The separately excited motor has an advantage over other motors in that some motor control can be obtained by controlling only the field voltage (or field strength), which means that the controller need handle only the relatively small current in the field as opposed to the much higher current in the armature. The disadvantage of this type of motor is that its speed cannot be controlled down to zero speed using only field control. The lowest speed to which the motor can be reduced is dependent upon the maximum field strength attainable.

The series-wound motor has the field windings connected in series with the armature; thus the field and armature currents are the same. The series-wound motor has a very high starting torque, which makes it desirable for vehicular applications. A controller used with this type of motor must be capable of handling the maximum armature current permissible in the motor, typically several hundred amperes.

The compound-wound motor has both series and shunt field windings. The shunt field windings may or may not be separately excited. This motor retains the high torque characteristics of the series-wound motor but also permits the low current field control over part of the speed range. The AC type of motor which is normally used in traction systems is squirrel cage induction. It is considerably lighter, smaller, and less costly than a DC motor of comparable power; hence the interest in AC traction systems. However, its
high operating speed dictates the use of gear reduction for acceptable vehicle performance. The comparison, advantages and disadvantages of different types of motors are:

1. AC induction motors
   a. Advantages—higher HP/lb than in DC motors; can be over loaded for short periods of time.
   b. Disadvantages—requires AC current, which must be converted from DC battery power.

2. DC Motors
   a. Advantages—control circuitry very simple; wide range of control available.
   b. Disadvantages—low HP/lb ratio and tendency to overheat in high load low speed situations. Tendency to overspeed if control circuitry shorts out.
   c. Type of DC motor—(two main types used in autos) series-wound armature and field are connected in series so that the same high current flows through both. Separately excited-field windings, which require only a very small excitation current, are isolated from the high current armature windings.

3. DC Permanent Magnet Motors
   a. Advantages—high HP/lb ratio, flexibility in design, long life for DC motor.
   b. Disadvantages—still experimental, high cost special design.
While the AC motor would appear to be a better choice for an electrical drive system, this choice has been rejected due to high control circuitry costs.

The DC separately excited motor is the best choice for the maximum conversion because:

1. Separate field and armature excitation allows maximum power utilization.
2. Separate control of armature and field current provides wide range of speed control.
3. Direct current operation allows control circuitry and its associated losses to be by-passed when full current is used in either field or armature windings.
4. Use of separately excited motor allows for most efficient circuitry for both armature and field control. This is a significant factor, since field and armature currents are quite different.
5. Over speed condition minimized in separately excited motor.

**Motor Control Circuitry**

The speed of an electrical motor depends upon the voltage at which it operates and the amount of current passing through it. In order to control the speed of an electric motor the operator must control one or the other of these parameters.

One of the oldest and simplest control methods for electrical
vehicles is to use a variable resistance between the power supply and the drive motor. Usually this variable resistance is produced by inserting and deleting fixed resistors in series and/or parallel configurations so as to produce a step resistance control. These various configurations can be indexed by moving a rotating contactor as was done in early electric street cars. A more sophisticated technique for this indexing process is to open and close various mechanical relays. These relays can be activated by an accelerator pedal linkage. Alternatively, the relays may be activated by switches whose closure depends upon vehicle speed so as to give a programmed acceleration. Two examples of variable resistance controls are indicated in Fig. 4.1.

![Variable Resistance Control Systems](image)

**Fig. 4.1.** Representative variable resistance control systems
While the resistance control is simple it has two obvious disadvantages; it is wasteful of energy in that power dissipated through the resistors is lost and it tends to produce a jerky motion in the vehicle as the various resistors are stepped through by the controller. The dissipation of energy as heat can be used in heater to warm up the air in the car in cold weather, but it will be wasted in other times. This disadvantage is of course fundamental and cannot be eliminated. The second can be minimized by using several resistance steps but this will add to the complexity and cost of the controller. The jerkiness could be eliminated by using a rheostat control, but rheostats capable of handling the large current demand of the motor are very heavy and costly.

Another method of voltage control is to connect the individual batteries which constitute the proper supply in various series and parallel configurations so as to produce multiple voltage steps up to the maximum available from the power supply. Two examples of such battery switching systems is indicated in Fig. 4.2. Obviously, the voltage increments possible in such a system will be some integral multiple of the individual battery voltages, usually 6 or 12 volts. As with the step resistance control, the various parallel and/or series configurations can be indexed by mechanical relays. The parallel-series battery switching eliminates the waste of dissipated power in the resistance control but it also produces a jerky vehicle motion as the voltage is incrementally changed. This undesirable feature can be reduced by making the voltage
Fig. 4.2. Representative battery switching control systems increments as small as possible, but this in turn adds to the complexity of the system.

Battery scanning is another voltage control method. In this method individual batteries are added in series up to the desired voltage level through mechanical relays. Each time the controller is returned to the off position, a stepper or scanning switch alters the sequence in which the relays close so as to prevent the same battery from being discharged in the low voltage range. Thus if four batteries labeled 1, 2, 3, and 4 are used the sequence of series connections might go 1-2-3-4, then 2-3-4-1, then 3-4-1-2, etc. This system also has the disadvantage that incremental voltage changes can lead to a jerky vehicle motion. An example of this technique,
Fig. 4.3. Representative battery scanning control systems as well as a more sophisticated battery scanning method, are indicated in Fig. 4.3.

The three methods just discussed might be described as mechanical controls in that mechanical means are employed to change the voltage by incremental amounts. However, the development of power semi-conductors has led to electronic control systems in which the voltage can essentially be varied over a wide range up to the maximum of the power supply. This variation is attained by using full power supply voltage but varying the fraction of time in which the battery is turned on by high frequency switching of the semi-conductors. By varying the fraction of on time, the motor can be made to receive an average voltage over a wide range. This interrupted control method is referred to as chopping and the controller is called a chopper control. The type of semi-conductors used in chopper controls are usually transistors and thyristors (SCR's).
1. Principle: Solid state components act as high speed solid state switch (low power dissipation).

