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A SURVEY OF PROPULSION SYSTEMS FOR HIGH CAPACITY PERSONAL RAPID TRANSIT

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16. Abstract

The high-capacity personal rapid transit (HCPRT) system must operate with very short headways. To achieve safe operation at these headways, the propulsion system should meet certain unconventional requirements. They include:

1) reversible thrust capabilities,
2) short response time,
3) peak thrust exceeding three times nominal thrust.

These requirements were determined by analysis, computer simulations, and data provided by DOT/TSC. Five propulsion systems capable of meeting these requirements have been surveyed in this report. As background to the survey, several vehicle resistance curves were calculated for a "baseline" vehicle with assumed dimensions and weight. Four types of vehicle suspension methods were considered.

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PREFACE

The work described in this report was performed in the New Systems Division of the Office of Research and Development of the Urban Mass Transportation Administration.

The objective of this work was to examine the applicability of various state-of-the-art motor and motor drive systems for propulsion of High Capacity Personal Rapid Transit vehicles. The work was performed by Alexander Kusko, Inc. under contracts DOT-TSC-203, Task Directive 90, and DOT-TSC-965, Task Directive 7.

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Glossary

Chopper. DC-to-DC converter drive circuit using solid-state switches.

Closed-loop control system. One or more measurements of the controlled variables are used.

"Deep bar" rotor design. Conduction bars of squirrel-cage rotor embedded deeply into the rotary body.

Drive circuit. The electrical power circuit providing drive power (ac or dc) for the traction motor.

Headway. Ratio of the distance between equal points on consecutive vehicles to vehicle speed.

Inverters. DC-to-AC converters.

Magnetic levitation. Vehicle support using magnetic fields.

Nominal thrust. Rated (name plate) motor thrust or equivalent torque.

Open-loop control system. No measurement of the controlled variables is used.

Peak thrust. Maximum thrust (or equivalent torque) capability of the motor.

Primary voltage control. Speed and torque control of ac induction motors by means of motor input voltage variation.

Propulsion range. Total thrust capability. Expressed as T_{max}/T_{nom}, where T_{max} is maximum or peak thrust and T_{nom} is nominal or rated thrust.

Propulsion system. All components necessary for vehicle propulsion.

(cont'd)

Thrust. Obtained by coupling to wheel in the case of the rotary motor; obtained directly in the case of the linear motor.

Thrust-brake crossover. Characteristics of drive as thrust is reversed.

Thyristor. Solid-state unidirectional switch, also an SCR.

Torque. Rotary motor shaft output.

Variable frequency drive. Drive circuit providing a primary voltage of variable frequency.

I INTRODUCTION

A good illustration of a vehicle operating at short headways is the automobile on a highway at rush hour. It operates at high speeds with short headways. In order to keep the headway within safe bounds, the automobile must accelerate and decelerate over a wide range with a minimum of delay. This translates into a need for a wide propulsion range with thrust reversibility and a short response time. "Tailgating" poses the problem of position control as well as speed control.

In order to maintain the minimum safe distance from the car ahead, the driver must be able to respond quickly. By replacing the driver with a "linear" control model, a quantitative estimate of the required response time for a propulsion system can be made.

Such a model has been used here to control vehicle spacing and speed by the use of two feedback loops. This particular model is useful for establishing high-performance speed control requiring accurate positioning. By assuming high acceleration rates for the vehicle ahead, the response times required for the propulsion system to avoid "rear end" collisions have been found by adjusting the parameters of the model. The results of the model analysis, which is given in the appendix of this report, are used to establish propulsion system response characteristics.

Vehicle baseline and propulsion system requirements have been developed to establish a common framework for comparing propulsion system characteristics. Four classes of vehicles are considered for the HCPRT system. The vehicle baseline is described in Chapter II.

This report will consider the relative merits of five different propulsion systems. In each system, a different type of motor and its appropriate drive systems are discussed. Each of the systems considered can theoretically meet the special performance requirements necessary to ensure safe operation of a small-vehicle HCPRT. These requirements include reversible thrust capability, short response time, and a propulsion range of at least 3/1.

Conventional exclusive guideway transportation networks are not commonly equipped to meet the rigid vehicle and control system specifications required for an HCPRT system. Hence, the systems discussed here are in varying stages of development. Their suitability must also be weighed in the light of such considerations as: speed control; torque; efficiency; weight; cost; and reliability.

Only systems in which the thrust can be reversed when appropriately conditioned power is applied are considered, since reversible thrust is desirable for achieving close headway control. Although it may be possible to design a mechanical braking system that can blend thrust and brake with sufficient speed and accuracy to provide the equivalent of a reversible-thrust system, such systems are not within the scope of this report.

The propulsion systems discussed are:

(1) DC motors with
    (a) chopper drive for dc or rectified single-phase ac wayside power.
    (b) ac-to-dc thyristor drive for 3-phase wayside power.

(2) AC rotary induction motors with inverter drive
    (a) for dc wayside power.
    (b) for rectified ac (single-or 3-phase) wayside power.

(3) AC linear induction motors (LIM) with
    (a) motor primary windings on board plus inverter drive.
    (b) motor primary windings distributed along the guideway.

(4) AC Rotary synchronous motors with inverter drive
    (a) for dc wayside power.
    (b) for rectified ac (single-or 3-phase) wayside power.

(5) AC linear synchronous motors with

  (a) motor primary windings on board plus inverter drive.

  (b) motor primary windings distributed along the guideway.

II VEHICLE BASELINE AND PROPULSION SYSTEM REQUIREMENTS

This chapter provides the frame of reference for the survey of propulsion systems. Included are:

A) vehicle classes,
B) baseline vehicle description,
C) thrust requirements and resistance characteristics,
D) propulsion system performance requirements
E) introduction to propulsion motor types.

A Vehicle Classes

Four classes of vehicles are being considered as candidates for the HCPRT system:

(1) air cushioned,

(2) rubber tire wheels,

(3) steel wheels on steel rails,

(4) magnetic levitation (attraction type).

B Vehicle Baseline Description

The baseline vehicle dimensions and weights are summarized in Table 1. Also in Table 1 is a list of maximum expected operating characteristics and conditions. These characteristics apply to all the vehicle classes listed above.

Table 1. Vehicle Baseline Characteristics and Operating Conditions

Vehicle Dimensions	
Length	7.5 ft
Height	5.8 ft
Width	4.33 ft
Vehicle Weight	
Empty	1600 lb
Fully Loaded	2600 lb
Cruise Speed	40 mph (58.7 ft/sec)
Max. Acceleration	0.2 g (6.44 ft/sec^2)
Max. Deceleration	0.4 g nominal
	1.0 g absolute max.
Allowable Jerk	0.2 g/sec
Headwind, max.	30 mph
Grade, max.	6%

C Thrust Requirements and Resistance Characteristics

The thrust required for vehicle propulsion can be determined by considering the factors that contribute to vehicle resistance. These factors are:

1) the force required to accelerate the mass,
2) the force required to move a vehicle up a grade,
3) the force required to overcome resistance to motion, and
4) the force required to overcome air drag and wind.

A good approximation of total vehicle resistance can be made with the following equation:

$$F = Wa + WI + W\left(K_1 + K_2\sqrt{V} + K_3 V\right) \pm K_4 (A+V)^2 \qquad (1)$$

where

F = force in pounds required to propel the vehicle

a = acceleration in g ($g = \frac{\text{acceleration in ft/sec}^2}{32.2 \text{ ft/sec}^2}$)

I = grade (elevation per unit length)

V = vehicle velocity in ft/sec

A = wind velocity in ft/sec

K_1 through K_4 are constants, which depend on cross-sectional area, shape, and suspension method. The first expression, Wa, is the acceleration term; the second expression, WI, is the propulsion effort required to move a vehicle up a grade. The expressions associated with K_1, K_2, and K_3, $W(K_1 + K_2 \sqrt{V} + K_3 V)$, approximate the propulsion effort required to overcome the running friction. The last expression, $K_4 (A + V),^2$ is the wind drag.

Estimates of the constants in this equation for the four vehicle classes are given in Table 2. The constant K_1 corresponds to the component of the resistance to motion, which is independent of vehicle speed, commonly known as coulumb friction. Such friction is found in all classes but magnetic levitation. K_2 yields a component of friction which is peculiar to magnetic levitation. Similarly, K_3 is peculiar to air cushion suspension. K_4 is dependent on the vehicle size and shape.

Resistance vs. vehicle speed curves for each of the four vehicle classes are based on the values in Table 1. These curves are shown in Fig 1a, b, c, and d for constant speeds of 0 to 60 ft/sec and for various combinations of maximum grade and maximum headwind. The maximum nonaccelerating thrust requirements are indicated in the upper right-hand corner of each figure.

A comparison of the vehicle resistance curves is given in Fig 2. The curves are replotted for all four vehicles under the two sets of extreme conditions: no wind and no grade, and 30 mph headwind plus 6% grade. A comparison of the effect of vehicle resistance on acceleration for the four vehicle classes was obtained by assuming a constant accelerating thrust and calculating the vehicle speed as a function of time. These curves, which were generated assuming a no-resistance acceleration of 0.13g, are shown in Fig 3. The results show that the time for the rubber tire vehicle to reach cruising speed is about 30% longer than for the other vehicles.

Table 2. Estimated Values of Constants for the Thrust-equation (Eq. 1)

	K_1	K_2	K_3	K_4
Air Cushion	4.13×10^{-3}	0	5.7×10^{-5}	1.8×10^{-2}
Rubber Tire Wheels	2.3×10^{-2}	0	0	1.8×10^{-2}
Steel Wheels	4.6×10^{-3}	0	0	1.8×10^{-2}
Magnetic Levitation	0	4.7×10^{-4}	0	1.8×10^{-2}

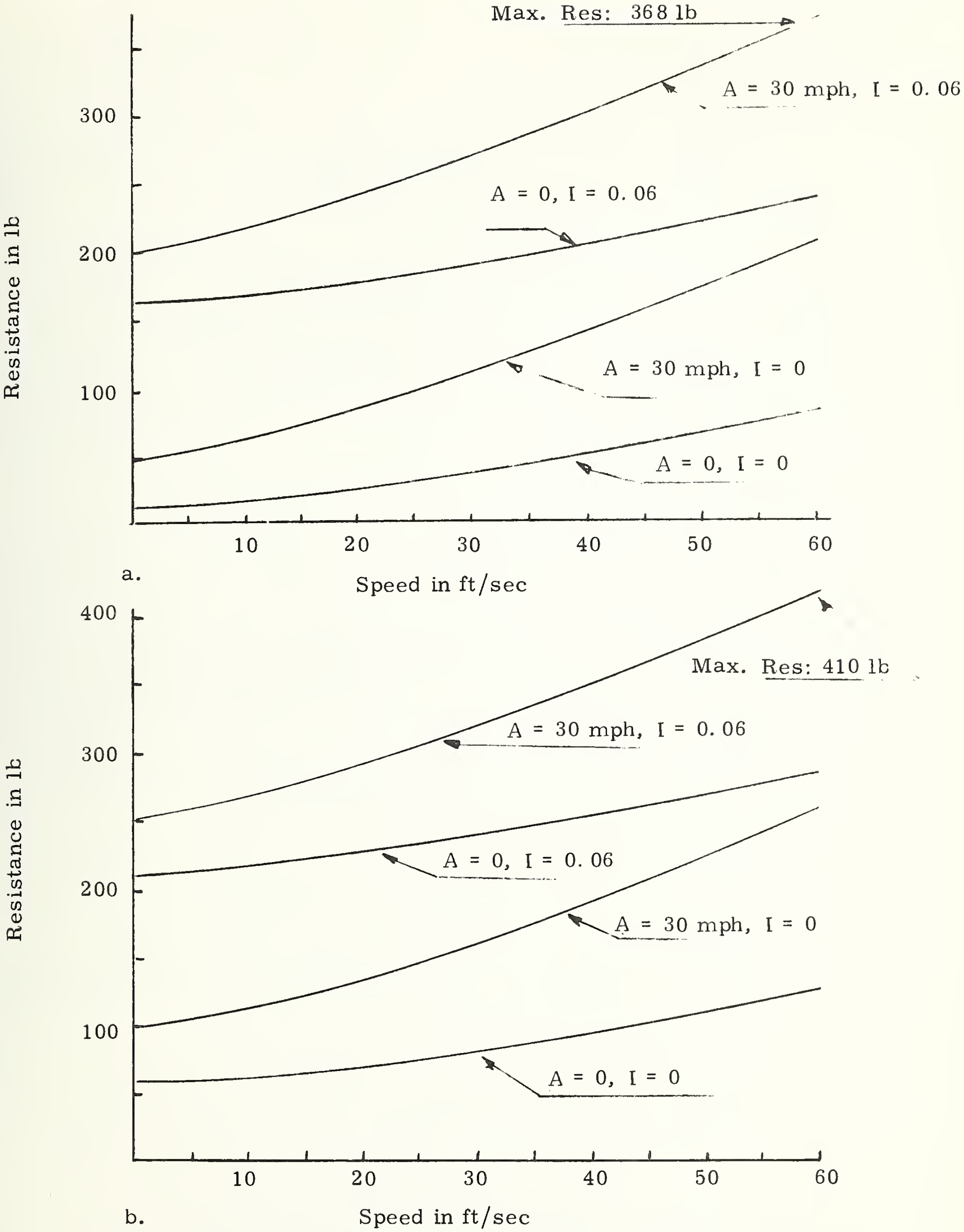

Fig 1a and 1b. Calculated vehicle resistance vs. vehicle speed for (a) air cushion and (b) rubber tire wheels. (Eq. 1).

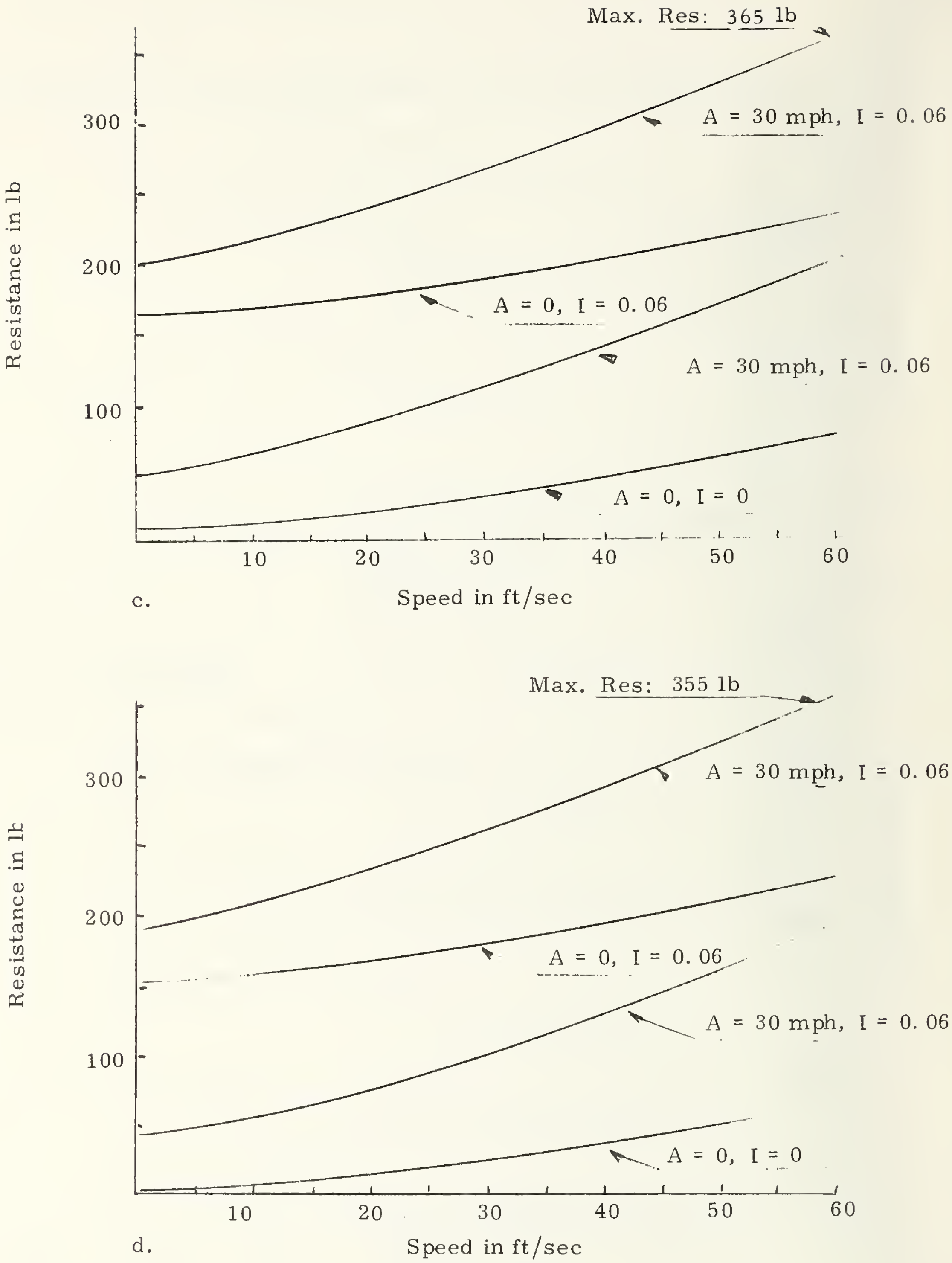

Fig 1c and 1d. Calculated vehicle resistance vs. vehicle speed for (c) steel wheels and (d) magnetic levitation. (Eq. 1).

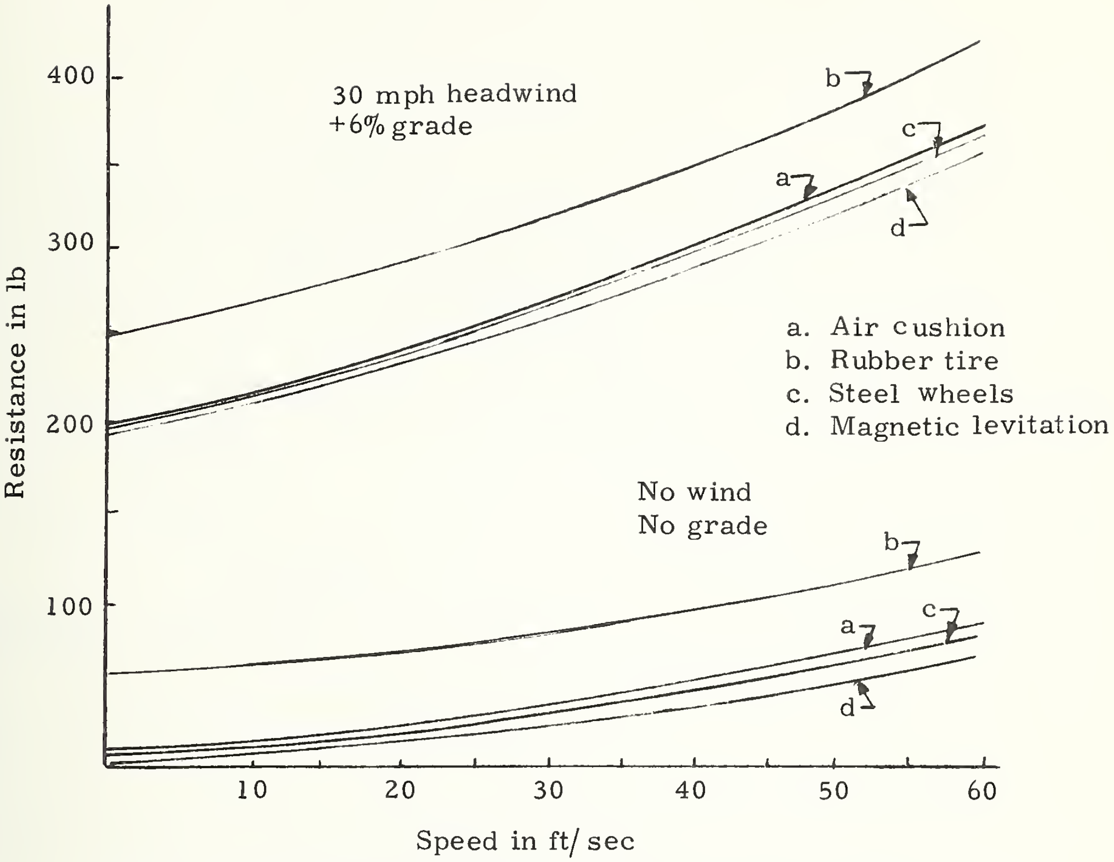

Fig 2. Comparison of vehicle resistances for all four vehicles under conditions of no wind - no grade, and wind plus grade.