2. Types of solid state control components.
   a. Transistor (low switching current used to turn on and off).
      i. very fast
      ii. very efficient
      iii. simple operation
      iv. high cost for high current transistor
   b. SCR
      i. slower switching speed than transistor
      ii. needs low current to turn on, special circuitry involving heavy inductor to turn off
      iii. much lower cost than transistor for high current applications

3. Types of SCR Controllers
   a. DC to AC inverters—convert direct current to alternating current by alternately switching two SCR's having opposite polarity in the circuit.
      i. Advantages
         1. motors using alternating current have a higher HP/lb ratio.
         2. when used in three phase configuration, the maximum current through any single
SCR is reduced. (This reduces cost of components.)

ii. Disadvantages

1. circuitry complicated—two SCR switches and supporting circuitry required for each phase (six switches for three phase operation.)
2. high peak current required in single phase operation.
3. supporting circuitry required to fire switches in proper order to obtain phase differences and frequency characteristics. This circuitry becomes more complicated with each added phase.

b. DC to DC Chopper—controls current from a fixed voltage supply by rapidly turning current on and off (switching times in micro seconds) so as to allow only a certain percentage of available current into motor circuit.

i. Advantages

1. simple circuitry
2. lower component costs than with inverter. (approximately 1/3 of cost of three phase inverter).
3. no phase monitoring circuitry needed. lower weight than inverter

ii. Disadvantages

1. possibility of switches failing to turn off when necessary, causing a power surge.
2. possibility of chopper over supply due to failure of current limiting sensor circuitry failure. This again causes loss of power control.

In Fig. 4.4 all types of DC motor and control combinations are shown. Control circuitry for vehicles must provide smooth operation and very low power loss. Resistors are plagued with high power loss while mechanical switches in reasonable numbers are unable to provide a smooth change of voltage. The following are

1. Solid state components provide high efficiency because they limit rather than waste the power going into the motor circuit. Their high speed capability makes possible a smooth variation in current flow to the motor.

2. DC choppers are preferable to AC inverters at this time owing to their lower cost, simpler circuitry, and lighter weight.

3. Transistor switches are more expensive than SCR switches of comparable current rating for electric vehicle use. However, costs and weight of switches and supporting circuitry make it desirable to examine the individual chopper circuit with respect to its current requirements, weight, complexity and costs before choosing one type over others.

The chopper control has a drawback in that the high frequency current interruption tends to produce a high frequency noise. This
noise can be reduced by adding inductance coils but this adds to the weight and cost of the controller. The chopper control tends to have a high efficiency in normal operating ranges, but the efficiency tends to decrease in the low voltage control region. Frequently a bypass contactor is used in control when full voltage is desired so as to eliminate any voltage loss across the semi-conductors.

Basic Methods for Motor Control in Electrical Vehicles

The foregoing paragraphs describe the basic methods for motor control in electrical vehicles. In practice only one (or combinations of two or more) of these methods might be used in the vehicle control system. As an example, a DC motor control system combining
several basic control techniques is shown in Fig. 4.5.

The major features desired in a motor controller for an electric car are:

1. To provide drive comfort and safety, the controller must respond quickly and smoothly in varying the vehicle speed.

2. To obtain maximum vehicle range, the controller must not only have low electric losses, but must also operate in a manner which minimizes the internal losses of the battery and motor.

3. To promote component life and reliability, the controller should protect itself as well as the motor and drive train from damaging overloads.

4. As an additional safety feature, the controller should assist in braking the vehicle and in preventing "free-wheeling" down hills. By accomplishing this with regenerative braking the vehicle range is also increased.

Of various types of controllers available for electric drive systems, the solid state controller offers the best method for obtaining the above features. Resistance controllers can offer smooth control but have very poor efficiency, and battery and motor switching schemes offer good efficiency but fail to provide smooth control. For future higher power vehicles solid state controllers offer the most practical and best performing control scheme available.\textsuperscript{13}
Fig. 4.5. DC control system combining several basic control techniques

Solid state switching devices, namely transistors and thyristors, are the key elements of a DC controller. Because these devices can rapidly switch on and off and have fairly low losses during both their on state and off state they have made possible the development of an efficient method of achieving a continuously variable DC output from a fixed voltage DC source. The significant characteristics of these devices are that they can switch within 50 micro seconds or less, have a voltage drop when conducting of only 1.5 volts or less, and when properly used are rugged and reliable components.

The concept of a switching type controller or chopper is illustrated in simplified form in Fig. 4.6. If the switch is opened and closed for fixed time periods the average voltage across the load is:

\[ V_{\text{Load}} = \frac{t_{\text{on}}}{t_{\text{on}} + t_{\text{off}}} \cdot V_{\text{Battery}} \]

By varying the ratio of the on time to the off time the average output voltage can be made any value from zero up to the full
An important characteristic of a chopper operating with an inductive load, such as a motor, is that the average motor current can be several times greater than the average battery current. When the duty cycle \( \frac{t_{on}}{t_{on} + t_{off}} \) is low, the average motor current may be as much as 10 times higher than the average battery current if the motor circuit time constant is sufficiently high. In electric vehicle applications this characteristic is particularly advantageous during acceleration from standstill when the torque demand (and consequently the current demand) of the motor is very high.

The switching frequency of most high power choppers falls between 50 and 500 pulses per second. Since losses occur each time the device is switched, the efficiency of the chopper decreases as the...
pulse frequency is increased. If the frequency is made low the
higher AC ripple component of the motor current causes higher
motor losses and the torque pulsations produce noise and vibration
of the vehicle.

Controller Operating Modes

Using the switching concept previously outlined three different operating modes, which depend on how the pulse duty cycle and repetition frequency are varied, are available. For example, the pulse repetition frequency of the controller may be held constant, while the pulse width is varied as shown in Fig. 4.7a. A second mode is variation of the pulse repetition frequency while holding the pulse duration constant. By combining pulse width modulation and pulse frequency modulation, a third mode results in which the pulse duration and frequency are both variable, as shown in Fig. 4.7c.