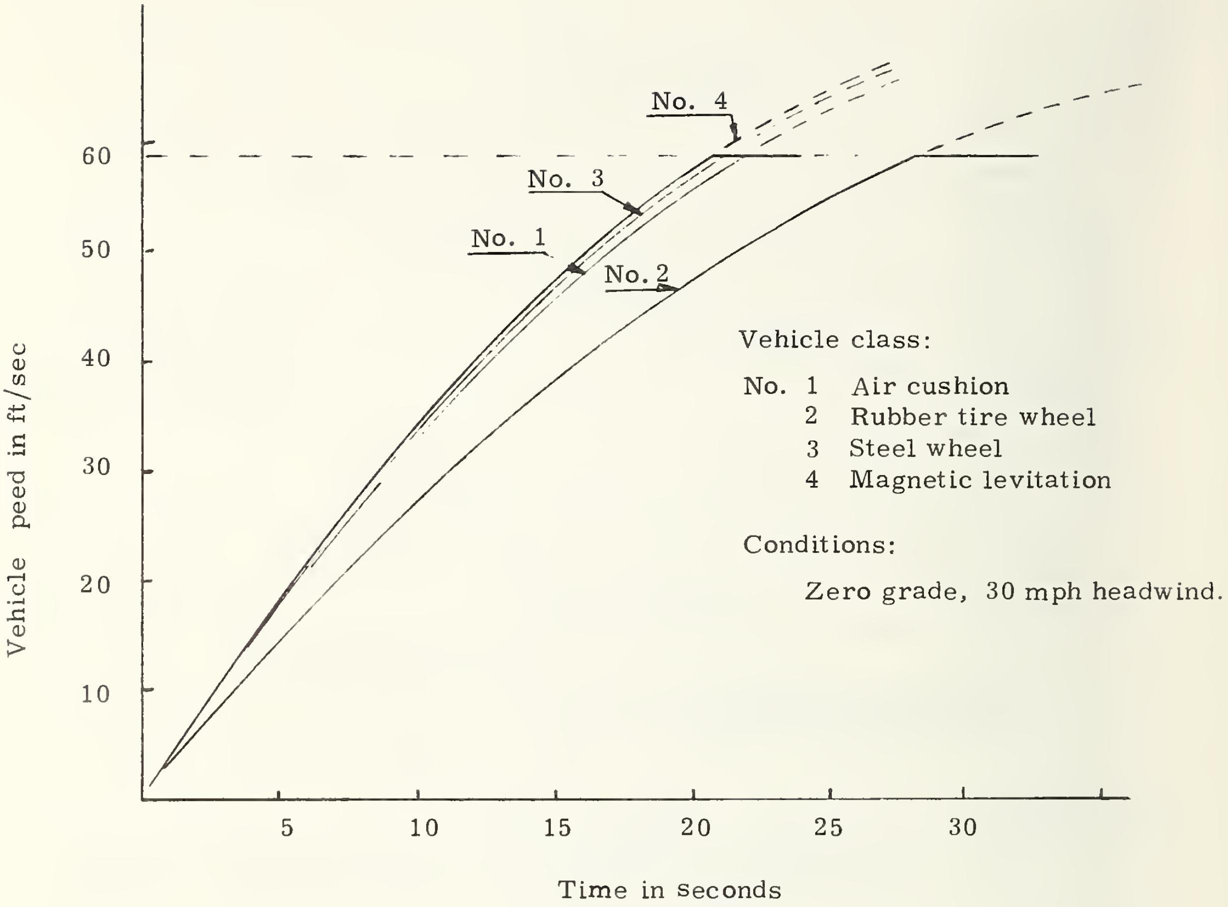

Fig 3. Vehicle speed vs. time during an accelerating period for four classes of vehicles. Propulsion force is assumed constant at a level which would produce an acceleration of 0.13g in absence of vehicle resistance.

D Propulsion System Performance Requirements

To maintain the vehicle headway under variations of speed, grade, and vehicle drag, the propulsion system must provide closed-loop control of vehicle speed and position relative to the vehicle ahead. A propulsion system of this type has two control inputs; vehicle speed command and vehicle headway command. These control inputs may be generated externally to the vehicle and/ or on board. They are compared to outputs of on-board speed and headway sensors, and the differences are used as closed-loop control signals.

An analysis of the closed-loop control characteristics as they relate to the HCPRT vehicle is given in the appendix of this report. Also included are the results of a preliminary computer study of emergency stop characteristics. This analysis has made it possible to formulate a set of preliminary performance requirements for the propulsion systems.

Requirements for response times, drive characteristics, and the propulsion range are given in Table 3 below.

Table 3. Performance Requirements for HCPRT Propulsion

Response	Time	Bandwidth
Velocity control	$\leq$80 ms	$\geq$2 Hz
Relative positional control	$\leq$320 ms	$\geq$0.5 Hz
Propulsion (motor and drive)	$\leq$20 ms	$\geq$8 Hz
Drive characteristics		
Type	Fully reversible thrust (2-or 4-quadrant)	
Thrust-brake crossover	Continuous, no dead-band Additional delay < 0.1 sec.	
Motor characteristics		
Torque	Reversible	
Propulsion range (T_{max}/T_{nom})	Over 3/1	

1. Response Time. The first three sets of values in Table 3 are the desired minimum response time figures for the control loops and the motor/ drive combination. These response characteristics are expressed in time (time constant of a simple lag system) and by the corresponding bandwidth in Hz. The preliminary computer study indicates that collision-free stops during emergency braking are improbable unless a completely controllable, decelerating thrust is available with a delay of less than 0.1 sec.

2. Drive Characteristics. The decelerating thrust described above can only be obtained through drives producing thrust reversal without the use of relatively slow contactor switching. Such drives are called "two-or four-quadrant" drives. The term, quadrant, refers to the four possible combinations of the direction of the motor torque and speed as shown in Fig 4.

In the first quadrant the speed is positive. The torque is in the same direction. The motor will deliver mechanical power to a load, and the quadrant is therefore called a "motoring" quadrant.

In the third quadrant, where both the motor speed and torque directions have been reversed, the motor will deliver mechanical power, but in the reverse direction. The third quadrant is therefore also called a "motoring" quadrant.

In the second and fourth quadrants, either the speed or the torque has reversed direction and mechanical power is received by the motor. These quadrants are called "generating" quadrants.

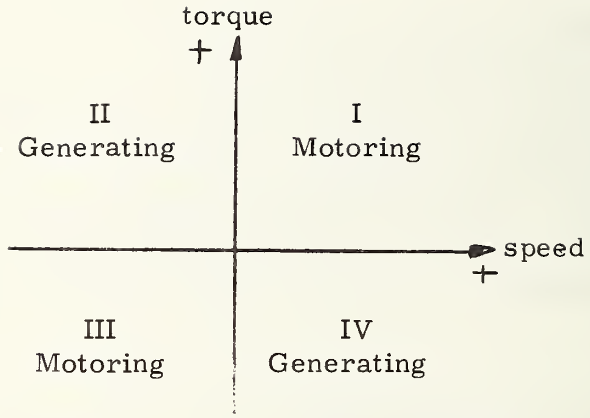

Fig 4. Four quadrants of motor operation as defined by the directions of motor torque and speed.

The minimum requirement is that the propulsion system provide motoring and generating operation for one direction of motor travel. This requirement translates to a minimum of two quadrants of operation. The "thrust-brake crossover" specification in Table 3 indicates that transfer of operation from one to the other quadrant must not result in any discontinuity or in additional response delay.

3. Motor Characteristics. The motor must be of a type that can be reversed by a reversible drive. This means that the motor must have reversible torque characteristics.

The motor must be able to deliver torque in excess to what is required for nominal missions. The excess is necessary to meet the demands produced by extreme conditions of wind, acceleration, and grade. This propulsion range, T_{max}/T_{nom}, has been arrived at from data for other systems, since the HCPRT mission has not been defined. For example, the propulsion range of the Morgantown PRT vehicle is approximately 2.5/1. It is known that the HCPRT will require a greater range.

E Introduction to Propulsion Motor Types

A number of propulsion motor types, all of which can satisfy the propulsion requirements, are discussed in the following sections. Both rotary and linear motors are included. The rotary motors, which deliver thrust through coupling to either rubber or steel wheels, are:

(1) DC (separate field excitation),

(2) AC induction,

(3) AC synchronous.

The linear motors, which provide propulsive thrust directly through magnetic coupling to the wayside rail system, are:

(4) AC linear induction,

(5) AC linear synchronous.

In summary, the motor requires a fast response time for speed control, positional control, and thrust control. In order to obtain controllable decelerating thrust a power conditioning unit or "drive" providing thrust reversal is used. The drive circuits and systems presented in this report are examples of "state-of-the-art" methods; others may also be used. The motor is characterized by reversible torque and a propulsion range of at least 3/1.

III DC MOTOR

The dc motor is practically the only motor that has been used for vehicle traction on railroad and rapid-transit vehicles in revenue service. Speed and torque control of this motor has been accomplished satisfactorily by using series-parallel switching of a number of motors and series (cam-controlled) resistors. More efficient, smoother control has been achieved within the past few years with thyristor choppers. There are two characteristics that have not before been required in railroad and transit vehicles and are of concern for the HCPRT application: effective control in the presence of negligible dead zones and the necessity for short response times.

A DC Motor Characteristics

The propulsion range of the dc motor is quite adequate. The T_{max}/T_{nom} is approximately 3.5/1, exceeding the requirement of Table 3. However, overload of dc motors is limited by the heating effect of higher-than-rated current and by commutator capacity. A frequently repeated overload should not exceed 150% rated current, although emergency overloads up to 350% may be applied for short periods.

High-speed dc motors are best for vehicle propulsion because they are lighter. As the rated maximum speed of the dc motor is increased for the same horsepower rating, the torque requirement goes down proportionally, and the weight of the motor will drop as a result of the smaller frame size. However, maximum safe motor speed is limited by the armature commutator, which tends to decrease the speed of dc motors to well below that of brushless motors. Higher speeds increase the voltage between commutator segments and decrease dc ionization time. Both of these conditions contribute to flashover and motor damage. The weight of the "optimum" dc motor, therefore, will in all probability remain higher than that of the optimum brushless types.

B DC Motor Types

Three types of dc motors, which are classified by the connection of the stator field, are considered:

1) the series dc motor,
2) the shunt field dc motor, and
3) the separately excited dc motor.

The series dc motor is characterized by a low-impedance winding, which is connected in series with the rotor armature. It is the preferred motor for vehicle traction because:

1) it is self-regulating with respect to sudden changes or transients of the source voltage, and
2) it yields relatively constant horsepower and efficiency characteristics under varying tractive loading.

These characteristics, which are a result of the increasing motor field strength as a function of loading, are indicated by the curves in Fig 5.

In spite of its virtues, this type of motor will not be considered because of difficulties associated with thrust reversal. (See Sec. III-C.)

The shunt field dc motor is characterized by a high-impedance winding, which is connected in parallel with the armature. However, it is connected for operation with a narrow range of voltages where no speed adjustment is required. Therefore, the speed control characteristics of the shunt field connection are very poor, and this type of motor will not be considered for HCPRT.

The separately excited dc motor is characterized by a high-impedance winding that is connected to a separate field supply. It maintains a very stable speed with motor loading as indicated in Fig 6. The motor speed is proportional to the applied armature voltage and inversely proportional to the field current. These characteristics make the separately excited dc motor well suited for controllable industrial-speed drives. The armature current in all dc motors has a cross-field effect, which reduces the net field at high currents. In the separately excited motor, this cross field results in a significant increase in motor speed at high loads as indicated in Fig 6. This type of motor is a good candidate for HCPRT.

Compensated dc motors and compound motors were not considered because of problems associated with torque reversal.

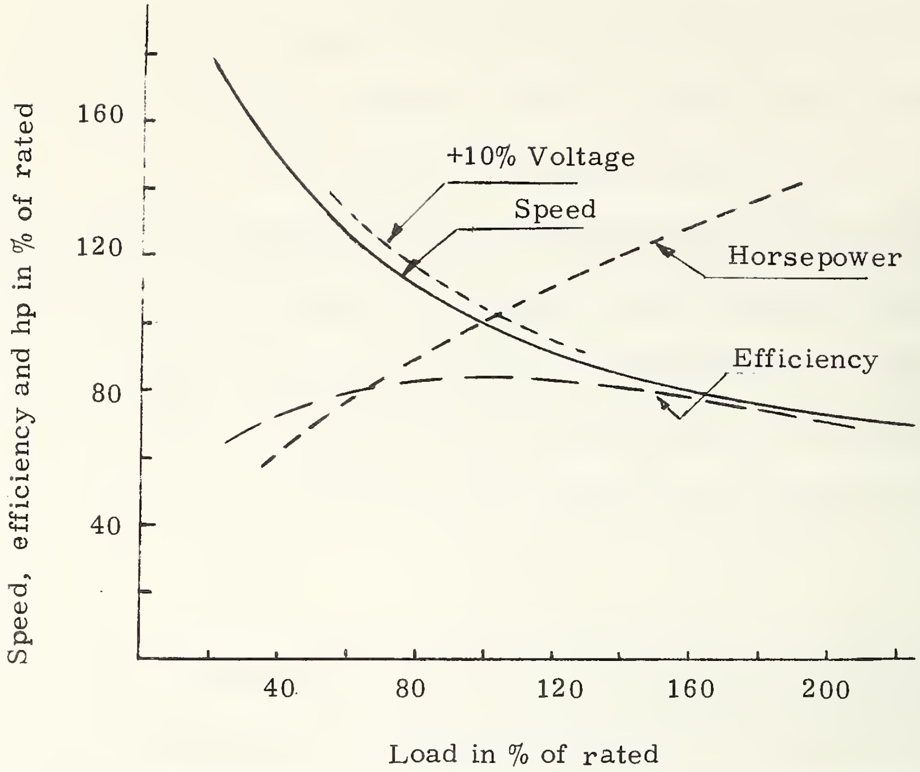

Fig 5. Variation of motor speed, efficiency, and horsepower with load torque for typical dc traction motor with series field winding and fixed dc drive voltage.

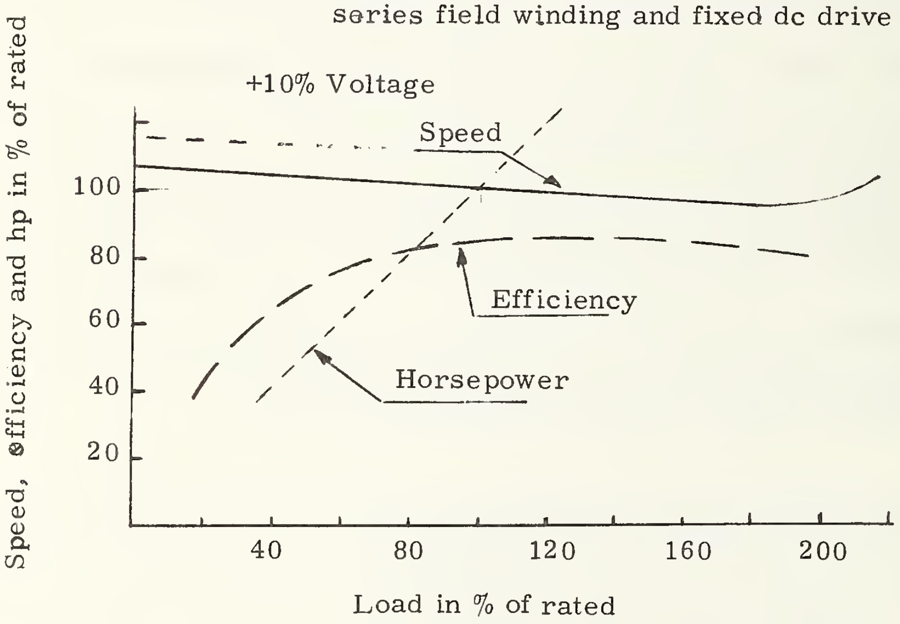

Fig 6. Variation of motor speed, efficiency, and horsepower with load torque for typical separately excited dc motor.

C Type Selection

The desirable characteristics of the series dc motor mentioned earlier have led to the selection of this type of dc traction motor in most (dc) electrical vehicle propulsion systems. There is, however, one very important problem associated with the series dc motor when considering it for the HCPRT application. Thrust reversal in all known drives is accomplished by the use of relatively slow-acting contactor circuits, resulting in response time delays exceeding the desirable 0.1 sec by an order of magnitude. Furthermore, even if contactors could be replaced by fast-acting solid-state switches, the response of the propulsion motor would still be relatively slow due to the long time constant of the combined field and rotor inductances. For the HCPRT, therefore, the separately excited dc motor, powered by a solid-state reversible drive, would seem a better choice.

Under closed-loop control, the separately excited dc motor is an excellent choice for propulsion systems requiring fast response times and accurately controllable speed and torque characteristics. For smooth speed and thrust control, the armature voltage must be controlled by a drive giving a continuous zero-to-full voltage variation. When reversed thrust is required, as in the HCPRT application, the drive must be able to regenerate or absorb power as the vehicle decelerates. These characteristics are obtained with "two-quadrant" drives; they are discussed in the following subsection.

The most troublesome characteristic of the separately excited dc motor vehicle propulsion for application has been sensitivity to source voltage transients. When the source voltage changes suddenly to a different level, or undergoes a transient in a series motor, the speed of the motor is regulated to a large extent by a change in the motor current. (See Fig 5.) In the separately excited motor the effect of a sudden change in the source voltage must be regulated by the action of the field supply and armature drive. However, the state-of-the-art thyristor technology makes it possible to achieve this regulation with response times that are sufficiently short for effective compensation against source voltage transients.