Solid state controllers for electric vehicles must be able to control currents of several hundred amperes from batteries having voltages of from about 36 volts to about 120 volts. A variety of controller circuits have been developed and employed in electric fork lift trucks, industrial vehicles, and experimental electric cars. To illustrate the types of power components and circuitry currently available, a controller which has been used in an electric car is discussed. As a first example an electric car was built to verify the feasibility of wide range field control of a separately excited DC motor, and to develop a control system which was simple, reliable, low in cost, and which duplicates as closely as possible
the characteristics of a conventional automobile (as an aid to consumer acceptance). For the drive system a shunt wound DC motor with field control was used. This eliminated the need for high power speed control circuitry, which has always been very expensive and usually troublesome in past electric car designs. Field control requires only a low power chopper circuit which is not subjected to variations in current due to motor load. The motor "idles" at its rated base speed with full field current supplied, and increases speed as field current decreases. The upper speed is limited by the construction of the armature and brushes. The armature windings are subjected to tremendous centrifugal forces at high RPM, and the brushes tend to "float" on the commutator. The lower speed limit is
determined by available field flux density and armature windings. The body and chassis came from a 1967 Corvette for this experimental electric car. The specifications for motor and controller are:

- Motor separately excited direct current 21 HP, 1000 rpm, 96 V, 220 amperes, 1 hour (General Electric BT 2376) controls, hybrid analog/digital design using CMOS IC logic, pulse width modulation applied to motor field. The control circuit block diagram is shown in Fig. 4.8. An important design goal was to make the drive system "feel" as nearly as possible like a conventional drive system to the driver. Proper balancing of negative armature current feedback with accelerator pedal voltage produces the desired result. The feedbacks also stabilizes the system under conditions of low field current, when fluctuating battery voltage can cause the drive to oscillate.

Another feature of the controller is the automatic sequencer which accelerates the motor from a stand still to 80% of base speed using series resistors in the armature circuit.

The controller then shorts this resistor out with a contactor to bring the motor up to base speed. This occurs only when starting the car. A switch on the clutch pedal prevents the motor from being started while in gear.

The controller is presently set up to limit armature current to about 375 amperes. The only way the motor current can rise above this value is if the drive shifts to a gear which is not appropriate to the vehicle speed at the moment, or if the driver releases the
clutch too quickly. In these situations, the controller can't slow the motor down enough even with full field, so an over-current situation is created. As soon as an armature current of 400 amperes is detected, the controller opens the main motor contactor, removing the load from the motor. The motor is automatically restarted when the clutch pedal is depressed to the floor.

A digital integrator circuit is used to control how long the motor is allowed to draw full current (approximately twice rated continuous current). Whenever the motor is drawing more than rated current (220 amps), a counter counts up. Whenever the motor is drawing less than rated current, the counter counts down by a clock which is eight times slower than the count up clock. If the counter counts up to a full count, the feedback constants in the controller change, limiting maximum motor current to about 200 amperes instead of 375. The controller is reset when the counter reaches 0 again. A numerical
display on the instrument panel indicates the integral count.
Other instruments in the panel include an ammeter, expanded scale voltmeter, and an indicator light for high current.

The control circuitry is powered from an isolated DC-DC converter on the 12 volt auxiliary system. The entire control circuit consisted of 17 IC's mounted on a single plug-in wirewrap board. The field driven circuit was mounted on a separate heat sink over the motor. The basic diagram for motor and control system is shown in Fig. 4.9.

There was some difficulty with the field control circuit. The first problem arose with the field contactor. A low-cost AC type contactor was derated and used to handle the high voltage DC. Unfortunately, the contactor still arced continuously. Another contactor (derated further) cured the problem.

The power transistor driving the motor field was the other problem area. The original design used a single SVT 6061 power Darlington. This could not handle the surge of current to a cold field. After studying the safe operating area curves of many different devices, as well as price and availability the SEN T-173 was selected for use in a new drive circuit. The driver consisted of three devices in parallel (with small emitter balancing resistors) driven by a fourth device. This circuit was predicted to handle all reasonable temperature extremes. A free wheeling diode and RC network across the field worked to limit voltage spikes to 15 volts above the battery voltage. Losses in the field driver circuit
Fig. 4.9. Basic diagram for motor and controller were on the order of 10 watts.

Several minor changes could be incorporated into this controller to improve its performance. One change would be to sense
armature voltage instead of armature current to determine when the starting resistor can be by-passed. Right now, an armature current of less than 30 amperes is required. However, if the starting resistor were to fail, this condition would be reached immediately, enabling the main contactor to pull in while the motor was at rest. Changing the controller to check armature voltage instead would eliminate this possible occurrence. However, the fuse would protect the motor from damage in either case.

A much more flexible system could be built if a microprocessor were used. All the functions of the present controller could be programmed in, in addition, many new features and improvements could be added. For instance, the present controller uses an up-down counter for the integration of armature current. When the preset level is reached, the current limit point is lowered, preventing further heating and possible damage. This function could be programmed to be proportional, gradually reducing the current limit point as the motor heats up. If could also be programmed to perform the instrumentation functions (its outputs would provide a digital volt-meter and ammeter). It could also use battery voltage and battery current to provide a digital "fuel gauge" which could either display percent battery capacity remaining or miles to go at present current drain.  

Mechanical Types of Electric Car

In purely mechanical terms, there are two types of electric car:
1. Motor is linked to the wheels using the fly wheel or directly.

2. The drive uses the gear box and clutch in the car.

In the first case the full range of speed can be obtained by switching between the armature and field controller. By turning on the ignition the control circuitry will be powered and in full field excitation (DC separately excitation) the motor will speed up to reach the base speed. The motor will be designed such that the base speed is the "idle" speed for the car. In order to start the motor a sequential circuit or automatic starter might be used. For low speed and high torque an armature chopper circuit can be used. (Varying the armature current with full field excitation.) Higher speed (over the base speed) will be achieved by weakening the field excitation by means of a field controller. There will be a feed back loop to stabilize the speed by the accelerator voltage as a reference voltage for the controller. A proportional analog controller will switch between the field and armature controller. The block diagram for this technique is shown in Fig. 4.10.

In this case a series wound motor which has a high starting torque is preferrable.

In the second case the motor will start and speed up to base speed without load. (There is a switch under the clutch pedal to start the motor.) Whenever the ignition is on, the control circuit is powered and field is in full excitation. By pressing the clutch the switch will be turned on and activate the starting sequencer or
Automatically starter in order to speed up the motor to base speed (idle). By shifting the gear and releasing the clutch (load the motor) and pressing the accelerator simultaneously to increase the motor speed. As soon as the motor becomes loaded it will slow down, but by pressing the accelerator the field controller will weaken the field and the armature chopper will send more current to the armature; therefore speed will increase to reach the desired speed.