D Two-quadrant Drives

To obtain propulsion and regeneration in both directions, either a four-quadrant drive or a two-quadrant drive with contactors that can reverse the direction of travel must be used. Since the dynamic requirements for reversing are not critical, either two-quadrant drive or four-quadrant drive is acceptable. Two-quadrant drive provides a single-polarity voltage for propulsion in one direction only, but will accept reverse current for regeneration. Four-quadrant drive provides both polarities for voltage and current. In this case contactors are acceptable because they are operated only after the vehicle is stopped.

1. Two-quadrant Chopper Drive for DC Motor Operating from DC Source.

An example of a circuit for this type of drive system is shown in Fig 7. The thyristors Th1 and Th2 are switched on and off in an alternate sequence usually with a fixed period. The direction of the current determines which thyristor conducts. The motor voltage, e_o, in the driving mode is shown in Fig 8. The conducting periods for Th1 in the driving mode are indicated; the conducting periods for Th2 in the regenerating mode are analogous. The thyristors are switched on by application of trigger pulses at the gates, "G," and switched off by a power pulse circuit, called the thyristor commutation circuit. For a detailed explanation of the operation of this circuit the reader is referred to the literature.[5,11]

In chopper drives of this type, the switching rate is made high so that the ripple of the motor current is low compared to rated current levels, as indicated in Fig 8. The average current may be expressed as follows:

$$I_o = \left\{ \frac{t_1}{to} E_s - E_M \right\} \frac{1}{R_a}$$

$$= (E_o - E_M) / R_a \qquad (2)$$

where

R_a = the motor armature resistance

E = the average value of e_o,

E_M = the motor back, emf, or speed voltage

($E_M = K_v$ x RPM).

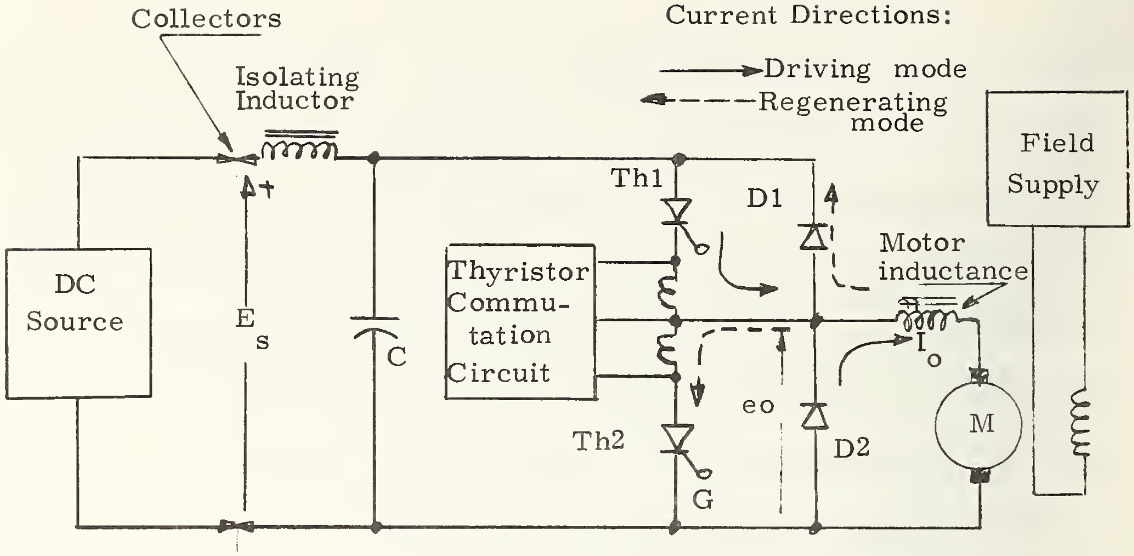

Fig 7. Simple two-quadrant chopper drive.

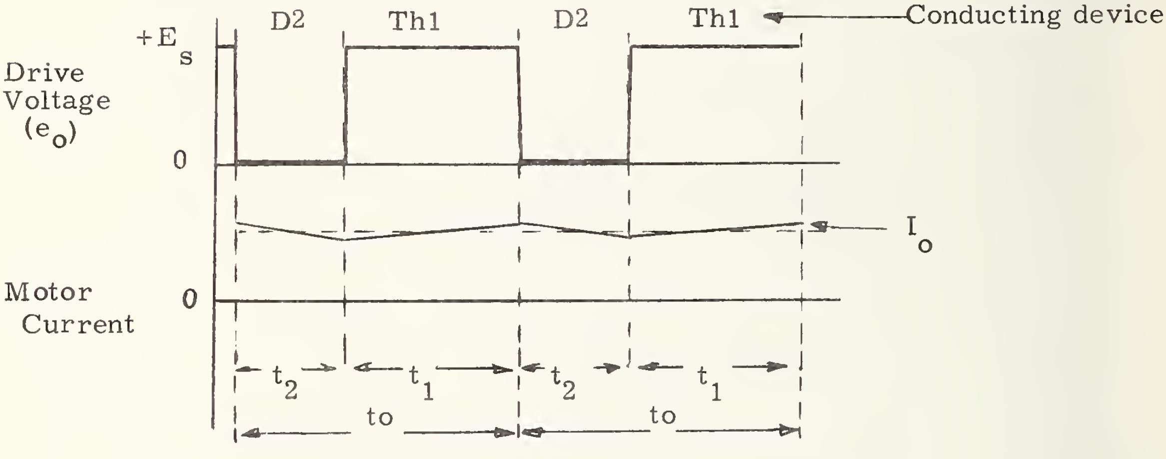

Fig 8. Motor voltage and current waveforms for the circuit of Fig 5 in the driving mode.

Eq. 2 shows that the current, and therefore the motor torque, $T = K_T I_o$, can be controlled by adjusting the t_1/t_o ratio. The current will reverse when $E_M > E_o$. Since E_o is positive, the reverse current regenerates power from the motor back to the dc source. The solid arrows in Fig 7 indicate the current flow during the motoring mode of operation, and the dotted arrows indicate the current under the regenerating mode. Actual power regeneration occurs only when current flows back through D1. This current is forced by the energy stored in the motor inductance.

2. Two-quadrant Chopper Drive for DC Motor Operating from DC Power Rails. If dc power rails are used, an isolation inductor should be provided to prevent the chopper drive from drawing pulsating current from the rails, and to provide a continuous flow of dc power to the chopper. A low impedance at the chopper frequency is ensured by the smoothing capacitor, C.

3. Two-quadrant Chopper Drive for DC Motor Operating from AC Power Rails. If ac power rails are used, the dc power must be obtained by rectification as indicated in Fig 9 for single-phase ac power. Diode rectifiers, however, prevent current reversal for power regeneration. A double set of rectifiers must be provided for this purpose. A rectifier circuit, which provides regeneration by the use of an autotransformer and a set of thyristors Th1-4, is shown in Fig 9. Rectifiers CR1-4 provide the fullwave rectified dc power for the chopper drive. The thyristors provide current conduction paths back to the line, but must do so at a higher ac voltage level. The higher ac

operating voltage is required for the thyristors since they operate in an inverter mode that calls for a conduction angle smaller than the full 180°. The autotransformer provides the higher ac voltage, which must be about 10% above the line voltage.

The two-quadrant chopper of Fig 7 has no transient, delay, or dead-band associated with current reversal. This is because the motor current is reversed simply by adjusting the t_1/t_o time ratio. (See Fig 8.) The response time of the chopper is primarily a function of the chopping frequency, f_c, which may be as high as 400-600 Hz. Higher frequencies, however, increase chopper losses significantly. A control bandwidth (the inverse of response time) of approximately $F_c/2\pi$ Hz can be design-specified, giving a chopper of this type a capability of up to 100-Hz bandwidth. This is well within the propulsion system performance requirements.

4. Two-or Four-quadrant Drives for DC Motors Operating from AC Power Lines. These are standard drives produced today by many manufacturers. For motors of less than 10 horsepower, single-phase full-wave or 3-phase half-wave rectification is favored for its simplicity and low cost. At higher power levels, the low dc form factor of these drives causes excessive motor heating and unacceptable levels of harmonics in the ac line currents. Also, the 120-or 180-Hz ripple in the dc of these drives gives rise to significant vibrations in the motor. Thus, at power levels higher than about 10 hp, 3-phase full-wave rectification is used almost exclusively in two-and four-quadrant drives.

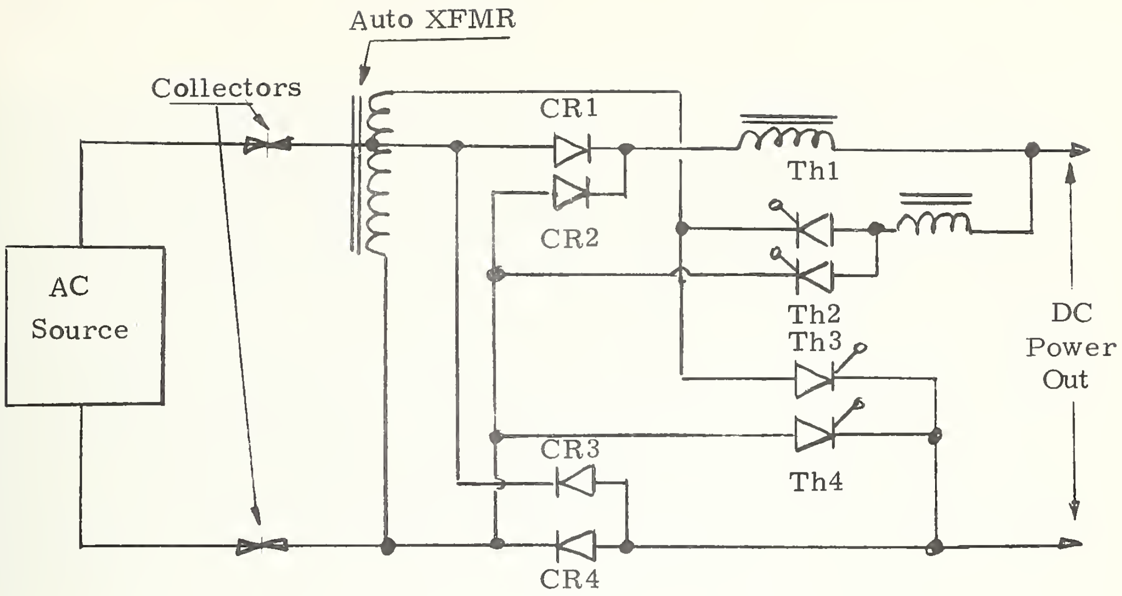

Fig 9. Rectifier with thyristors and autotransformer for power regeneration.

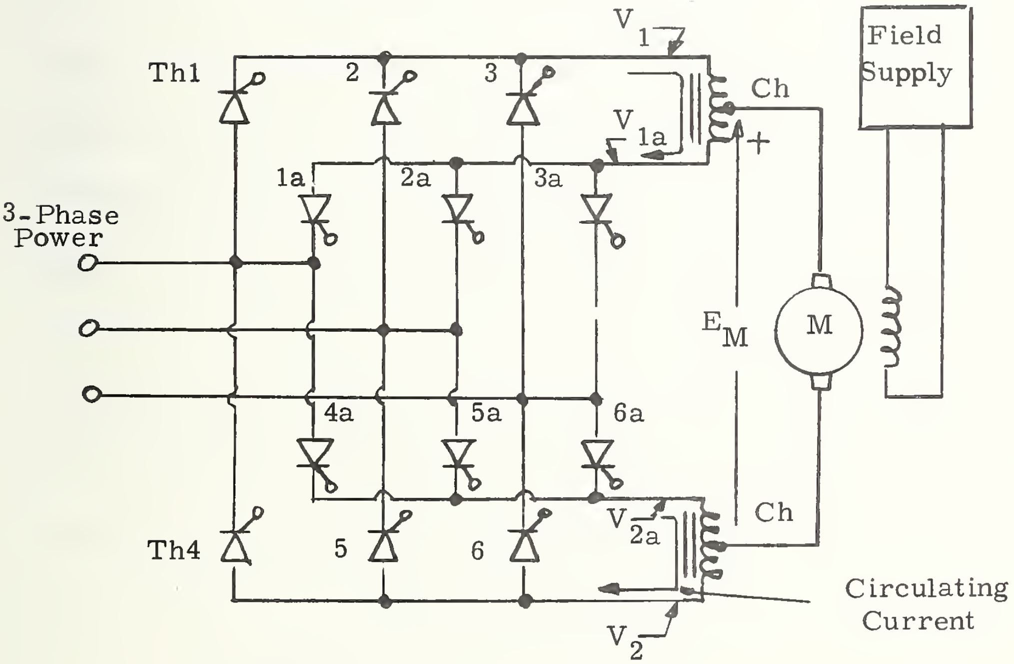

Fig 10. Three-phase, full-wave four-quadrant (fully reversible) drive.

A typical circuit diagram for a two-or four-quadrant, 3-phase, "six-pulse" phase delay rectifier (PDR) drive is shown in Fig 10. In this circuit, thyristors Th1-6 are fired with a phase delay, which is decreased to produce a more positive output $V_1 - V_2$. Similarly, thyristors Th1a-6a are fired with a phase delay, which must be increased to produce a more positive output $V_{1a} - V_{2a}$. The firing sequences are synchronized and controlled so that $V_1 = V_{1a} + V_\epsilon$ and $V_2 = V_{2a} - V_\epsilon$ where V_ϵ is a small voltage difference (roughly two percent of the maximum output voltage) producing a circulating current as indicated by the arrows. The purpose of this current is to ensure that the thyristors conduct when they are fired and to provide a path for the motor current in either direction without delay. The conventional method of connecting back-to-back PDRs would result in dead-band delay time when producing thrust reversal. However, the thyristors must be accurately controlled to keep the circulating current to a minimum. The motor voltage is zero when the firing angle (α) of all the thyristors is 90°. Full positive output (in the direction of the arrow for E_M) occurs for $\alpha \simeq 20°$ for Th1-6 and $\alpha \simeq 170°$ for Th1a-6a, and full negative output occurs as these firing angles are reversed. The response time of this drive is increased somewhat because of the chokes. However, well-designed current and tachometer feedback loops can extend the drive bandwidth to 10 Hz or more for 10-to-60 hp motors.

The response time of ac-to-dc drives such as that of Fig 10 may by special design techniques be pushed to about one-half the period of the power frequency.

Assuming 60 Hz power, this corresponds to 8.3 ms or a bandwidth of $\simeq$ 30 Hz. The dc chopper drives may be designed with a considerably faster response time. The limiting factor is the slower motor response time.

Both drives must be coupled with the motor. The combination of the motor with the drives increases the total response time. However, the use of either the chopper or PDR will result in a drive response bandwidth better than the required 8 Hz.

E Summary

The dc motor, which is used extensively for vehicle propulsion, may be used in the HCPRT applications, but a separately excited field winding should be used rather than the more commonly used series field winding. This motor provides a T_{max}/T_{nom} well within the required range. For minimum weight, the motor speed should be the highest commensurate with good life and high reliability. Nevertheless the motor weight of the dc motor will be greater than that of a comparable ac motor. Relatively simple solid-state dc-to-dc power circuits, which provide the required response time, are available for reversible drive of the dc motor. These drives are designed for regenerative braking, and proper operation depends on the ability of the power source to absorb the regenerated power; a rectifier station must be designed to meet this requirement. These drives require special on-board rectifier circuits which provide power regeneration if ac collector power is used. Reversible power circuits are also available, which operate directly from 3-phase ac power. These are generally more complex than the dc-to-dc circuits, but they have the advantage of eliminating the need for reversible power rectifier stations. Reversible drive characteristics may be achieved with dynamic brake resistors, but these drives generally do not yield the required braking effort over the full operating speed range, and presently available designs use relatively slow-acting power contactors. The main problems with the dc motor are associated with the commutator. Maintenance is required to replace brushes and to check commutator wear. Overspeed or overload will cause flashover failures.

IV AC ROTARY INDUCTION MOTOR

The induction motor is the simplest and most compact electric motor. There are no brushes or commutators; thus, the motor requires less maintenance and is not subject to the problems associated with commutator and brush wear, and flashover failures. It has two characteristics of concern: First, the speed and torque of the motor are not linear functions of the motor terminal voltage when supplied from a conventional fixed frequency supply. This tends to complicate its control. Second, the motor becomes very inefficient when attempts are made to control speed and torque under the conditions of a fixed frequency supply. Because of these disadvantages, the induction motor has not been used for traction of PRT, rapid-transit, or railroad vehicles in revenue service.

A Motor Types and Characteristics

There are two types of induction motors; the squirrel-cage motor and the wound- rotor motor. The more commonly used is the squirrel-cage motor. Three-phase power is used almost exclusively.

1. Squirrel-cage Motor. This motor operates at a speed slightly less than its synchronous speed, which is proportional to the number of poles and the excitation frequency. The "slip,"s, of the induction motor is defined as the ratio $(\Omega_s - \Omega_m) / \Omega_s$ where

Ω_s = synchronous speed at the applied frequency

Ω_m = speed under load.

The increase of the slip under load and the slip at which peak torque occurs is a function of the per-phase resistance of the rotor winding.

Various torque-speed characteristics for squirrel-cage motors can be obtained by changing the design of the rotor. Torque-speed curves for NEMA Designs A to D are shown in Fig 11. The Design A rotor winding has a low resistance; the Design D rotor winding has a relatively high resistance. The Design B and C characteristics are achieved by the use of "deep bar" rotor designs. In these motors the rotor current occupies the entire bar cross-section at low slip, and the rotor winding appears as a low resistance. At high slip, the reactance of the bar crowds the current into the top portion so that the winding appears as a high resistance.

2. Wound-rotor Motor. The speed of the wound rotor motor is controlled by adjusting resistance in series with the rotor winding. This is an inefficient method because of high-power dissipation in the rotor resistors. It would therefore be an unlikely choice for HCPRT.

B Type Selection

Motor types are normally selected on the basis of efficiency, peak torque, starting torque, and starting current. A compromise must be made between starting torque and efficiency, since the high-resistance rotors, which give high-starting torque, will also yield a low efficiency under normal operation.