For a second example, an advanced electronic control system for a separately excited DC motor is described. Performance characteristics of an electric vehicle using this control are discussed and recommendations for future systems are given.

The complexity of the control system for battery-power electric vehicles is strongly influenced by vehicle performance requirements. The concern is with the control of commuter-type electric vehicles having a top speed in the 55 to 60 mph range, and 0 to 40 mph acceleration times in the range of 20 seconds. Since a vehicle of this
type may carry 1000 lb of batteries and operate in hilly terrain, regenerative or dynamic braking will be assumed as a safety requirement.

The force required at the driving wheels may be expressed by the equation:

\[ F = W \left( R_0 + \frac{R_1}{P} + \frac{R_2}{P} V^2 \right) + \frac{1}{2} \rho v^2 DA + W \left( \sin \alpha + \frac{a}{g} \right) \]

where

- \( W \) = gross vehicle weight
- \( P \) = tire pressure
- \( R_0 \) = static tire resistance coefficient
- \( R_1 \) = tire pressure resistance coefficient
- \( R_2 \) = dynamic tire resistance coefficient
- \( V \) = vehicle speed
- \( \rho \) = air density
- \( D \) = aerodynamic drag coefficient
- \( A \) = frontal area
- \( \alpha \) = terrain grade
- \( a \) = vehicle acceleration required
- \( g \) = gravitational constant.

The power needed for maintaining a given vehicle speed, which is proportional to force times vehicle speed, is given as a function of grade in Fig. 4.11. For a 3000 lb experimental electric vehicle having a 19 ft\(^2\) frontal area. Although the power requirements are modest at most speeds on a level road, climbing grades can require considerable power. Power for accelerating the vehicle is needed
Fig. 4.11. Vehicle power requirements

in addition to the value in Fig. 4.11.

The use of a transmission or torque converter between the electric motor and the drive wheels can multiply the torque available at low speeds, thereby enhancing low speed performance and hill climbing ability. The added transmission losses are offset by permitting the battery-controller motor system to be operated in a more efficient range. System trade-offs become more favorable to the use of a transmission as top speed and grade climbing requirements are increased.

Armature chopper control, illustrated in Fig. 4.12, has gained wide acceptance because of its ability to provide smooth control over
Fig. 4.12. Armature chopper

Fig. 4.13. Armature chopper waveforms
a wide range of motor speed. The voltage applied to the motor can be varied continuously from 0 volts to full voltage by controlling the conduction ratio of thyristor switch TH1. Commutation components TH2, TH3, L2 and C are needed to turn thyristor TH1 off. The inductor L1 absorbs the difference between the motor voltage and chopped voltage V, while diode D1 provides a current path when thyristor TH1 is blocked. Battery current I_b is drawn in pulses as shown in Fig. 4.13, which increases the I^2R loss in the battery unless an additional filter is added between the battery and thyristors. Motor torque and power capability as a function of speed for this system are shown in Fig. 4.14 for a fixed maximum armature current value. Point p corresponds to the application of full battery voltage. Torque is constant for motor speed n < np, and power is proportional to n. At speeds above point p, a series motor
with a constant voltage source operates with reduced armature and field current. In the simple series motor the armature current is reduced in proportion to field current and power output is reduced as shown. Power may be better maintained at speeds above np by shunting current from the field winding.

High speed motor performance can be improved by using a separately excited field. In the armature control region of Fig. 4.15, the armature chopper controls the voltage applied to the armature while full field excitation is maintained. In the field control region, full battery voltage is applied to the armature and the field is reduced so as to be inversely proportional to speed. Horsepower remains constant with the torque being inversely proportional to speed. At higher speeds, commutation considerations may impose a reduction of armature current as indicated by the dashed curves of Fig. 4.15. The advantage of using a transmission to multiply motor torque is illustrated in Fig. 4.16 for series motor with a three-speed manual transmission. Low speed performance and hill climbing ability are greatly enhanced by the increased available torque. The further advantage of field and armature control is illustrated in Fig. 4.17. The constant horsepower obtainable in the field control region provides maximum power over a wider speed range.

From a safety standpoint dynamic braking may be obtained by switching a resistance across the motor. This provides the desired retarding torque in a simple manner but dissipates energy that
Fig. 4.15. Separately excited motor characteristics

Fig. 4.16. Series motor with transmission
Fig. 4.17. Separately excited motor with transmission could be returned to the battery.

Regenerative braking requires the establishment of a path for reverse armature current for charging the battery. This path is provided in Fig. 4.18 by diode D2. Switch TH4 is controlled to maintain the average value of voltage $V$ somewhat lower than the regenerating motor voltage, thereby controlling the value of $I_a$. Switch TH4 conducts only when switch TH1 is blocked. The commutation components required for turning off thyristors TH1 and TH4 are not shown. Although regenerative braking returns energy to the battery and thereby increases vehicle range, it requires the addition of both power handling devices and control circuitry.
The armature chopper control system requires that the electronics handle the full power required by the vehicle. The size, weight, power dissipation and cost of the electronics are largely a function of the power handling capability of the control.

An examination of Fig. 4.17 reveals that armature control is only needed over a small portion of the vehicle speed range. Operation over the remainder of the range can be handled by field control. The power requirement of the field is only a few percent of the armature circuit power, and therefore the power rating of the control electronic could be greatly reduced if armature control could be eliminated.

The development of a low power field control system for a separately excited DC motor was undertaken because of the size, weight, and cost benefits available if satisfactory low speed
vehicle performance could be obtained without an armature chopper. A diagram of DC chopper control system is shown in Fig. 4.19.

The torque speed curves for the motor in this experimental vehicle are given in Fig. 4.20 for two different systems: 96 volt and 50 milliohms and 48 volt at 12.5 milliohms connections. Full torque with 400A armature current at full field for the 96 volt connection corresponds to 34 HP while the corresponding torque for 48 volt connection corresponds to 18 HP.