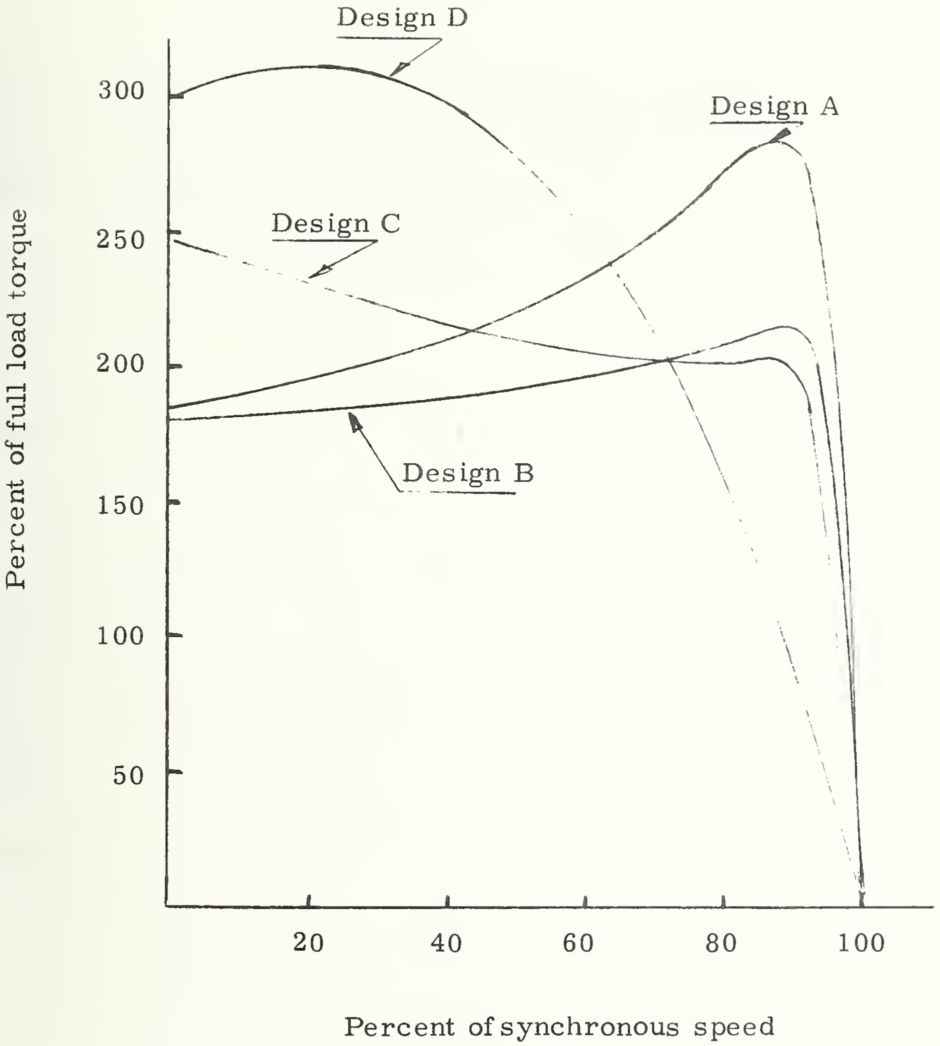

Fig 11. Torque-speed characteristics for the NEMA-design motors.

Design B is used most frequently for most industrial applications because it offers the best compromise. The Design B motor can deliver a peak of about three times the rated torque, or a T_{max}/T_{nom} of approximately 3/1, just meeting the propulsion range requirement in Table 3. The Design A motor provides a higher T_{max}/T_{nom} ratio and is therefore perhaps a better choice for the HCPRT.

The induction motor for HCPRT should be designed for operation at frequencies of approximately 400 Hz or above. This is considerably higher than the industrial type squirrel-cage motor, designed for operation at frequencies of 50 or 60 Hz. It is similar to aircraft or other special motors, which are also designed for operation at 400 Hz or above. There are two major reasons for increasing the operating frequency:

1) The maximum speed of the motor is proportional to frequency so that for a given horsepower, the motor size and weight will decrease. Aircraft and other 400-Hz motors are significantly lighter than their 60-Hz counterparts up to a ratio of 1 to 7. Some of this weight reduction is counteracted by the heavier gear box, which is the result of the higher gear-reduction ratio required to match the axle speed.

2) The potential control bandwidth increases with the operating frequency, and a 400-Hz motor will perform with better closed-loop stability than the 60-Hz motor for a given closed-loop bandwidth.[13]

C Methods of Speed Control

Speed and torque control in a 3-phase induction motor can be accomplished through (a) primary voltage control or (b) the simultaneous adjustment of voltage and frequency. Reduction in primary voltage causes a drop in the torque at all speeds, as illustrated in Fig 12. If the load torque drops off with speed, the operating points will be shifted in a stable manner from points A to B as shown. A downward adjustment of the voltage and frequency results in a proportional shift to the left of the torque-speed curve as illustrated in Fig 12. Using the same load-line as before, the speed would drop to point C.

1. Primary Voltage Control. Primary voltage control is not recommended for rotary-motor propulsion systems for the following reasons:

1) Operation at low speed may be unstable if motor speed is controlled entirely by primary voltage adjustment; for example, when the motor torque-speed curve rises faster than the load curve.

2) Primary voltage control at low speed requires high-slip motor operation, hence high power dissipation and motor overheating in the rotor. During extended operation at low speed, excessive heating of the motor will occur.

3) The 3-phase sequence must be reversed to obtain braking torques. Braking in this manner, known as "plugging," causes high power losses in the motor during the braking period.

2. Simultaneous Adjustment of Voltage and Frequency. Speed control of the squirrel-cage induction motor using power at adjustable voltage and frequency, may be done in two ways. In one method the frequency and voltage of the motor power are adjusted proportionally to control the motor speed, as illustrated in Fig 13. The motor will run at a speed where the slip frequencies* nearly proportional to the load torque. However, analysis and simulations have shown [1,2] that this control system will exhibit poor stability and sustained oscillations with this type of control, particularly at low speeds.

The other method of speed control is to use a variable frequency drive with constant slip frequency control. This drive control operates the motor at a constant slip frequency, Δf. As the motor speed changes, the frequency is changed proportionally to keep Δf constant. When decelerating torque is required, the motor excitation frequency is decreased so that the slip is made to change sign, and the machine operates as an induction generator on the "negative" torque-speed curve as shown in Fig 14. Good control stability has been reported with this control system.[3]

Thus, a variable voltage/frequency drive system with constant slip frequency should be used with the ac rotary induction motors.

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*The "slip frequency" is the frequency of the current in the rotor and is equal to the difference between the source frequency and the frequency corresponding to the rotor speed.

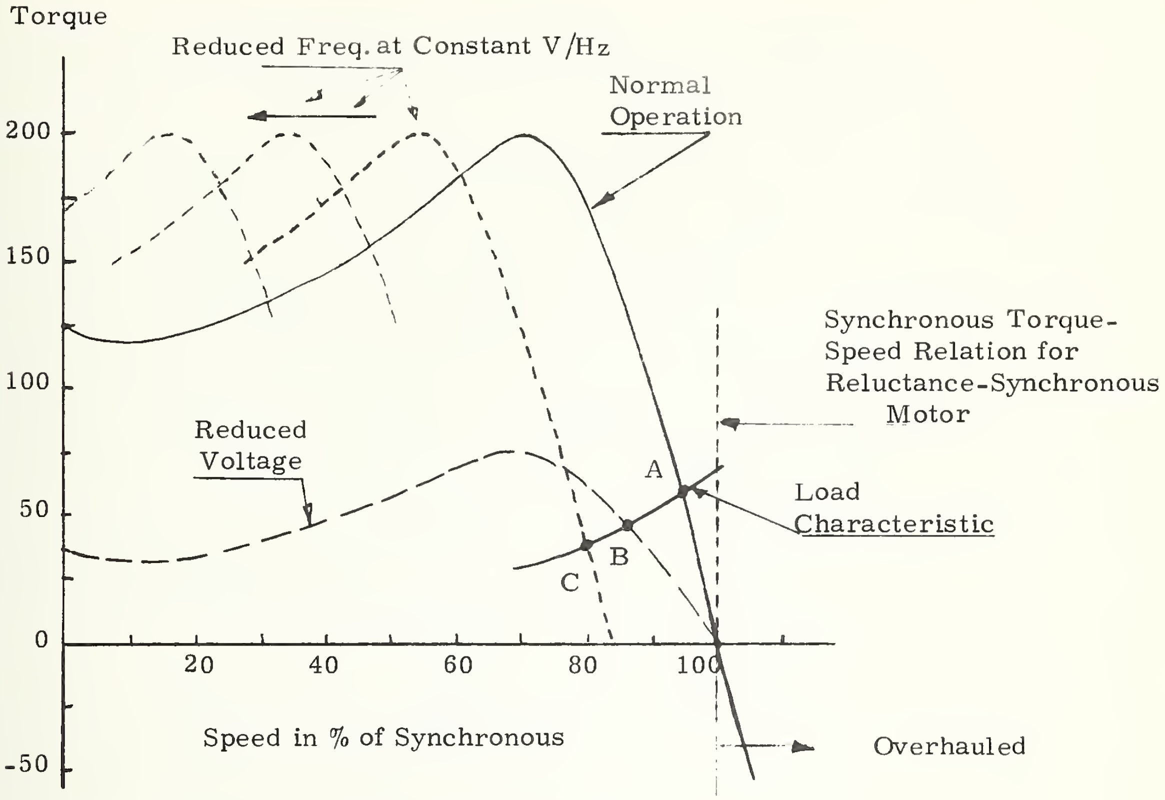


Fig 12. Typical Design B induction motor torque-speed curves.

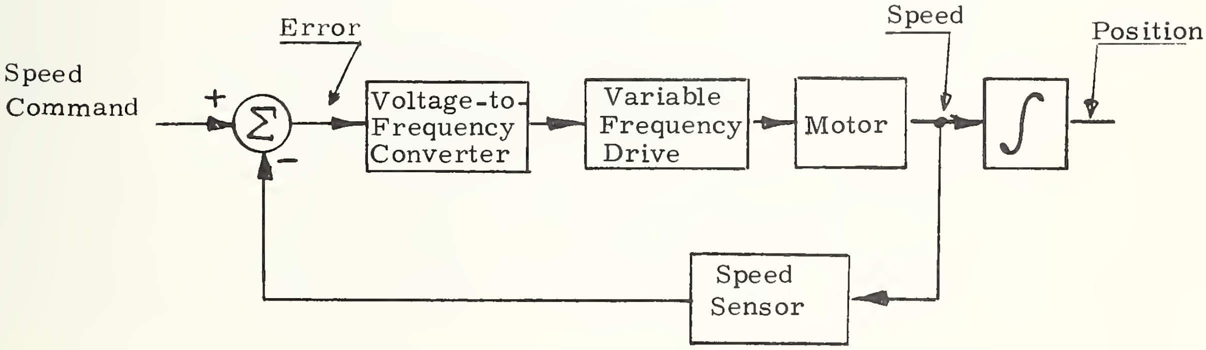


Fig 13. Variable frequency speed control of the squirrel-cage induction motor.

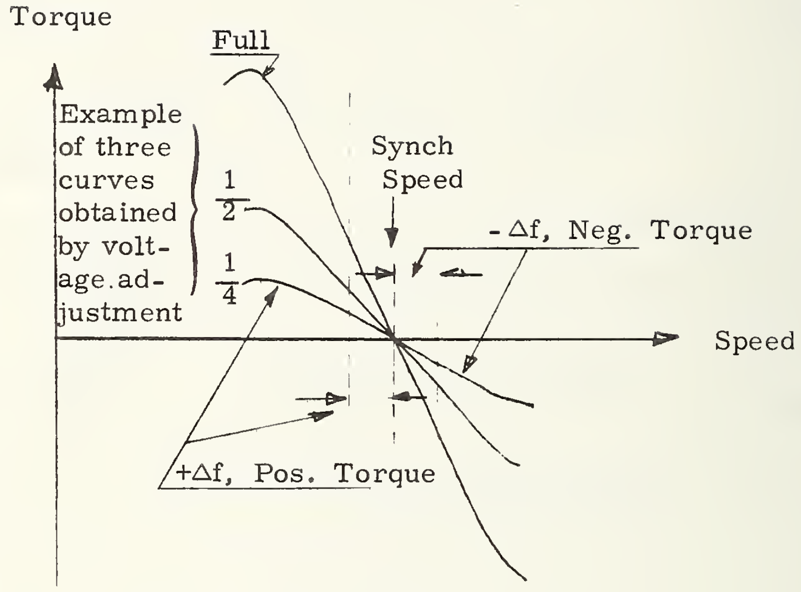


Fig 14. Illustration of induction motor torque control under constant slip (Δf) drive.

A block diagram of this control system, called the "constant-slip" control system, is shown in Fig 15. A signal from the speed sensor on the motor shaft is used first in a speed controller, where the actual motor speed and a speed command signal are compared to produce a torque (command) signal. The speed signal is used also in an inverter frequency controller, where the slip frequency signal is either added to or subtracted from it, depending upon the polarity of the torque signal. An increase of motor load reduces the speed. This results in an increase of the level of the torque signal by increasing the motor voltage, and thus compensates the reduction of speed.

When a constant-slip control system is used, the response to load variations of the ac rotary induction motor is analogous to the dc motor. The response of the motor to changes in speed command is also similar to that of the dc motor. AC motors designed for 400-Hz operation in a constant-slip system should be equal or be less than the response time of comparably sized dc motors and easily meet the 8-Hz bandwidth requirement for the HCPRT application. Constant-slip operation also tends to optimize motor efficiency and power factor, which typically will be about 90% and 0.9, respectively, at rated motor speeds.

D Variable Frequency Drive Designs

In variable frequency drive systems, adjustable frequency can be generated either from a fixed-frequency supply line using cycloconverters or from a dc bus using inverters.

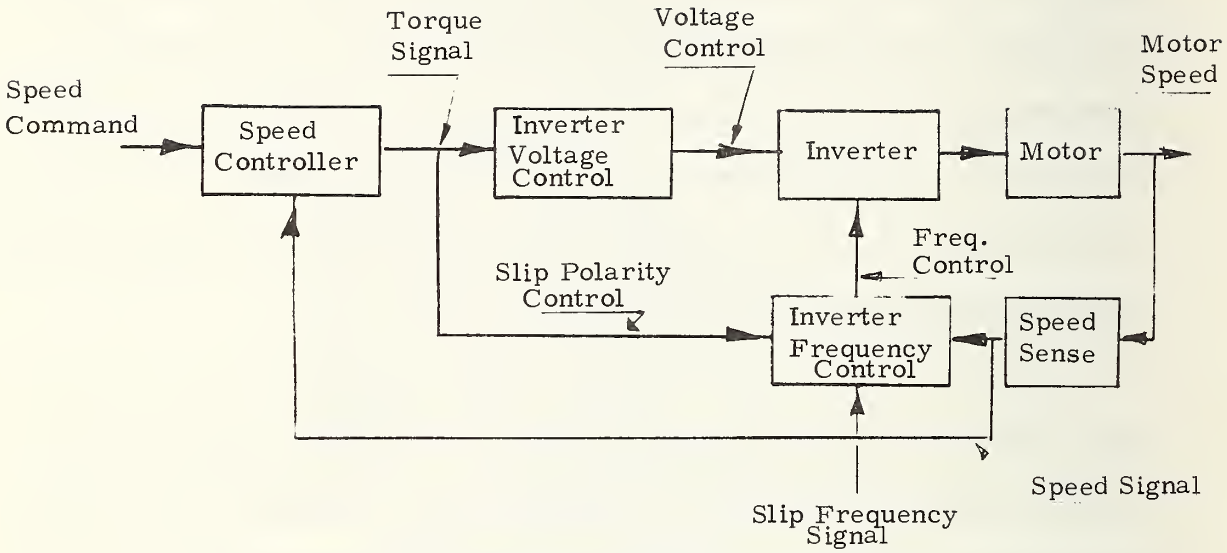


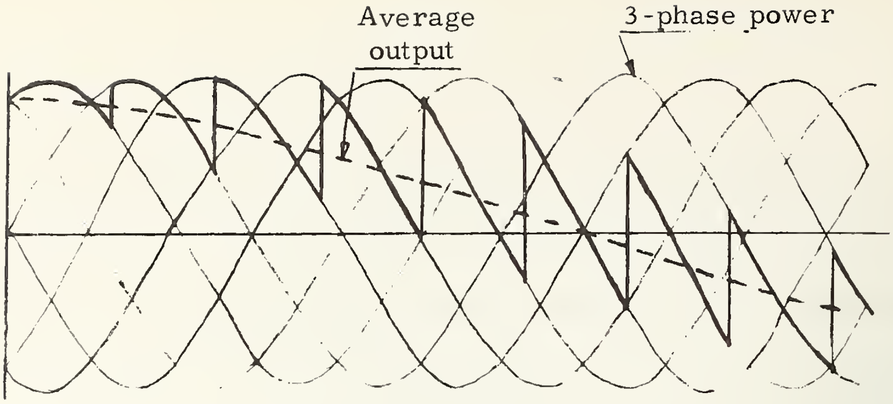
Fig 15. Adjustable-frequency, constant-slip speed control system.

1. The cycloconverter. The cycloconverter represents one of the more recent developments in adjustable-frequency drives. It is effective for applications where the maximum motor frequency required is less than one-half the supply frequency.[12] As illustrated in Fig 16a, it converts fixed-frequency 3-phase power directly into adjustable-frequency power. Due to its low output frequency the cycloconverter will not be considered for the HCPRT.

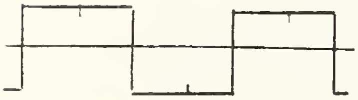
Use of forced commutation circuits makes it possible to generate power at frequencies considerably higher than the supply frequency, but at the expense of simplicity and efficiency. At this time, not enough is known about the characteristics of the force commutated cycloconverter to consider its application to the HCPRT.

2. Inverters. To drive the induction motor, switch-type inverters are used to produce ac voltage with sinusoidal-like waveforms. Sinusoidal-like waveforms are preferable since they are relatively free of harmonics. Harmonics increase motor losses.

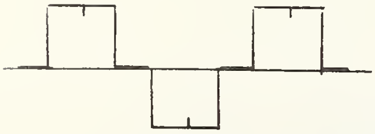
The simplest and most coarse approximation to a sinusoidal-like waveform produced by the switch-type inverter is the square wave shown in Fig 16b. However, this wave, also called a 4-pulse wave, has significant harmonics, starting with the third. Higher-pulse waves can be produced by switched inverters: 6-pulse waves, which start with the fifth harmonic; and 12-pulse waves, which start with the eleventh. (See Fig 16c and d.) The 6-pulse wave is



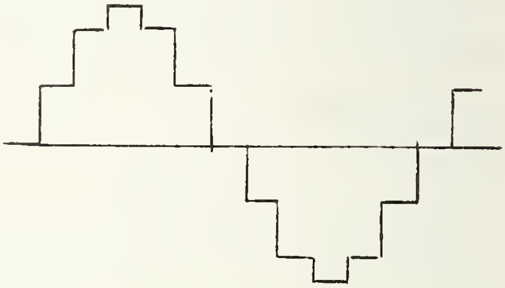
a. Cycloconverter wave generated from full-wave 3-phase power.



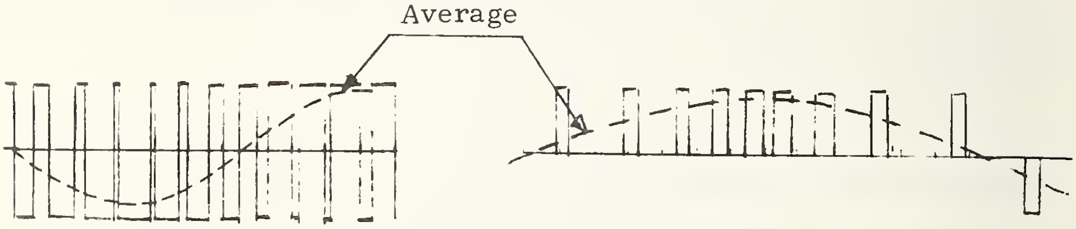
b. Four-pulse wave



c. Six-pulse wave



d. Twelve-pulse wave



e. Pulse-width modulated wave

f. Pulse-time modulated wave

Fig 16. Generation of approximations to sinewaves using switched waveforms by 6 commonly used methods.

applications up to 100 kW.