If the armature chopper is eliminated and the 96 volt battery is connected to the armature, the motor may be field controlled at or above the speed indicated by the 100% field excitation line S-S of Fig. 4.20. This line is significant since it corresponds to the generation of the maximum back emf at a particular motor speed. Armature current is determined by the difference between the battery terminal voltage and the back emf divided by the armature resistance. Battery resistance has a substantial effect on the slope of this line since the battery terminal voltage will decrease about 20 volts when a 400A current is drawn.

The low speed performance of a vehicle driven from this motor through a conventional transmission will be unsatisfactory for 96 volt battery connection. The zero torque speed determined by line S-S may be thought of as corresponding to the idle speed of an internal combustion engine. An idle speed of 1900 rpm is highly unsatisfactory.
The situation can be greatly improved by reducing the battery voltage applied to the motor. By reconnecting the 96 volt battery into two parallel 48 volt sections, full field excitation corresponds to line P-P of Fig. 4.20. The new zero torque speed of 950 rpm is close to that of an internal combustion engine and the field control system with battery reconnect can be used with either a manual or automatic transmission. The experimental vehicle was operated with an automatic transmission having a torque converter stall characteristic as indicated in Fig. 4.21 and Fig. 4.22. Smooth performance was obtained over the entire speed range by suitable coordination of the field excitation and battery reconnection.
Fig. 4.20. Field control of separately excited motor

Fig. 4.21. Motor with torque converter
The field control system described below was developed to meet the following goals:

1. Provide smooth transitions between parallel and series battery connections;
2. operate in the series battery connection whenever possible;
3. Provide good low speed and high speed control;
4. provide adjustable regenerative braking;
5. provide safety features to ensure trouble-free operation;
6. minimize power losses and;
7. be compatible with large scale integration.
A block diagram of the system is shown in Fig. 4.23. The accelerator setting is converted to an armature current reference signal. This reference current signal is compared with a signal proportional to armature current, and the error signal is processed to obtain a field current reference signal. The field reference signal controls a 2 KHz pulse width modulator which contains a power transistor output stage capable of providing the 12A full field current. If the accelerator setting is increased, an increased armature current is demanded. This results in a reduced field current demand. Decreasing the field current of the separately excited motor decreased the motor back emf which in turn increases the armature current for a given speed and battery voltage. Speed control is accomplished by the driver as in a conventional automobile. The problem of achieving stability of the current feedback loop is aggravated by the nonlinear field current to field flux characteristic and the poor regulation of the battery. These problems were overcome by using nonlinear pulse width modulation and a feed forward battery voltage signal to cancel the effect of battery voltage variations on field current.

When starting from standstill, the logic senses an acceleration setting T greater than zero and closes the low voltage contactors, L, thereby applying 48 volts to the motor. With minimum accelerator setting the motor will run with maximum field excitation of about 950 rpm which corresponds to idle speed. As the accelerator is depressed, the field is weakened and the armature current is
Fig. 4.23. Feedback field control

increased. This causes the motor and the vehicle to accelerate.

If low values of acceleration are demanded as when operating in
a parking lot, the controller will operate the motor in the parallel
battery connection, region A of Fig. 4.20, with armature currents
below the maximum value of 400A. When the motor rpm increases so
that the operating point reaches the full field line S-S, the logic
will initiate a transition to the high voltage connection, region
B. First the low voltage contactors are opened. The field current
is increased to its full value and then the high voltage contactor
H is closed. This eliminates any high current motor surge which
would produce a jerk. At the same time, the armature current re-
ference for the given accelerator setting is reduced from the value
indicated by the dashed line of the accelerator transfer
characteristic of Fig. 4.24 to the solid line value. This armature current value is selected to provide the same motor torque with the new 96 volt connection as was previously provided with the 48 volt connection. This provides smooth control so that the vehicle does not suddenly accelerate after reconnection. If on the other hand high acceleration is demanded, the controller will provide maximum armature current when operating in the low voltage connection of region A. As soon as the motor rpm increases to a value equal to the rpm on line S-S which corresponds to the current demanded in region B by the accelerator setting, the contactors will operate as described above to provide a transition to the high voltage operation in region B. In this case, however, the new torque will exceed the low voltage connection torque since high acceleration is demanded.

Controllable regenerative braking is readily provided in a field control system. A gradual transition from motoring to regeneration is provided by the accelerator to armature current reference transfer function shown in Fig. 4.24. The previously discussed armature current reference is a function of motor speed as well as accelerator setting. As the accelerator demand is reduced at a given speed, the positive armature current demand is reduced and then goes negative. This results in an increased value of field current, which increases the back emf of the motor. The motor acts as a generator and charges the batteries. As the vehicle speed is reduced, the field current will be increased to maintain the desired
regenerative current. Once the maximum field excitation is reached, any further decrease in motor speed will cause the negative armature current magnitude to decrease toward zero. As soon as the armature current becomes positive for a zero accelerator setting, the logic will initiate a battery reconnection to the low voltage connection.

For most efficient operation, the system should be operated in the series connection when possible. The S–S line of Fig. 4–20 shifts considerably depending on the open circuit voltage and resistance of the battery. The battery parameters are a function of battery temperature and percent charge. A circuit in the logic calculates the optimum switching point based on motor speed, battery voltage, armature current, and accelerator position.
Performance

The electric vehicle was first equipped with a 400A armature chopper, series wound DC motor, and a manual clutch and transmission. It was instrumented to record speed, mileage, grade, battery current, motor current, battery voltage, and motor voltage. The motor was later rewound to obtain a separately excited field. The feedback field controller was used with a three-speed automatic transmission incorporating a torque converter and battery reconnect. Performance comparisons are given in Table 2. The torque transient resulting from the battery reconnect was judged to be less than that of the automatic transmission during gear changes.

TABLE 2
Performance Comparison Between Field and Armature Control

<table>
<thead>
<tr>
<th>Acceleration</th>
<th>Field Control</th>
<th>Armature Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 15 mph</td>
<td>3 sec.</td>
<td>5 sec.</td>
</tr>
<tr>
<td>0 - 30 mph</td>
<td>10 sec.</td>
<td>14 sec.</td>
</tr>
<tr>
<td>0 - 45 mph</td>
<td>27 sec.</td>
<td>32 sec.</td>
</tr>
<tr>
<td>Top Speed</td>
<td>65 mph</td>
<td>60 mph</td>
</tr>
<tr>
<td>Range</td>
<td>47.8 mi.</td>
<td>44.5 mi.</td>
</tr>
</tbody>
</table>

0 - 40 mph acceleration

Constant 40 mph for 3 miles

40 - 0 mph deceleration
Conclusion and Recommendations

The range improvement of the field control system with respect to the armature chopper is partially due to regeneration and partially due to elimination of battery losses caused by the pulsed chopper wave form. The acceleration performance improvement results from improved torque availability and the elimination of manual gear shifting. The saving in size, weight, power dissipation and cost of the field control system are also important advantages. The power output stage need handle only a 12A field current as compared with the 400A armature current. The power circuit can be derated with less cost penalty, thereby providing increased reliability. The low power CMOS logic is suitable for large scale integration, which can further reduce the cost, size, and wiring complexity.

Further simplification of the system may be possible by incorporating a four-element hydraulic torque converter and a wider speed range motor, which could eliminate the need for reconnecting the batteries.

Full realization of the potential of battery powered electric vehicles will require substantial improvements in battery energy and power density, development of light-weight high-performance motors, development of low weight vehicles with low aerodynamic drag, and further controller improvements. Although the need for high energy density batteries is most pressing, efforts in the other areas will also contribute to increased range and performance.

In addition to the power and control circuitry previously mentioned, a controller installation will include several additional
major components and features. A contactor or switch can be connected in series between the battery and controller to provide a complete open circuit and to serve as a final emergency disconnect in event of a failure of the controller. A double-pole, double-throw contactor is used to reverse connections of the field or armature for operating the vehicle in the reverse direction. The reversing switch can also incorporate the above mentioned disconnect feature. To supply motor current higher than can be safely handled by the solid state controller, the main switching device can be by-passed with a contactor or mechanical switch. Energizing of the by-pass circuit often causes a jerk in the vehicle motion, but this is a small penalty to pay for the increased current and resulting higher torque made available for the more severe load conditions. With the by-pass circuit in operation the controller losses are eliminated, thus improving the efficiency of the drive system when full output is desired.

Additional electronic circuitry may be added to the controller to improve the safety and reliability of operation. Among the features which can be provided are: undervoltage detection to prevent loss of control due to excessively low battery voltage, a commutation circuit interlock to prevent firing the main thyristor prior to charging the commutating capacitor, and over temperature detection to prevent over loading and consequent failure of the solid state devices.
As it was said before, dynamic braking and regeneration are two optional features that may be added to the motor and controller. Without either of these features, the drive motor does not provide retarding torque and as a result, the vehicle free wheels or coasts much faster than a conventional car. Not only is this condition unsafe when descending steep hills, but it also requires excessive use of the brakes on hills and during stopping. To eliminate this condition, the motor can be reconnected as a generator so that a retarding torque is produced. The generated power can be dissipated in resistors to obtain dynamic braking or can be used to charge the battery for regenerative braking.

Dynamic braking is relatively simple and inexpensive to accomplish. Contactors or switches are used to reconnect the motor as a generator and to switch in the required braking resistor. The resistor value is selected to give a comfortable and safe deceleration. The dynamic braking can be automatically brought into operation by energizing the switches when the accelerator pedal is released.

Regenerative braking is more difficult to accomplish (and more expensive) but does have advantage of returning energy to the battery. Again, contactors or switches are used to reconnect the motor as a generator and to provide a current path to the battery. Additional circuitry must be added to obtain a voltage high enough to charge the battery. One specific technique is to step up the generated voltage by using a thyristor controlled inductor charging and
discharging circuit.

Theoretical calculations of recovered energy by regenerative braking make this feature appear especially attractive; however, the actual benefit derived will be far less than expected. Until a very inexpensive means of providing regeneration is found, it is unlikely that this feature can be proven advantageous in normal driving. Special purpose vehicles such as delivery vehicles which make many stops per mile may, however, benefit sufficiently to justify the added cost and complexity of a regenerative system.

**Electrical System Efficiency**

We examine the factors affecting the efficiency of conversion of stored energy to mechanical energy at the rear axle. Among the losses to be considered are those due to the battery, controller, motor, and transmission.

During each current pulse (assuming rectangular pulses) of the controller the portion of the battery's stored energy lost due to internal resistance is:

\[
\text{Energy Lost} = I_B^2 R_B \Delta t \text{ (watt-sec)}
\]

where \( I_B \) = peak battery current

\( R_B \) = battery resistant

\( \Delta t \) = pulse duration in seconds

The energy available at the output of the controller is given by:

\[
\text{Energy to load} = I_B^2 R_L = (E_0 - I_B R_B) I_B \Delta t \text{ (watt-sec)}
\]
where \( R_L \) = load resistance

\[ E_o = \text{battery open circuit voltage} \]

The efficiency during the pulse period is given by:

\[ \eta_B = \frac{\text{Energy to load}}{\text{Energy to load + losses}} = \frac{(E_o - I_B R_B) I_B \Delta t}{E_o I_B \Delta t} \]

\[ \eta_B = 1 - \frac{I_B R_B}{E_o} \]

with a switching controller the average battery current may be much lower than the load current; however it should be noted that the losses are not determined by the average current, but by the peak current during the pulse period.

The controller efficiency is determined by the switching losses and forward drop of the main thyristor, the commutating circuit losses, and the control circuit losses. Due to all of the factors involved it is somewhat difficult to give an accurate general expression for controller efficiency. The control circuit and commutating losses remain relatively constant independent of load, and at the low frequencies employed in these controllers the switching losses are a small portion of the total loss. In a well designed controller the fixed loss will be less than 3% of the controller rating. A major portion of the loss occurs due to the forward voltage drop of the main thyristor. This voltage drop will vary from approximately 1.0 volts to 2.0 volts over the useful current range of the device. The approximate efficiency of the controller
will then be given by:

\[
\eta_c = \left(\frac{\text{forward drop losses}}{\text{input power}}\right) - \left(\frac{\text{fixed losses}}{\text{input power}}\right)
\]

\[
\eta_c = 0.97 - \frac{V_{FD}}{E_o - I_B R_B}
\]

where \(V_{FD}\) = thyristor voltage drop at \(I_B\) amperes

The remaining factor in determining the overall efficiency is the motor and transmission losses. Losses for DC motors are given for steady DC excitation rather than the pulsed type excitation produced by the switching type controller. The effect of the pulsating current is to cause additional heating losses in both the magnetic and electrical circuits of the motor. As the chopper frequency and motor inductance are increased the magnitude of the AC component is reduced and the added losses are minimized. In a well designed system the losses caused by the AC current should reduce the motor efficiency by no more than 2 or 3%.