Inverters are designed with transistors or thyristors (SCRs). Transistors operate both as linear and switching devices, but for high power applications, they usually operate as switches. Thyristors operate as switches.

The 6-pulse inverter is the most frequently used inverter for adjustable frequency induction motor drives. The configuration of 3-phase 6-pulse inverters for adjustable-frequency induction-motor drives depends upon the type of thyristor commutation that is used. To achieve commutation with low losses, designers of high-power inverters used auxiliary thyristors to force-commutate the load-carrying thyristors. A typical inverter of this type is shown in Fig 17. The thyristors in bold lines are the load-carrying devices, and the others serve to provide commutation pulses. For a thorough description of the operation of this circuit the reader is referred to the literature.[4,5] To provide a 3-phase waveform, the load-carrying thyristors are switched on and off, producing square-waves at the output terminals. The switching is controlled so that these square-waves are phase-shifted 120 electrical degrees as shown by the upper three waveforms in Fig 18. The lower three waveforms are the resulting 3-phase line-to-line voltages, which are the 6-pulse stepped waves discussed earlier.

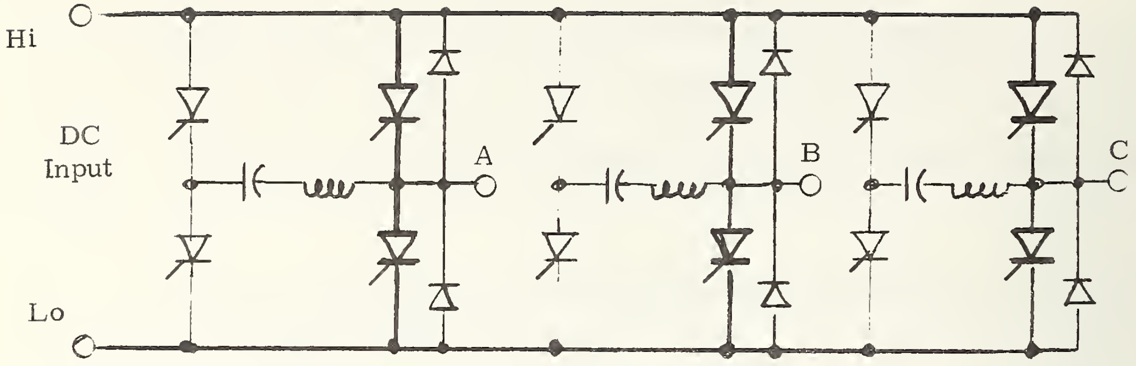


Fig 17. Three-phase inverter circuit using auxiliary commutating thyristors.

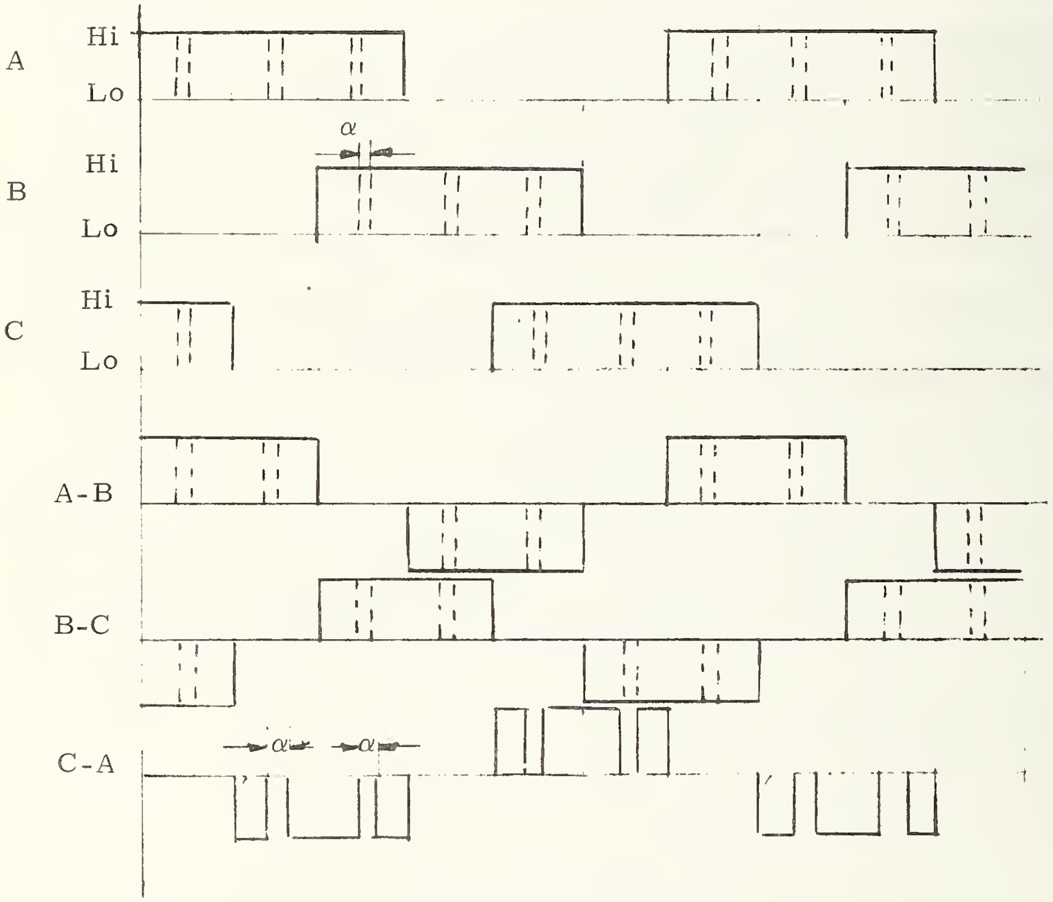


Fig 18. Output waveforms for the inverter of Fig. 14 showing a principle of multiple switching for voltage reduction.

The control of fundamental-frequency waveform amplitude is achieved by pulse-width control. Multiple switching is one technique of pulse-width control which has been found satisfactory[3] in motor drives. Fig 18 shows how multiple switching modifies the 6-pulse output by the dotted lines and more clearly by the bottom waveform. The variation of the amplitude of the fundamental wave with pulse-width control is shown in Fig 19. The dotted curves in Fig 19 are the variation of the lowest existing harmonics relative to the fundamental amplitude as a function of the pulse-width reduction angle α (indicated in Fig 18).

At low-motor speeds where angle α is large and the voltage is low, the harmonics become very significant. This is shown in Fig 19. As an example, suppose that both the fundamental voltage and the frequency are adjusted to 20% of full value. The 5th harmonic is then 75% and the 7th is 100% of the fundamental. The 5th harmonic at 20% speed and frequency corresponds to a frequency near the rated motor drive frequency. Assuming that the motor is nearly stalled in relation to the 5th harmonic, the motor loss from this harmonic approaches that of a stalled motor at rated frequency, but at 15% voltage. The total loss at rated motor torque and 20% speed is approximately 40% higher than the rated motor losses. These losses are tolerable when the acceleration periods are relatively short, but the motor must be force-cooled if operation at low speed and high torque is required for several minutes, such as climbing a steep hill. The harmonics can be further reduced by increasing the number of switchings per pulse over the three used in the above example.

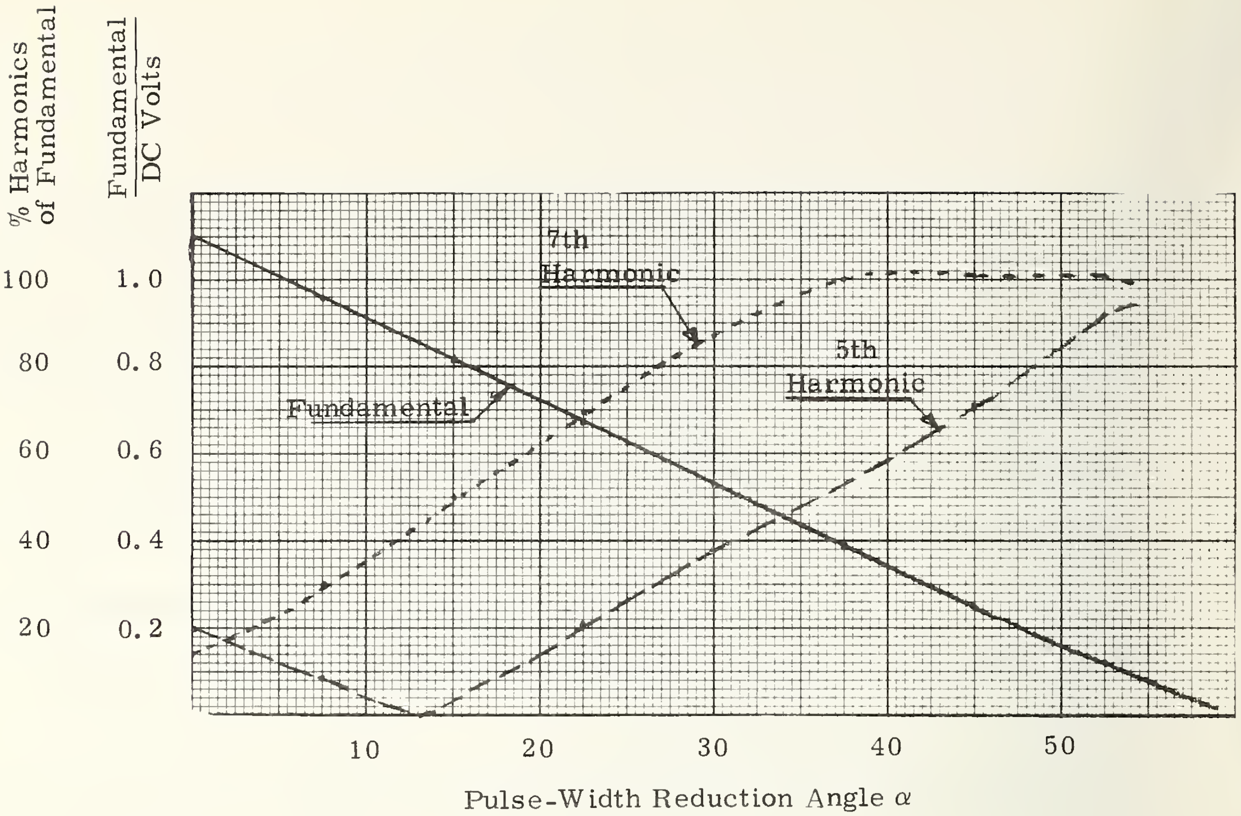


Fig 19. Variation of the amplitude of the fundamental and relative value of the two lowest harmonics with the angle α. (See Fig 18.)

Other methods of producing nearly sinusoidal voltages include pulse-width modulation and pulse-time modulation as illustrated in Fig 16e and f. In pulse-width modulation the inverter output terminal is switched between a plus and minus polarity supply bus at a relatively high frequency to produce an average output voltage at a lower frequency as indicated in Fig 16e. The inductance of the motor, plus additional filters which are often used, smoothes the resultant current. The switching circuits and their operation are usually similar to that shown in Fig 7; three such circuits are required for a 3-phase supply.

Pulse-time modulation is used primarily with switching circuits that produce output pulses of constant width. By controlling the time distribution of these pulses as indicated in Fig 16f, an average sine-wave output is obtained. The current is smoothed by the motor inductance and other filtering components. A typical circuit which makes use of this type of modulation is shown in Fig 17. The thyristors of the plus and minus pulse circuits are controlled to provide pulse distribution and polarity as indicated in Fig 16f. An output capacitor, C_o, provides averaging and smoothing. Circuits such as those in Fig 20 have certain inherent advantages such as higher operating reliability than conventional inverters, but they generally require a greater number of thyristors and higher thyristor current ratings for a given output volt-ampere.

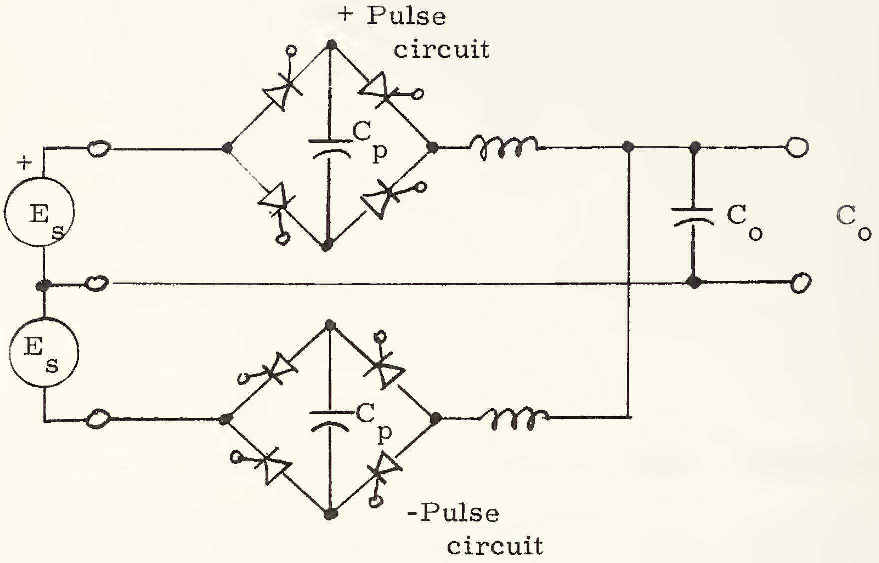


Fig 20. DC to ac inverter using thyristor pulse circuit and pulse-time modulation to produce a sinusoidal average voltage.

E Summary

Rotary ac induction motors have been used infrequently in vehicle propulsion, primarily because of the complex drive system required. However, reliable drives with effective methods of control have become available, which provide both torque reversibility and power regeneration. One such drive now frequently used is the 6-pulse inverter with pulse-width voltage control. With these new developments these motors possess the advantages of the dc motor without the disadvantages associated with commutators and brushes. To meet the required response time the motor should be designed for 400-Hz operation, generally available in aircraft motor designs. The drive system should be based on the constant-slip, variable-frequency principle of control for good system stability. Under this type of control the motor can provide T_{max}/T_{nom} values that fall within the required range.

V. AC LINEAR INDUCTION MOTOR (LIM)

The nature of the LIM makes it a practical consideration for both on-board and guideway propulsion systems. In the on-board propulsion system, the powered or "primary" member of the motor is carried on board the vehicle, and the passive or "secondary" member is stretched out along the guideway. In the guideway propulsion system, the primary is imbedded in the guideway structure, and the secondary is carried on board. The use of the LIM in both of these systems will be examined.

A. Primary On-board System

Consideration is given to the use of LIM for slow vehicles and to the methods of speed control, which are the same as those for rotary speed control.

1. Motor Characteristics and Selection. The LIM is in effect a squirrel-cage motor that has been split along the axis of its armature and unrolled into a flat plane. The squirrel-cage secondary member is a flat sheet, which in the primary on-board system constitutes the reaction rail stretched out along the guideway. The LIM and its application to ground transportation has been discussed extensively in the literature.

Attention has been given primarily to the use of LIM propulsion for high-speed vehicles (150-300 mph). In these applications it is possible to obtain good thrust characteristics and reasonable efficiencies. In applications involving relatively slow vehicles such as the PRT systems, however, it is difficult to achieve similar motor efficiencies. The reason for this can be seen from the following discussion:

First, the slip, s_m, at which maximum LIM thrust occurs, can be expressed as[6]

$$s_m = k_1 \frac{g}{V_s \tau} \tag{3}$$

where

g = the motor air gap

V_s = the LIM synchronous speed

τ = the motor pole pitch

k_1 = a constant whose value is a function of design parameters such as the resistance and thickness of the reaction rail and the distortion of the magnetic field around the ends of the LIM, known as the end effect.

Second, as a general rule for any induction motor, the full-load efficiency decreases as the operating slip increases. Since the full-load operating slip for most LIM designs is proportional to s_m, it follows that

$$\eta \sim (1 - k_2 s_m) \tag{4}$$

where

k_2 = a relatively constant fraction related to the operating slip.

To keep the efficiency high, a decrease in the synchronous speed, V_s, in Eq. 3 should be accomplished without a corresponding increase in s_m. This can be done in principle by;

1) increasing the pole pitch, τ;

2) decreasing the air gap, g; or

3) improving the rail conductivity.

The first option is not recommended. Although it leads to lower operating frequencies and fewer pole segments, it also leads to more severe end effects and heavier LIM motors. The second and third options may be carried out to some extent, since better air-gap control is feasible for lower-speed motors, and higher conductivity metal may be used. However, no data is available showing that an increase in s_m does not also result in a subsequent drop in η in low-speed LIM designs.

Representative performance curves for an optimized low-speed LIM are shown in Fig 21. These characteristics are for a double-sided LIM running on an ac power frequency of 60 Hz. The air gap is assumed to be about 0.2 in. It may only be possible to achieve such a small gap on guideways with limited curvatures. The ratio of peak operating thrust of the LIM to the nominal operating thrust is close to 3/1, as in the case of the rotary induction motor.

Generally speaking, the LIM will operate at lower efficiencies and lower power factors than rotary induction motors. For example, operation of this LIM at 35 mph, as indicated by the vertical line in Fig 21, would yield an efficiency of about 67% and a pf = 0.42. Assuming that the power required to propel the vehicle at 35 mph is 25 hp; the loss in the motor is

$$P_{loss} = 746 \times hp \times (1 - \eta) = 6150 \text{ W} \tag{5}$$

This loss is almost three times that of a 25-hp rotary induction motor. Even though most of this loss occurs in the reaction rail, a significant loss occurs in the LIM, and it would have to be force-cooled, resulting in further overall reduction of efficiency.

2. <u>Speed Control and Drive Systems.</u> The methods available for LIM speed control are the same as those for rotary speed control. Both primary voltage control and frequency control may be used, although, as with the rotary motor, the frequency control is preferable because of its higher thrust and efficiency.

As discussed earlier, to obtain favorable efficiency characteristics for the low-speed LIM, the operating frequency should be kept low, typically no higher than 60 Hz as in Fig 21. This requirement conflicts with the requirement for fast response time discussed in the previous chapter. Thus, even with constant slip control, the bandwidth of the 60-Hz LIM would probably fall short of the required 8 Hz.

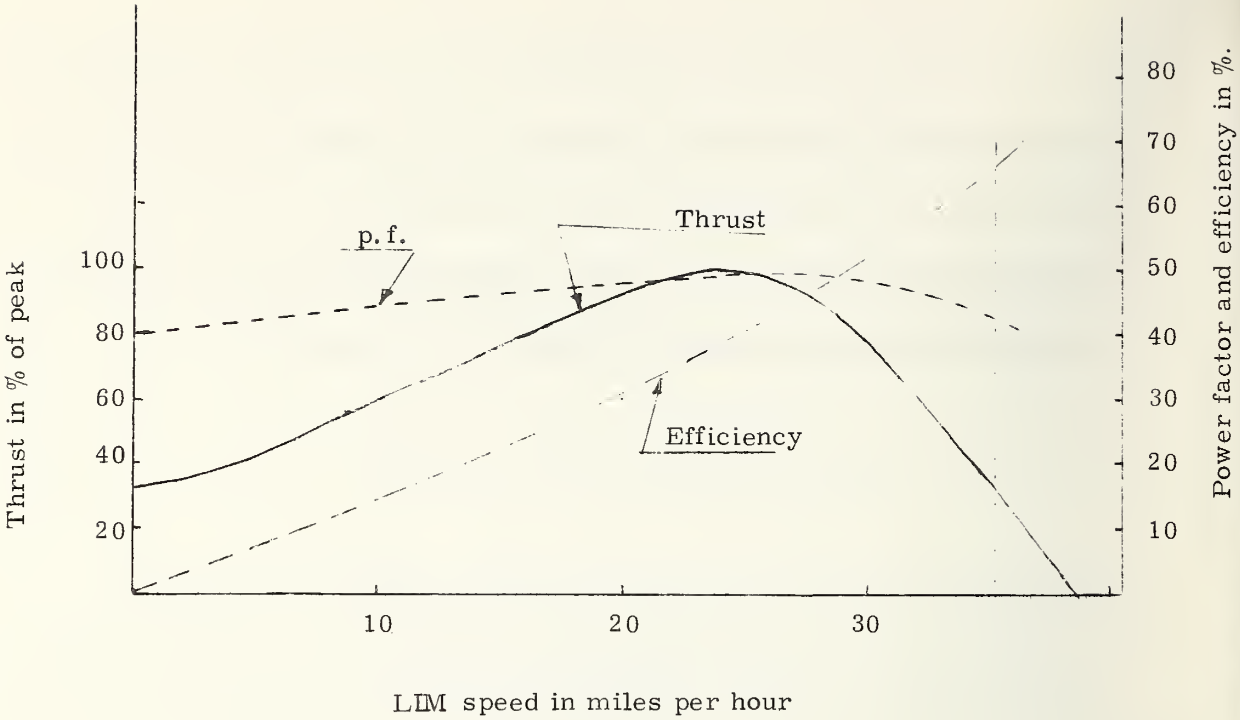


Fig 21. Representative performance curve of optimized linear induction motor operating at 60 Hz 3-phase power.

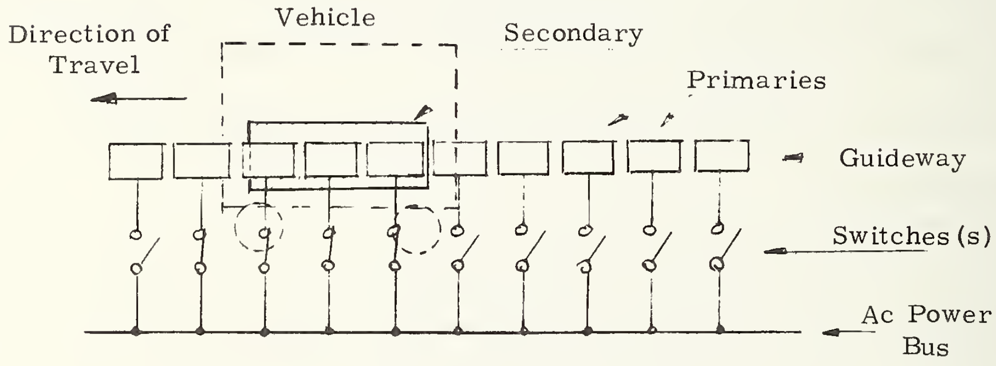


Fig 22. Primary on guideway system using switches to power primaries near and under the vehicle.

The drive system or power conditioning equipment for the LIM would be similar to that described for the rotary induction motor (Chapter IV). The requirement for a regenerative drive (including a regenerative rectifier, if ac collectors are used) is also required for the LIM drive systems. When the speed of the LIM exceeds the synchronous speed for a particular operation frequency, the LIM will regenerate mechanical power back to its drive, as does the rotary motor. Thus, the LIM exhibits the reversible characteristics required for the HCPRT, when the drive is reversible (see Chapter II).

The pulse-width controlled, multiple-switched 3-phase inverter described in Chapter IV is equally well suited for the LIM drive. Due to the low power factor of the LIM, there are high reactive power requirements. The inverter of Fig 18 circulates reactive power through the diodes across the thyristors. Large ripple currents will flow in the dc filter capacitors as a result of this power; therefore, the filter capacitors must be sized to handle the high ripple current.

B Primary On-guideway Systems

A LIM motor system whose primaries are installed on the guideway is described, and the alternatives for speed control of this system are discussed.

1. Description and Characteristics. In a LIM propulsion system using fixed primaries, a large number of LIM primary windings are installed along the guideway. The secondary reaction plate is carried on the vehicle.

This system is depicted in the sketch of Fig 22, which indicates sections of the guideway energized through switches S. By appropriately adjusting the length of each LIM primary section, the switches may be operated so that only that part of the guideway corresponding to the length of the secondary is energized.

Application of the fixed primary system to high-speed ground transportation has been evaluated by Agarwal et. al.[7] They conclude that the fixed primary system can only be economically feasible if the guideway primaries are switched, thus avoiding the losses associated with the large reactive power requirements of unused sections. In HCPRT application, the switches that are used to energize the guideway sections could also be used for thrust reversal, as will be discussed later.

The characteristics of the LIM with the primaries on the guideway are not necessarily similar to those of the LIM with the primaries on the vehicle. When the secondary member is on the vehicle, the LIM designer is no longer economically tied to the simple flat-plate secondary-design concept. In fact it is possible to design the secondary with windings, as in a wound rotor induction motor, for the purpose of thrust and speed control.

2. Speed Control and Drive Systems. Control of vehicle speed and thrust with the primaries on the guideway can be done conceptually in at least three ways. First, vehicle speed may be controlled by adjustment of the

primary voltages and frequency. This method is similar to that recommended for the rotary induction motor. However, it would require a variable frequency drive for each primary section of the guideway. This is certainly feasible, but its probable high cost warrants a careful study. Second, vehicle thrust may be controlled by adjusting the primary voltage, which may be done by "phase-back" of thyristor switches. Third, vehicle thrust may be controlled by varying the resistance in a wound secondary member. In the following we will discuss these various control methods.

a) Variable Frequency Control.

This was the preferred method both in the rotary induction motor drive and the on board LIM. For the primary on-guideway system this method would require the division of the guideway into short primary sections, each of which would be powered by separate variable frequency drives. To conserve power these drives should probably also be switchable with fast solid-state switches as indicated in Fig 22 for the common ac power bus case. The preferred method of speed control would use the same principles as those for the constant slip frequency system described in Chapter IV.

b) Primary Voltage Control.

Two disadvantages of primary voltage control lead us to discard it as a viable control method. The disadvantages are poor stability at low speed and high secondary dissipation, both of which were reasons for discarding this control method in the case of the rotary induction motor.

c) Wound Secondary Control.

The secondary winding may be very similar to a set of primary windings wound around a flat magnetic structure to minimize the effective air gap. With the use of a secondary winding, the disadvantages which occur with the primary voltage control are lessened. Low-speed stability is improved and secondary dissipation may be reduced. While this control method was not recommended for rotary motors these and other advantages make it more attractive for LIM primary on-guideway.

Thrust and speed control using the wound secondary is achieved by use of adjustable loading resistors or their equivalent for each of the three phases of the secondary windings. Variation of the values of the loading resistances will result in a variation of the motor thrust-speed characteristics as illustrated in Fig 23. The three curves marked a, b, and c correspond to low, medium, and high secondary resistance values, respectively. The equilibrium speed of the vehicle mounted secondary will be at the intersection of the thrust-speed curve of the load, shown by the dotted curve in the example of Fig 23, and that of the LIM. If the secondary resistances are suddenly decreased from those corresponding to curve c to those corresponding to curve b, the LIM thrust will jump vertically to a higher value and accelerate the vehicle to the higher speed at the intersection with the b curve as illustrated by the arrows.

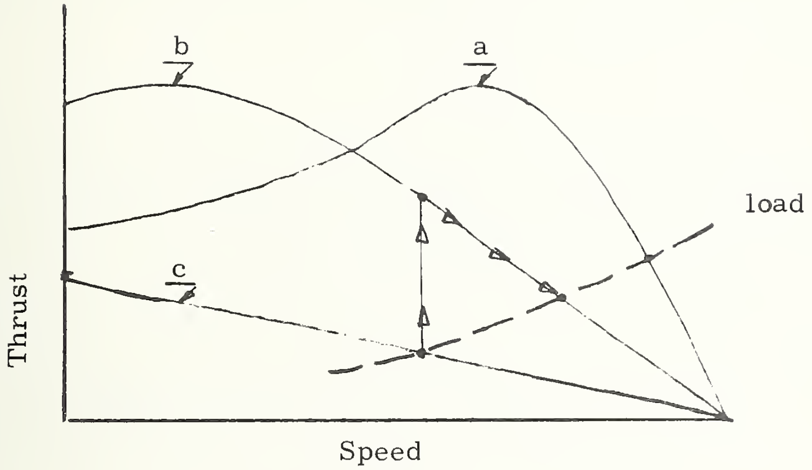


Fig. 23. Thrust-speed curves for increasing resistance values in a wound secondary. Thrust change and acceleration caused by a sudden drop in resistance values are indicated by arrows.

Variation of the secondary load can be accomplished quite readily with relatively fixed load resistances and a phase-delayed (thyristor) rectifier (PDR). The power transferred to the secondary at low speeds is high. However, this power can be put to good use as indicated in the diagram of Fig 24. First, the output of the PDR can be used to run heating, ventilating, and air-conditioning systems. Second, by using dc to ac inverters and regulating circuitry to make inversion possible over a range of the dc voltage, ac power may be extracted for use in the vehicle.

In the wound secondary propulsion system, the thrust and speed control can be done on board without control signal transmission to the primary system. To reverse the thrust, however, it is still necessary to reverse the sequence of the 3-phase power to the primary member. A block diagram description of the control scheme for the wound secondary LIM is shown in Fig 25. The on-board speed sensor and speed controller provide thrust level and direction signals, but only the thrust direction signal is transmitted to the primary thyristor switches.

C Summary

In applications to high-speed (150-300 mph) propulsion, the LIM has been found to yield reasonably good efficiency and weight characteristics. In the relatively low-speed HCPRT application, however, the LIM must operate at

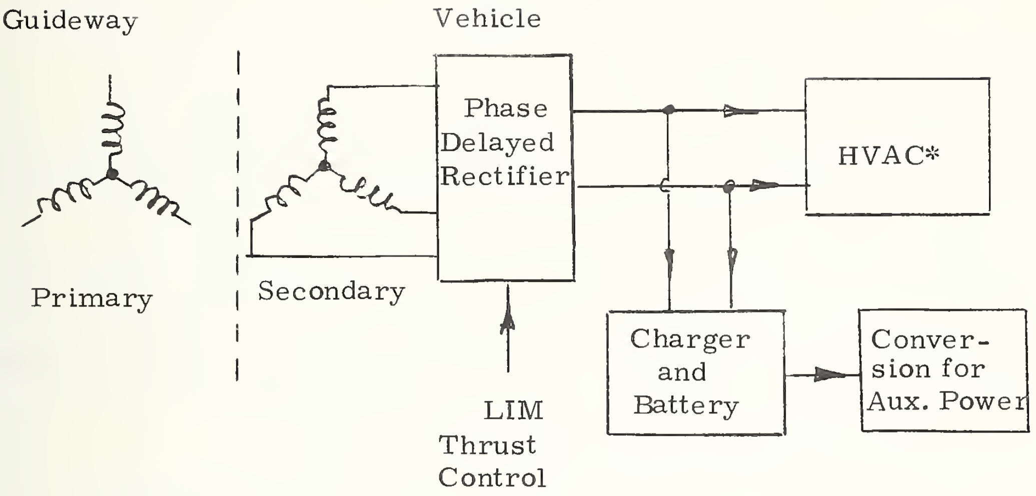


Fig 24. System for control of LIM thrust and use of energy transferred through a LIM wound secondary member.

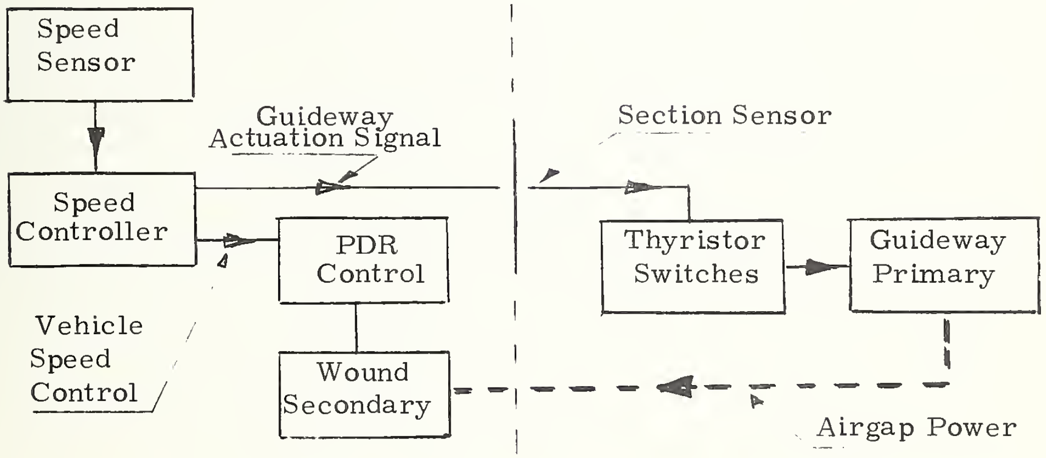


Fig 25. Descriptive block diagram of primary on guideway propulsion system using LIM wound secondary.

*Heating, ventilating, air conditioning

much lower frequencies (60 Hz or less) to reduce losses. The low-frequency requirement tends to increase motor weight, reduce efficiencies, and also make it difficult to obtain the required speed of response of the drive system. Both the required T_{max}/T_{nom} ratio and thrust reversibility, however, can be met.

The primary on-board system is best operated as a variable frequency, constant-slip drive, as in the case of the rotary induction motor.

The primary on-guideway system can also be built with variable frequency drives. However, this method would require a large number of drives and further studies should be made to evaluate system cost. This system can also be designed around a wound secondary using thyristor control for secondary loading and thrust/speed control. This system, however, is nonregenerative, and the efficiency is low, even though some of the losses may be recovered for vehicle auxiliary power. The T_{max}/T_{nom} for this system meets the requirement. Primary voltage control system is not recommended for the primary on-guideway system.

VI AC ROTARY SYNCHRONOUS MOTOR

The ac rotary synchronous motor has operating characteristics similar to the separately excited dc motor when a closed-loop speed control method is used. Under these conditions, the motor can retain its positioning characteristics while gaining the necessary dynamic stability. When an open-loop speed control method is used the motor cannot meet dynamic stability standards.

A Motor Characteristics

The rotary synchronous motor operates at a fixed speed proportional to the frequency of the ac power source and inversely proportional to the number of stator poles. The stator windings of this motor are wound for 3-phase power and produce a rotating field as in the 3-phase induction motor. The rotor is designed with magnets or other special structures to make it follow or rotate in synchronism with the stator field.

1. Regular Design. The output torque of the synchronous motor is a function of the displacement angle of the stator and rotor fields. The torque is given by the following equation:

$$T = k \sin \beta \tag{6}$$

where

β = the displacement angle

k = function of excitation field strength, motor dimensions, and other motor constants.

As seen from the previous equation, the maximum torque occurs when $\beta = \pm 90°$. The motor is usually designed to yield a full-rated output torque when $\beta = 30°$, or about one-half of its maximum torque. The maximum torque level at $\beta = 90°$ can be boosted further by an increase in the 3-phase voltage level. Therefore, the ratio of T_{max}/T_{nom} may be as high as 4/1 for the synchronous motor.

Since the rotary synchronous motor has no starting or accelerating torque an alternative starting technique must be applied. When the loading of the motor causes β to exceed ± 90°, the available torque drops off, and the rotor falls out of synchronism. When this happens the motor torque will simply oscillate between + and - T_{max}, yielding zero average drive.

2. Alternative Structures. To recover from a load transient and to accelerate during start, synchronous motors are often designed with a squirrel-cage or other type of structure to produce a torque at slip frequency. Among these structures are the synduction and permanent-magnet induction motors, which have magnets imbedded in the squirrel-cage type rotor; and the reluctance motor, which has salient-pole rotors with no permanent magnets. The latter, which is the more common in the 10-to-100-hp range, locks into synchronism by action of reluctance torque. The reluctance torque is produced by the characteristics of magnetic circuits, which cause the rotor to seek the path of least magnetic resistance.

In recent years reluctance-type motors have been designed with characteristics resembling those of the permanent-magnet synchronous motor at synchronous speeds and those of the squirrel-cage induction motor at other speeds. Thus, output power of reluctance-type motors may be 75-85% of that of an induction motor of the same size. Power factors of 0.65 to 0.75 and full-load efficiency of 85% have been reported[9] for reluctance-type motors as compared to 0.85 and 90% for the induction motor.

B Speed Control

The speed of a synchronous motor is precisely governed by the frequency of the ac power. It is also worth noticing that once "locked in," the synchronous motor becomes a positioning device with the position determined by the phase rotation of the stator field, and therefore by the phase of the ac waveform. This characteristic is put to use in industrial processes where many motors must run in synchronism. This is accomplished simply by running all the motors from the same variable frequency drive. Speed and position control is then provided through open-loop control. No speed or position sensors are used.

1. Open-loop Speed Control. Open-loop speed control with synchronous motors has the major disadvantage of poor dynamic stability. This characteristic of the synchronous motor stems from the fact that the shaft torque of the motor over a limited angle is proportional to the angular difference between the rotating field and the fixed rotor field. This situation is analogous to a spring that gives a thrust proportional to a displacement. Coupled with the mass of the rotor

and load, a spring-mass type resonance in the synchronous machine results. Most motors incorporate antihunt windings in the rotor, but the windings only provide light damping of this resonance.

2. Closed-loop Speed Control. To achieve dynamically stable control of the synchronous motor, the shaft position must be measured and this information used to control the frequency of the ac power in a closed loop. This can be done in a way which retains the positioning characteristics of the synchronous motor, while adding the desired amount of dynamic damping. Closed-loop control can also be implemented with a positional sensor in such a way that the speed of the motor becomes approximately proportional to the ac motor terminal voltage. This latter control method gives the synchronous motor operating characteristics that are very similar to those of the dc motor.

C "Brushless" Synchronous Drive

Since the synchronous motor has no brushes, closed-loop control can create characteristics in the synchronous motor that are similar to a "brushless dc motor."[10]

1. Principle of Operation. To better understand the operation of the brushless motor, first consider the dc motor In the separately excited dc motor, the field set up by the armature winding is always held at 90° with respect to the stator field by action of the commutator segments. In this way the torque produced is held at its maximum and is proportional to the armature current. Torque reversal follows with reversal of the armature

current. With a fixed voltage impressed across the armature terminals, the unloaded motor will accelerate until the winding rotating in the stationary field generates a counter emf which becomes nearly equal to the source voltage. The current then drops to a low value and the motor has reached its speed equilibrium.