Finally, the efficiency of mechanical automotive transmissions is very high. In the lower gears the efficiency is at least 93% and in direct drive it rises to a value of 98%. Now we consider how these efficiency factors influence the decisions made during the design of a vehicle's electrical system. To satisfy a given load requirement, it is obvious that the battery voltage should be made as high as practical so that the current will be a minimum. The battery voltage will, however, be limited by such factors as safety, compatibility with available motor voltage, mechanical configuration of available batteries, and allowed space for mounting, and other
practical considerations.  

An example for a vehicle system (100-v battery, 50-MSL battery, 100 A of average motor current is considered next. A comparison of power loss and efficiency of resistor and chopper power controller is given in Table 3.

Solid state controllers provide the most effective means of achieving comfortable and safe speed control as well as efficient operation of electric vehicle drive systems. In a design of electric vehicles there are some trade-offs on controller rating and drive efficiency in static flying the specific vehicle performance requirements. Vehicles will involve trade-offs to achieve the desired cost, performance, and efficiency objectives and will result in different electrical system designs. Since the solid state controller affects the efficiency of both battery and motor, it must be designed to be compatible with these components to achieve a good drive system. With state-of-the-art semiconductor devices most requirements can be satisfied; however, further development aimed at reducing controller cost, size, and weight is desirable.

Simulator for a 24 HP Separately Excited DC Motor

At this point a simulator for a 24 HP separately excited DC motor which is used in the electric car and a design for the controller which is suggested by the author is discussed.

The simulator consists of a small 12 volt DC motor and the pulse modulator which was discussed in Chapter Three as a driver for the armature. A power supply adjusted for 12 volts and producing a maximum 6 amperes current feeds the pulse modulator. The
### TABLE 3
Comparison of Power Loss and Efficiency of Resistor and Chopper Power Controller

<table>
<thead>
<tr>
<th>Percent of full motor speed</th>
<th>Resistance-controlled battery power consumption (kW)</th>
<th>Efficiency (%)</th>
<th>Power Loss (kW)</th>
<th>Chopper battery power consumption (kW)</th>
<th>Efficiency (%)</th>
<th>Chopper Power Loss (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>1.2</td>
<td>0</td>
<td>1.2</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>2.2</td>
<td>40</td>
<td>1.2</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>20</td>
<td>8</td>
<td>3.3</td>
<td>60</td>
<td>1.3</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>30</td>
<td>7</td>
<td>4.3</td>
<td>70</td>
<td>1.3</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
<td>40</td>
<td>6</td>
<td>5.3</td>
<td>75</td>
<td>1.3</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>50</td>
<td>5</td>
<td>6.3</td>
<td>80</td>
<td>1.3</td>
</tr>
<tr>
<td>60</td>
<td>10</td>
<td>60</td>
<td>4</td>
<td>7.3</td>
<td>83</td>
<td>1.3</td>
</tr>
<tr>
<td>70</td>
<td>10</td>
<td>70</td>
<td>3</td>
<td>8.3</td>
<td>85</td>
<td>1.3</td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>80</td>
<td>2</td>
<td>9.3</td>
<td>86</td>
<td>1.3</td>
</tr>
<tr>
<td>90</td>
<td>10</td>
<td>90</td>
<td>1</td>
<td>10.3</td>
<td>88</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Vehicle system: 100-V battery, 50-mΩ motor, 50-mΩ battery, 100 A of average motor current.

Note: most of the losses in the chopper system are due to motor and battery resistance.
motor was originally a series motor and drew high current for starting. As the separately excited motor is used in the electric car, the series winding of the small motor was replaced by the appropriate winding for a shunt motor. In order to determine the proper number of windings for the field coil a simple calculation was done. First the power for the series winding was calculated by considering approximately 6 amperes needed for 0.3 ohms resistor of the coil so: \( P = I^2R = 36 \times (0.3) = 10.8 \, \text{W} \)

\[
P = \frac{V^2}{R_{\text{s.h.}}}
\]

\[
R_{\text{s.h.}} = \frac{12^2}{10.8} = 13 \, \Omega
\]

Therefore the resistance of the shunt field should be almost 13 ohms, by looking at a wire table, wire number 26 (which has 41 \( \Omega \) resistance per 1000 feet) was selected. It was desired that the new coil have about the same amount of copper as the series coil. The motor was mounted on a piece of wood and linked to the aluminum disc by a rubber belt using two simulator belt gears, one fixed on the motor shaft, another one on the disc shaft. The aluminum disc was placed on a stand, so that it could rotate between two pieces of permanent magnet. During the rotation of the disc the magnets produce an eddy current through the disc, and that current through the field makes a load that is opposed to the direction of rotation. By moving the position of the permanent magnets more field would be cut by the current through the disc and various brake forces would be produced.
By this simple technique the motor could be loaded. A small roller was placed on the disc stand to represent the position of the magnets. The armature and field connections were taken out of the motor and were connected on the motor stand separately. The armature was connected to the output of the pulse modulator through an ammeter. A voltmeter was connected across the armature to show the armature voltage. The pulse modulator was fed by four laboratory DC power supplies, producing a maximum 6 amperes. The field was connected to a variable power supply, so the field voltage could be varied. A voltmeter was also connected across the field to show $V_f$. A picture of the simulator and its connection is shown in Fig. 4.25. Since there was no available data the basic speed of the motor was unknown. This fact does not affect the experiment very much, shifting the curves slightly. An attempt was made to simulate every function which could occur for the 24 HP motor in the electric car by this simulation, but some problems prevented complete success. The basic speed measured was 8800 rpm (for $V_a = 11.5$ volts, $V_f = 11.75$ V, $I_f = \frac{11.75}{12.7} = 0.93$ amperes). (The resistance of the field winding happened to be 12.7 Ω, which was close to the calculated value) with the motor loaded by the disc. The basic speed when the motor was not linked to the disc increased to 12,300 rpm (at $I_a = 2.5$ amperes, $V_a = V_f = 11.73$, $I_f = 0.92$ amperes). Due to the high basic speed and vibration of the slightly unbalanced disc and the possibility of the disc leaving the shaft and running away, the
(a) Simulator for the Electric Car

(b) Wiring Connection for the Simulator

Fig. 4.25. Representative for the Simulator and Wiring Diagram
speeds over the basic speed could not be achieved with the disc linked to the motor. But without load (by weakening the field excitation) speeds over the basic speed were achieved.