Now consider a synchronous motor driven by a 3-phase source of adjustable frequency. As shown in Fig 26 , the frequency can be controlled so that the rotating field is held at 90° with respect to the rotor and its field. The operation of this motor is then analogous to that of the dc motor; the rotor will accelerate until the 3-phase voltages induced in the stator windings by the rotor field are nearly equal to the voltages of the 3-phase power source. During the acceleration period, the frequency of the stator power will increase, but synchronous operation is ensured by the frequency control function in Fig 26, which yields a frequency proportional to the motor speed and power phase control dictated by the shaft position. If the rotor has a wound field, the speed may be reduced by increasing the field current exactly as in the separately excited dc motor. With special design, the field windings may be located on the stator.[10] This gives the brushless synchronous motor the additional advantage of operating without slip rings and using a common structure for cooling.

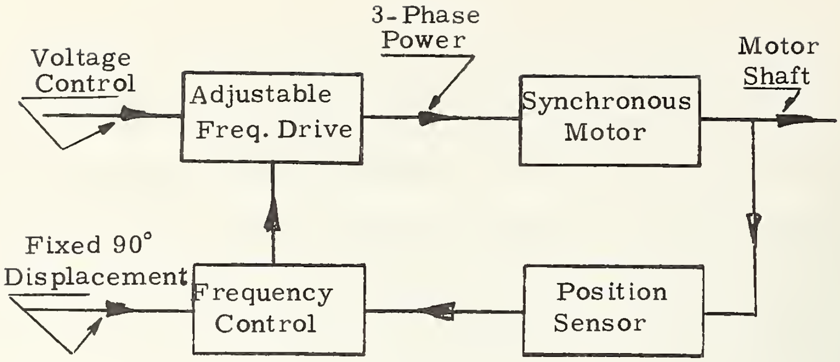


Fig 26. Control of synchronous motor which yields the characteristics of a dc "brushless" motor.

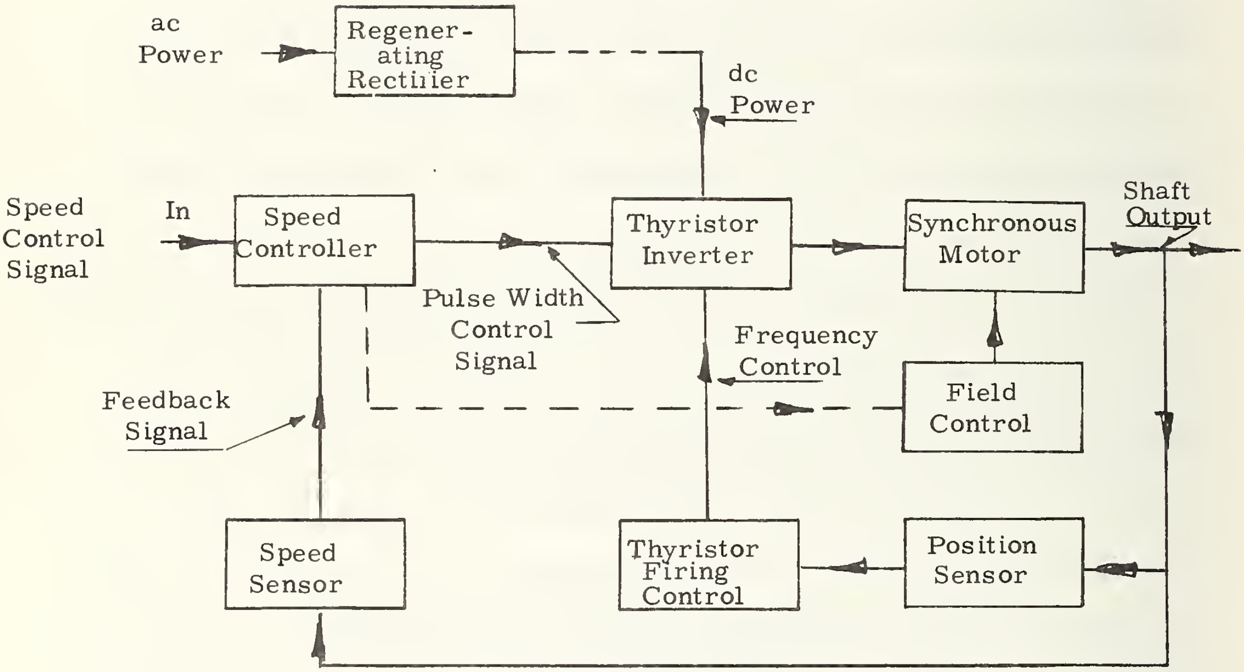


Fig 27. "Brushless" synchronous motor drive system.

2. Speed Control Systems for Brushless Synchronous Drive. A block diagram of a speed control system that operates a synchronous motor as if it were a brushless motor is shown in Fig 27. The brushless motor control loop consists of a shaft position sensor, which provides timing for a thyristor firing control circuit, and a 3-phase thyristor inverter, which drives the motor. The position sensor provides sufficient information so that the stator field set up by the 3-phase power can be held approximately 90° ahead of the rotor field, creating a field displacement for maximum rotor torque.

The speed of the motor is controlled by the amplitude of the 3-phase output voltage of the inverter. The inverter may be of the type described in Chapter IV, which can use pulse-width control for amplitude adjustment. It should be noted that the operation of the synchronous motor will result in losses due to harmonics in the ac waveform, as is the case with the induction motor, and switching rates for pulse-width control may have to be high to keep the harmonics at acceptable levels. Since the speed of the motor will be inversely proportional to the motor field current, speed can also be controlled with this type of synchronous motor drive by reducing the field current, as is commonly done at high motor speeds in dc drives.

If the drive is designed for dc collector power, this type of power may be used directly for the thyristor inverter (after some filtering in L-C networks). If the collector power is ac, a regenerative-type rectifier must be used to provide the dc. A circuit similar to that of Fig 9 described in Chapter III, may be used.

D Summary

The use of synchronous motors in vehicle propulsion is a relatively new concept. The speed of these motors must be controlled with a variable frequency drive. For industrial use open-loop control is used since the speed of the motor is proportional to the power frequency. However, such variable speed drives exhibit poor stability and unreliable operation under variable loads. Recent developments in variable frequency drives indicate that very good stability can be obtained with a feedback control system that gives synchronous motor characterisitcs much like the separately excited dc motor. These brushless motor drives have the potential advantages of lighter weight and longer life over the dc motor counterparts. To meet the required response time, the motor should be designed for frequencies of 400 Hz or higher. The T_{max}/T_{nom} for these motors would be as high as 4/1.

VII AC LINEAR SYNCHRONOUS MOTOR

The ac linear synchronous motor (LSM) differs from the LIM in that the secondary member is designed to lock in and travel at the synchronous speed. This characteristic is obtained, as in the rotating synchronous motor, by designing a secondary member with magnets or reluctance characteristics, which tend to make the field of the secondary travel in synchronism with the primary field. The primary of the LSM may be mounted either on the vehicle or on the guideway. Both of these approaches to HCPRT will be discussed below.

A Primary On-board System

In this system the on-board primary is energized by a 3-phase power source also carried on board. The secondary may be either permanent magnet or electromagnet poles strung along the guideway.

1. Motor Characteristics. The speed of an LSM is proportional to the product of the pole pitch and primary operating frequency, which was also the case for the synchronous speed of the LIM. But unlike the LIM, the LSM develops thrust by a displacement between the primary and secondary fields. The thrust will increase until the displacement is equal to one-half the pole pitch. If higher loads are applied, the LSM will fall out of synchronism. It is possible to design the LSM with induction motor characteristics. These characteristics cause the LSM to regain synchronism as in the case of the rotary synchronous motor (Chapter VI).

The LSM does not depend on slip to produce the secondary field. As a result the LSM does not have the design constraints of the LIM. For example, unlike the LIMs, low-speed LSMs can be constructed with a short pole pitch without sacrificing efficiency. There are two important advantages to lower poles pitches. First, shorter poles allows for more poles, reducing end effects. Second, shorter poles enable operation at higher frequency. This reduces the weight of the magnetic structure and enables the LSM to meet performance requirements for response time and control stability more easily than the LIM.

The electrical characteristics of the LSM are the same as those for the rotating synchronous machine. Under rated full-load operation the displacement between primary and secondary will be about 30 el. degrees as in the rotary motor, and the field strength may be increased by as much as 100%. This gives this motor also a T_{max}/T_{nom} ratio of about 4/1, well above the required 3/1 ratio.

2. <u>Speed Control and Drive Systems.</u> The speed of the LSM can be controlled only by adjusting the primary power frequency as in the case of the rotary synchronous motor. Attempts to control the speed by open-loop frequency control will result in poor stability. Dynamically stable and dependable speed control, therefore, must be done by a closed loop.

One proven method would be the same as that described in Chapter VI, which gives the synchronous motor the characteristics of a separately excited dc motor.

To implement the brushless motor drive system of Fig. 27, it is necessary to determine the position of the primary member with respect to the secondary members. In the rotary machine, the position can be derived from a shaft encoder or from special sensors mounted around the periphery of the rotor. In the LSM, with the primary and the controls on the vehicle, the best approach would probably be to use a number of magnetic or optical sensors distributed along the primary to detect the position of a magnet or light source, respectively, associated with each secondary pole.

In the LSM application, the ability to control the motor thrust-speed characteristics by variation of the field strength of the secondary member is complicated significantly by the need to transmit data to the guideway and the need for controls and equipment to provide variable field strength. Since this equipment would have to be supplied for each individual secondary pole, or for a small group of poles at best, the addition of field variation for the LSM might prove to be very costly. Without the ability to control the field strength it may prove difficult to reach the required 3/1 value for T_{max}/T_{nom}.

B Primary on Guideway System.

In this system a large number of primaries are placed along the guideway and a single secondary pole set is placed on the vehicle. To conserve energy, only the primaries under and immediately ahead of the LSM are switched on.

1. Motor Characteristics. The propulsion system would be similar to that for the LIM described in Chapter V with the important difference that except for transient conditions the vehicle would run at synchronous speeds only, i.e., the speed of the vehicle would be controlled directly by the frequency of the primary ac source.

If the secondary of this LSM is designed with permanent magnets or reluctance characteristics, there would be very little dissipation in the secondary and insignificant heating. Other characteristics of this LSM would be similar to those of the primary on-board motor. Auxiliary power for the vehicle systems could be picked off with a small wound secondary that extracts power from a stationary field along the guideway.

2. Drive System and Speed Control. In the case of the LIM, three systems for speed control were given as possible approaches. These control systems would make use of either primary voltage control, wound secondary resistance control, or variable frequency control. In a primary on guideway

system using the LSM, however, neither primary voltage nor wound secondary resistance controls are possible.

In the LSM system there appears to be no alternative to primary frequency control. An economically competitive arrangement might be to provide several thyristor switches for each primary so that these can be run at a number of fixed selectable frequencies. It would then be possible to speed up or slow down individual vehicles. For large speed changes, however, the vehicles would still depend on induction motor characteristics, which would have to be built into the secondary. With variable frequency control this system would be inherently thrust reversible.

C Summary

Although the LSM is a more complex motor than the LIM, requiring an active secondary, it is in some respects better suited for HCPRT. Higher power frequencies can be used, giving higher operating efficiencies and lighter weights. Vehicle speed can be accomplished by the same method used for the "brushless" drive for the rotary synchronous motor, giving good control stability and acceptable response time. High cost may exclude the use of field control, however, which would probably result in a lower than required T_{max}/T_{nom} value.

Since the LSM can only be controlled by variable frequency drives, it is not possible to control individual vehicles in the primary on guideway system without a large number of variable frequency drives distributed along the guideway. The cost of such an installation should be investigated.

VIII CONCLUSIONS AND RECOMMENDATIONS

Calculations of thrust requirements for a baseline vehicle using a partly empirical equation show that there will be little difference in these requirements for four types of vehicle suspension. The four suspension methods considered are air cushion, rubber tire, steel wheel on steel rails, and magnetic levitation of the attractive type.

A preliminary study of the dynamic propulsion requirements for safe vehicle operation under a 0.5 second headway show that some rather unusual characteristics must be provided. These include a high ratio of nominal to peak thrust (>3/1), reversible thrust characteristics, and high response rate to thrust control (8Hz bandwidth). High propulsion system efficiencies are desirable, but not required.

Based on these characteristics several motor types and drive systems were examined. It was found that the much used series type dc traction motor would not be appropriate for HCPRT because it could not be reversed without the use of slow contactors.

The separately excited dc motor with chopper drive is the most advanced propulsion system whose technology is tested. With a somewhat more advanced chopper, it is the most likely choice that would satisfy the HCPRT requirements derived in this report. However, the dc motor is not without its problems; commutators and brushes must be maintained frequently and the chance of failure by commutator flashover is high. For this reason, it is recommended that a brushless motor be used for HCPRT. There are presently several brushless motors available for use in propulsion systems that are in various stages of development.

The motor most likely to provide the desirable brushless propulsion system with satisfactory characteristics is the 3-phase ac induction motor. It is recommended as the first candidate for the HCPRT application. The motor must be designed for 400 Hz or over to satisfy the response time requirements and must be powered by variable frequency, reversible type (dc to ac) inverters. This system will require additional development of speed and torque control techniques. Control schemes using a constant motor slip approach is recommended for this system.

The rotary synchronous motor may be used in place of the induction motor with little change of the drive and control system. This motor may yield higher efficiencies and peak-to-nominal torque values, but will require more motor design development.

The primary on-board LIM system considered requires further investigation to determine if the desired response rate and efficiency can be obtained with LIM designs suitable for low-speed applications. The on-board linear synchronous motor would retain all the advantages of the rotary counterpart. Its application to the HCPRT would be determined primarily by economical considerations and should be high on the list for further study.

There are clear advantages to be derived from a propulsion system using linear motors and primaries on the guideway. The LIM system that makes use of a wound on-board secondary appears to have the definite advantages over others of allowing a fixed frequency drive and simple on-board control. The linear synchronous motor in the primary-on-guideway system, however, seems clearly to be limited to the variable frequency method for speed control. In the primary-on-guideway systems this method appears to be economically prohibitive. However, before any future work is done for any specific system of this type an intensive study should be made to establish economical feasibility.

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APPENDIX

Dynamic Control Model of the Vehicle Propulsion System

1A. Purpose and Model Type

In this report the purpose of a control system model for the HCPRT propulsion system is to establish an analytical representation of the control dynamics. This enables the calculation of approximate propulsion system response requirements.

The control model used here is a linear model that represents one of many possible approaches to the vehicle propulsion control. The design approach is based on well known and proven principles of high-performance closed-loop speed and positional controls. The control loops make use of a speed sensor and command signals for speed control, and a vehicle separation sensor with a variable separation command for vehicle separation control.

2A. Introduction to the Problem

In the HCPRT system a vehicle B following another vehicle A, which decelerates at a high rate, must be controlled to decelerate at nearly the same rate to avoid collision. As one approach to the control problem let us assume that the lead vehicle A starts to decelerate abruptly at a rate of a ft/s^2. Assume also that vehicle B, after an initial delay t_d, starts to develop a decelerating force rising exponentially with a time constant τ, to a final value such that vehicle B also decelerates at a rate of a ft/s^2. Calculations can now be made of the relative distance between the two vehicles, after they both have come to a stop, as functions of t_d, τ and initial velocity, V.

Results of such calculations are shown in Fig. 1A for an emergency stop at 32.2 ft/s^2, three initial velocities, and a single time delay of 0.1 seconds. It should be noted that the calculations were made with the assumption of a vehicle separation of V x headway (as opposed to the usual definition where V x headway is the vehicle front-to-front distance). The negative separation in Fig. 1A indicates that a collision would occur. The plots show that for a few feet of vehicle separation the propulsion system response time should be less than 1.5 seconds. However, this kind of controlled stop assumes that the braking effort can be controlled without significant errors. In a practical system this is not probable.

The model described in the following provides control of the braking effort with thrust errors which are diminished as the control loop response time is reduced. Computer simulations are carried out using this control model to find a set of control and propulsion system response requirement for the emergency stop problem discussed above.

3A. Model Description and Control Characteristics

In the block diagram of Fig 2A the vehicle control system has two input commands: (a) vehicle speed and (b) vehicle headway. The speed command

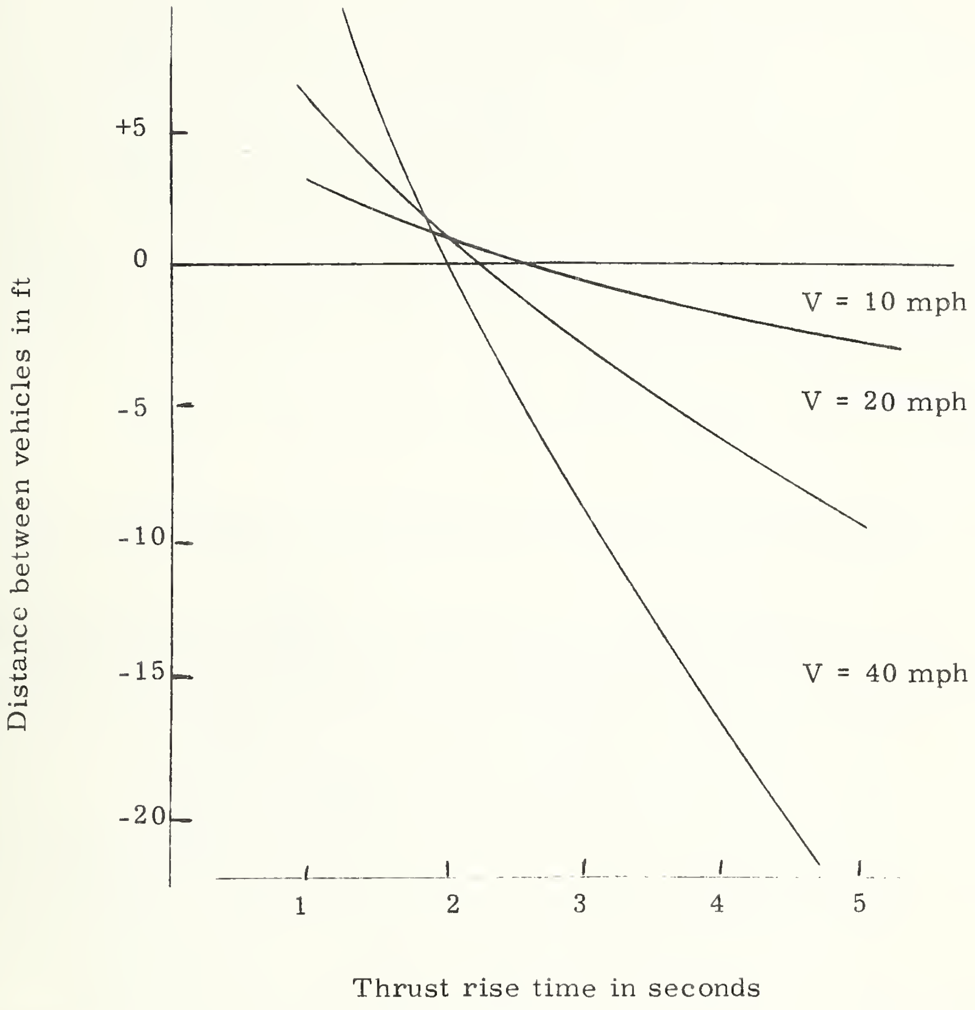

Fig 1A. Variation of distance between vehicles with thrust rise time after an emergency stop (32.2 ft/s^2) assuming a dead-time of 0.1 sec. and an exponential rise of braking thrust.

is fed directly to a vehicle speed control loop which holds the vehicle at precisely the desired speed under normal cruising operation. Both the speed and headway command signals are used to calculate the desire separation between the vehicles. This "separation command" signal is then compared with a measurement of the distance to the forward vehicle in a position controller which in turn responds with a speed correction signal. This signal controls vehicle speed to achieve proper headway. Should the vehicle in front decelerate sharply and stop, the speed correction will provide speed command cancellation and stop the vehicle.