The first thing tested was the pulse modulator. As mentioned before this circuit includes a positive feedback loop to sense the output current as it varies with the load and to make proportional voltage as its emitter. This voltage would be compared with the reference voltage in the input. Two different cases were tested, first with the feedback loop, second without feedback.

For the first case, the plots for two different armature currents in full load are shown in Graph 1. Field was in full excitation at 11.73 volts.

For the case without feedback the feedback transistor was unplugged. The plots are shown in Graph 2.

As a comparison between the two cases, a quick look at the plots shows that the feedback has little effect and that the motor has poor regulation. There is 66.2% regulation between no load and full load. This poor regulation can be caused by:

1. The circuit was originally intended for a permanent magnet motor, and might have better results with that type of motor.

2. During the experiment the motor temperature rose drastically because of its high losses, and this influenced the motor characteristics.
Graph 1. Speed versus load characteristic of simulator
(controller including feedback loop)
Graph 2. Speed versus load characteristic of simulator (controller excluding feedback loop)
3. Measuring speed by the strobotac was not accurate (because of the presence of multiple speed indications).

4. Replacement of the field coil increased losses, causing extra heat in the motor.

5. Mechanical losses, unbalanced disc, shaft tension by increasing temperature, length of rubber belt, etc. all contributed error.

In the original graph the regulation for the motor was 10%, which seems very low compared to 66% for the 12 volt DC motor. The pulse modulator was modified and scaled up to act as a field controller in the electric car. In the field controller there is no need for the feedback loop, so that part of circuit (which included the current feedback loop) was eliminated. In order to scale up the circuit to match the field of 24 HP DC motor and its 108 volt input the power transistors of the driver and output part needed to be replaced. Transistor Q4 (2N4901) was replaced by (RCA410) and instead of power transistor Q5 (2N9398) the matched three parallel transistors (RCA410) were used. The rest of the circuit was like the original. There must be two supply voltages: 12 and 108 volts (to excite the field). The 108 volt supply must handle up to 21 amperes current. It seemed that there is no need for the free wheeling diode D3 because this diode provides a path for armature current during intervals when transistor Q5 is in its off state, and the source of the current is the energy stores in the magnetic field of the motor. Later if there would be a need
for this diode it could be re-installed.

In order to simulate the low speed (from zero up to basic speed) and starting torque (accelerating the car in gear one or two) the field was set to full excitation and the armature was connected to the pulse modulator. Various constant loads were used and the plots are shown in Graphs 3, 4, and 5. It should be mentioned here that the 24 HP motor might not behave in the same manner as the simulator; for instance, the 24 HP motor's field coil is designed so that in the case of field disconnection from the supply the motor doesn't run away. As can be seen from the graphs, the pulse modulator could deliver as much current as needed to drive the motor with any load from its starting point. In the case of heavy loads, to draw lower current the field can be over excited. From the graph it is seen that for higher speeds the armature current increases drastically. The pulse modulator could deliver up to 6 amperes current without any extra heat in the power transistors.

A schematic of a conception at design of a controller, including the logic interface which interfaces between the armature chopper and pulse modulator, that is suggested for the electric car project is given in Fig. 4.26. The armature controller is the armature chopper GE-EV-1 S.C.R. control, and the field controller is the modified pulse modulator which has been discussed in Chapter Three. Both controllers are fed by 108 volt batteries, and the logic circuit and pulse modulator need 12 volts for inputs. The armature chopper is connected to a heavy current contactor 1A which will short out
Fig. 4.26. Schematic diagram for the electric car controller
Graph 3. Armature voltage current versus speed for full load in full field excitation.
Graph 4. Armature voltage current versus speed for half of full load in full field excitation.
Graph 5. Armature voltage current versus speed for 25% of full load in full field excitation.
the chopper when the voltage across the armature reaches 85% of
the battery voltage, and thereby connects the armature directly
across the batteries. The Ev-1 doesn't include dynamic or regenerative braking, but it includes the jogging braking. The accelerator
would be modified somehow so that after the armature chopper would
be shorted by pressing the accelerator the potentiometer which
varies the input voltage for pulse modulator will move to weaken
the field and increase the speed. The ignition switch will activate
the logic and pulse modulator circuits. For protection of the
motor a fuse is provided in the armature circuit, which will blow
when $I_a > I_{max}$ and the contactor fails to disconnect the armature
from the batteries. The control logic interface detects the armature over-current and cuts it back by dropping the field to full
excitation. The current sensor guages the armature current, and
the scaling and conditional block produces a low voltage proportional to the armature current. In the comparator $I_a$ will be compared
to $I_n$ (normal) and $I_{max}$ (maximum) armature current. When $I_a > I_{max}$
the comparator sends a signal to open contactor R to protect the
motor. When $I_a > I_n$ the comparator sends a signal to start a digital integrator to keep track of time. After a period of time (which
depends on the motor design) the digital integrator will send a signal to drop back the field to the full field excitation in order to
restrict the armature current. The temperature sensor acts as a
backup for overheating the motor. When $I_a$ drops and becomes less
than $I_n$ the counter will be reset and the field excitation will go
back to normal operation. These functions are carried out by a RS flip-flop AND and OR gates. Actually this is not complete circuit, and some extra circuits can be added to give a continuous range of field excitation proportional to $I_a$ in the case when $I_a > I_n$. 
REFERENCES CITED


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