The following assumptions have been made for the model of Fig 2A:

(a) The vehicle thrust is provided by a drive which can yield thrust reversal at any desired thrust level* and with a response time commensurate with good control loop stability.

(b) The vehicle separation sensors perform the measurements with insignificant dynamic lag.

(c) The separation command is constant during emergency stops.

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*If the propulsion motor does not have sufficient thrust to provide emergency braking a mechanical brake is blended in.

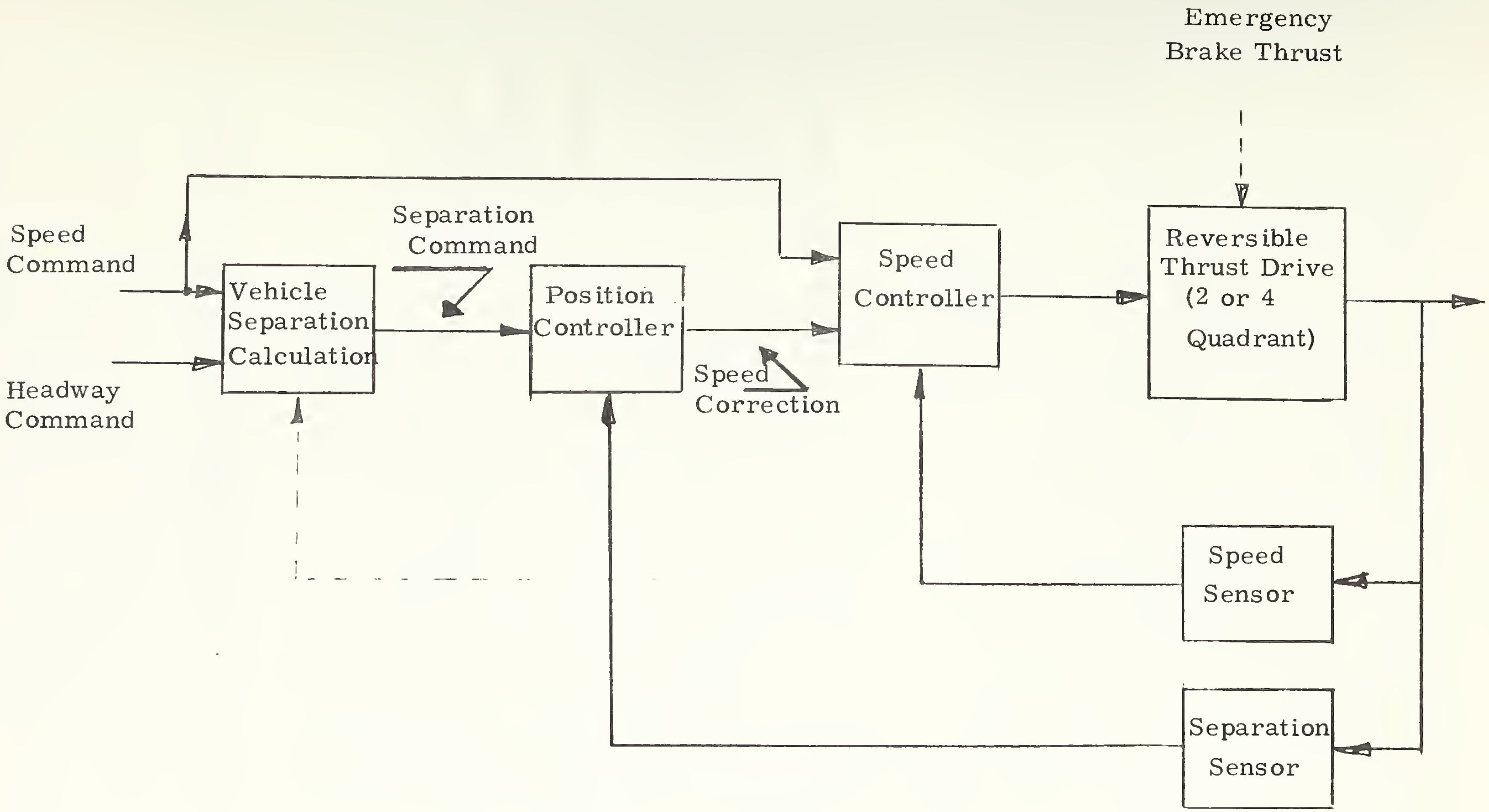

Fig 2 A. Control system block diagram.

The control system of Fig 2A consists of an "inner" speed feedback loop and an "outer" position feedback loop. An analytical block diagram of this control system is shown in Fig 3A. It has been assumed in this diagram that the motor and power drive can be modeled by a single constant K_M of dimension force per signal units. This approximation assumes that the bandwidth requirements of the speed loop do not approach the bandwidth of the motor and drive. Structural dynamics of the drive and vehicle are also neglected for the same reason, leaving a simple integration between motor thrust and vehicle speed.

The compensation shown for the position loop is a standard integral-plus-proportional compensation network which gives the control a zero error for constant speed commands and a fixed limited error for constant acceleration commands. The block diagram of Fig 3A may be simplified to that of Fig 4A in which all gains have been combined in three bandwidth constants and in which the Laplace representation, $1/s$, has been used to denote integration. In the following analysis we shall derive the minimum control loop bandwidth constants which are required to maintain a safe distance between two vehicles during an emergency stop.

In an emergency stop situation, the lead vehicle is assumed to experience a sudden but constant deceleration $\ddot{x}_p$.

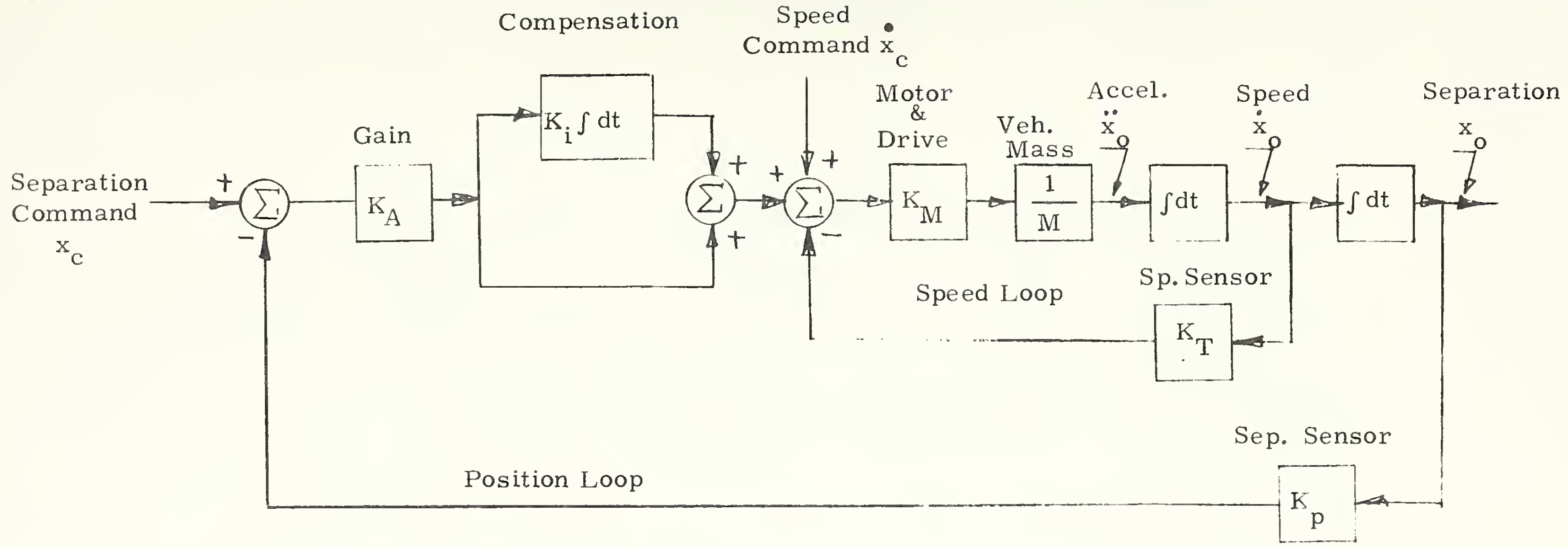

Fig 3 A. Analytical block diagram of the control loops.

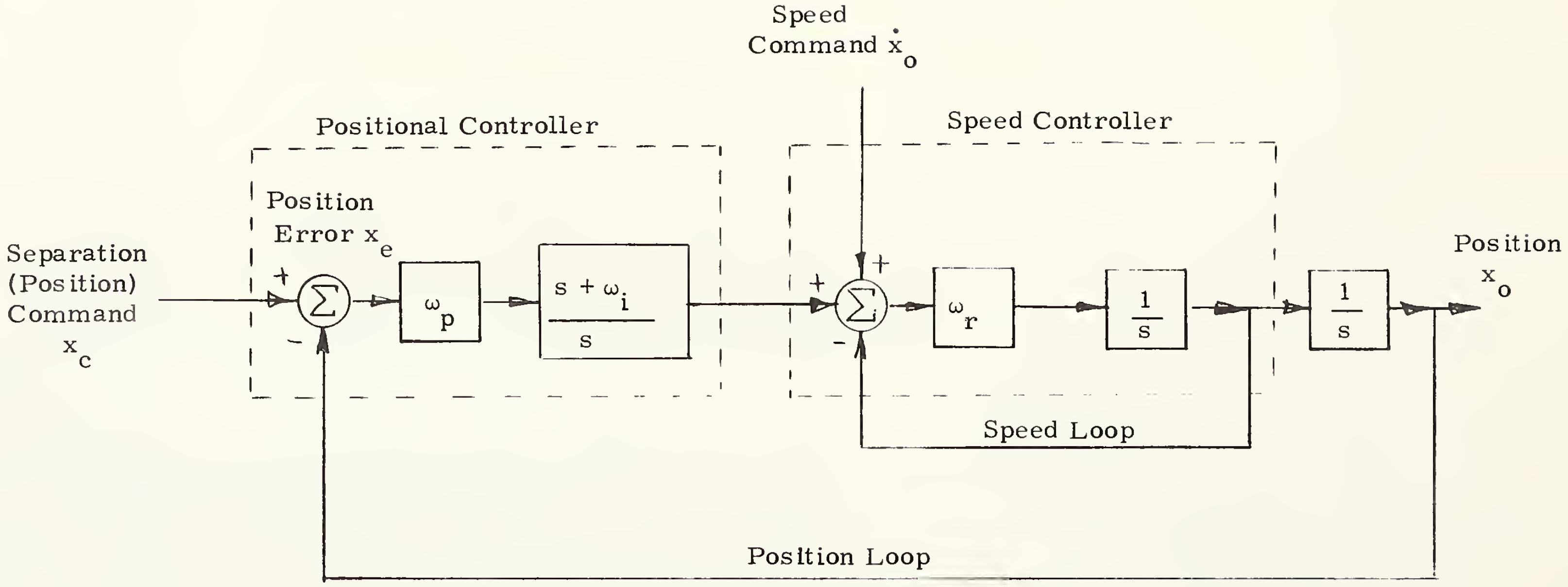

Fig 4A. Simplified analytical block diagram.

In Fig 4A, the position command x_c is the desired distance between the vehicles and the error x_e is the deviation from that distance. The transform function relating the two becomes

$$\frac{x_e}{x_c}(s) = \frac{1}{1 + \omega_p \omega_r \dfrac{s + \omega_i}{s + \omega_r} \dfrac{1}{s^2}} \tag{1a}$$

When the x_c undergoes a constant deceleration $\ddot{x}_p$, the La place transform is $2\ \ddot{x}_p / s^3$. The final error as a result of this input is

$$(x_e)_f = \lim_{s \to 0} \left[s \frac{x_e}{x_c}(s) \cdot 2 \frac{\ddot{x}_p}{s^3} \right] \tag{2a}$$

Substituting 1 we get

$$(x_e)_f = \lim_{s \to 0} \frac{2\ \ddot{x}_p}{s^2 + \omega_p \omega_r \dfrac{s + \omega_i}{s + \omega_r}}$$

$$= 2\ \ddot{x}_p / \omega_p \omega_i \tag{3a}$$

For good stability of the control loops it is usual to set $\omega_r \geqslant 4\,\omega_p \geqslant 4\,\omega_i$.
Using the lower ratio of 4, Eq. 3a may be written

$$(x_e)_f = 128 \frac{\ddot{x}_p}{\omega_r^2} \qquad (4a)$$

Assume that the maximum deceleration required is $\ddot{x}_p = -1.0\ G = -32.2$ ft/sec^2 with a headway of 0.5 sec. The initial distance between vehicles at a speed of 58 ft/sec is:

$$x_c = 58.7 \times 0.5 = 29.35 \text{ ft}$$

During the stop the error (4) must not exceed the 29.35 ft, thus from Eq. 4a:

$$\omega_r^2 \geqslant 128 \frac{32.2}{29.35} \ (\text{rad/s})^2$$

$$\omega_r \geqslant 11.9 \text{ rad/s}$$

and $\omega_p \geqslant 4$ rad/s

This result shows that the speed loop must have a minimum bandwidth of 1.9 Hz. Obtaining a speed loop bandwidth of about 2 Hz appears quite feasible with most reversible type propulsion systems which are based on dc and/or 60 Hz power.

4A. Computer Simulation

The performance of the vehicle propulsion system undergoing emergency braking maneuvers was simulated using the model of Fig 4A. The gains (or bandwidth parameters) of the model were chosen such that $\omega_r = 4\omega_p = 16\omega_p$ as they were picked for Eq. 4a. Several simulations were then run for the condition of 32.2 ft/sec deceleration of the head vehicle with different values of ω_r.

The results of a simulation run using ω-values for which the two vehicles stop with approximately 1.0 ft of clearance is shown in Fig 5A. It is seen that the requirements to control bandwidth is less stringent than those calculated in 3A. This is due to the finite time involved in the emergency stop. (The analysis assumes infinite time). The rise time of the vehicle thrust (acceleration) is a little over one second which compares to the requirement of 1.5 sec of the approximate calculations of 2A.

The response characteristics of the propulsion system must be sufficient to yield a velocity loop with good stability. If a velocity loop bandwidth of $\omega_r = 5.6$ rad/sec will be required as indicated by the simulation results, the propulsion system bandwidth should be at least six-nine times as high. Using the higher value this would indicate a propulsion system bandwidth of 8 Hz. This bandwidth must include all dynamic characteristics of the propulsion system such as drive response time, motor inductance, etc.

Data:

Speed = 58.7 ft/s, Initial Distance = 29.35 ft.

$\omega_r = 5.6$, $\omega_p = 1.4$, $\omega_i = 0.35$, Accel. = -32.2 ft/s^2

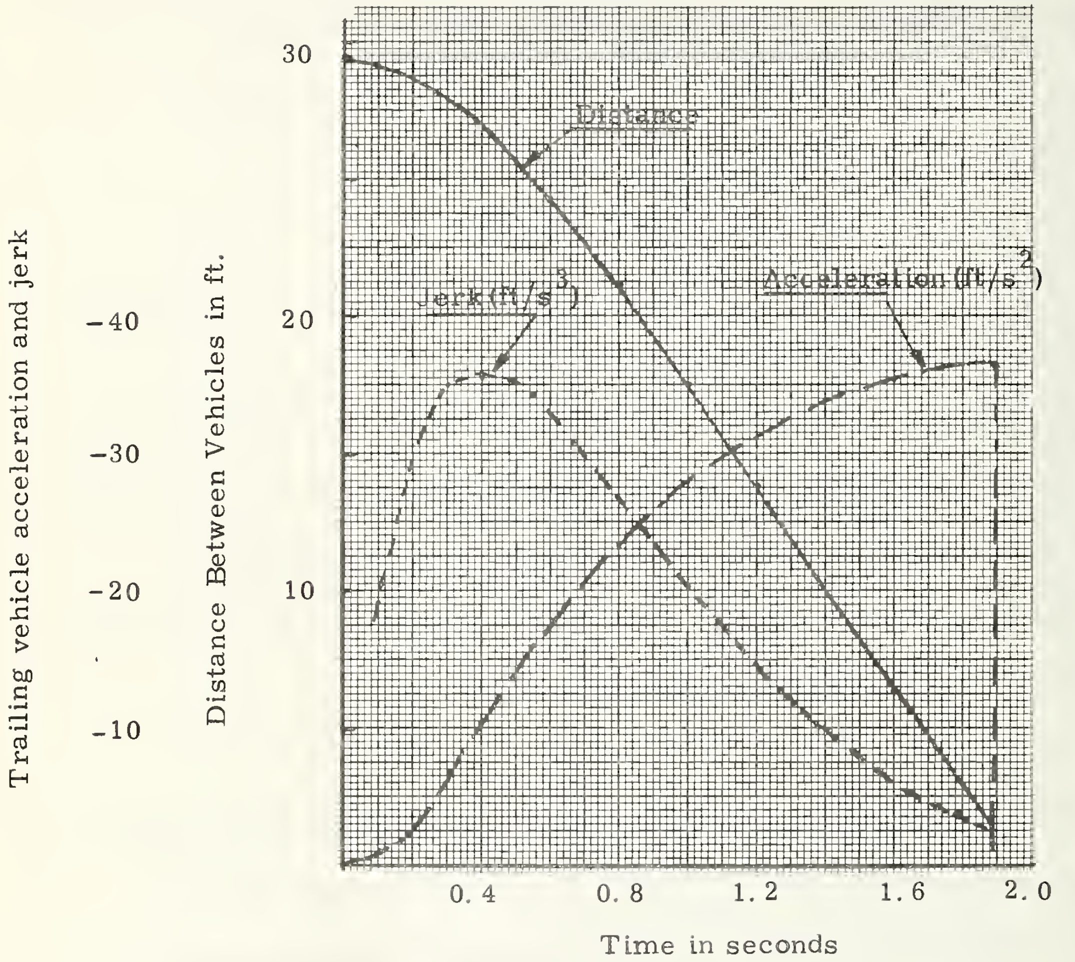

Fig 5A. Simulation of emergency braking performance.