Homework Set #11 (ECE743)

1. Read the attached papers.
2. Write a report on the use of Electric Machines in industrial system.

Note that your text should be at least 4,000 words and not greater that 4,500 words. You may use as many figures you wish. Please type your report and use font size 12.

SAE TECHNICAL PAPER SERIES

HW #8

910246

Integrated Electric Vehicle Drive

William M. Anderson and Craig S. Cambier
Unique Mobility, Inc.
Englewood, CO

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ABSTRACT

An advanced drive system for electric vehicles is described. The extremely compact and lightweight design features a high efficiency, high power density permanent magnet brushless dc motor with an integral gear reduction and differential. The electronic controller features full four quadrant operation with regeneration capable to zero speed.

INTRODUCTION

Unique Mobility is an Englewood, Colorado based R & D company active in the development of drive systems for electric and hybrid electric vehicles. The key technology is based on lightweight permanent magnet motors coupled with solid state electronics and forms the basis for the company's effort to develop an advanced electric drivetrain, that is capable of operating from any available source of electricity such as batteries, on board engine generators or fuel cells.

Unique's motor and controller technologies are currently being evaluated in various applications such as the recent GM sponsored Sunrayce from Florida to Detroit, Michigan, held in July 1990. Of the 32 university teams entered, 18 vehicles employed Unique motors and controls.

MOTOR AND CONTROLLER TECHNOLOGY

Figure 1 shows an exploded view of a typical Unique motor. Radially positioned permanent magnets are mounted on a hollow rotor which is co-axial with the radially thin stator winding. The stator windings are directly pierced by the magnetic field and a high magnet pole count is employed. The use of narrow magnets permits use of a relatively thin steel mounting ring for the rotor and a correspondingly thin stationary return path in direct contact with the stator winding. Figure 2 shows the stator winding in various stages of construction. No laminations are employed. Hysterisis and eddy current iron losses are minimized in this design. Copper utilization is also high as the ratio of active length to end turn length is much higher than in a conventional motor wound using silicon steel laminations. Continuous power densities on the order of 3 kW/kg are readily obtained using air or liquid cooling means. The winding structure has good mechanical strength because it is encapsulated in high temperature epoxy.

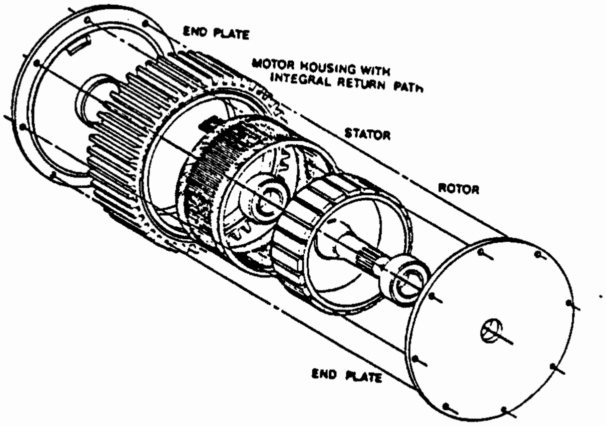


Figure 1

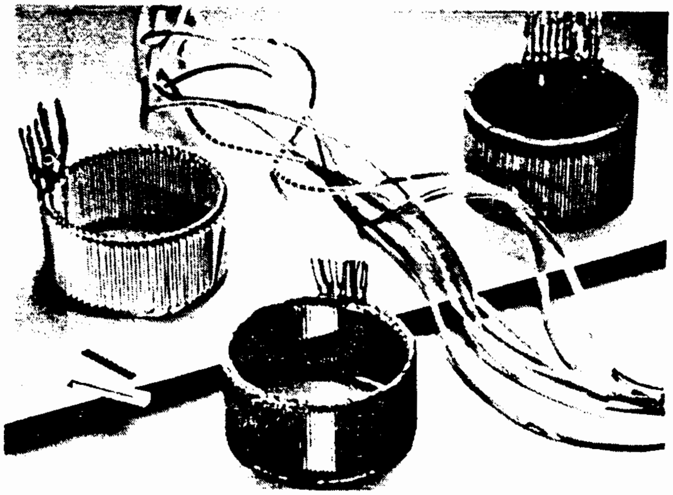


Figure 2

The motor has no brushes and is commutated electronically by using solid state devices. The power switching devices switch the current on and off to the motor windings in a series of pulses which controls the motor speed and torque. The characteristics of the motor are such that it has a very low inductance as well as a low resistance. High commutation frequencies (up to 1.5 khz) are employed. Both MOSFETs (metal oxides semi-conductor field effect transistors) and IGBTs (insulated gate bi-polar transistors) may be employed as they have the requiste switching speed. Figure 3 shows the basic controller topology typically employed for the 3-phase wye winding configuration of the motor.

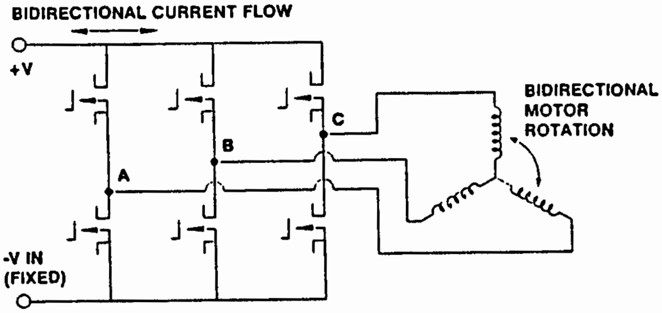


Figure 3

The controller is capable of full four quadrant operation. Regeneration is possible down to near zero speed. Hall effect sensors in the motor provide the timing signals required for commutation. Figure 4 shows a typical motor current wave form under pwm operation. The controller operates with an efficiency greater than 95% over most of the operating speed range.

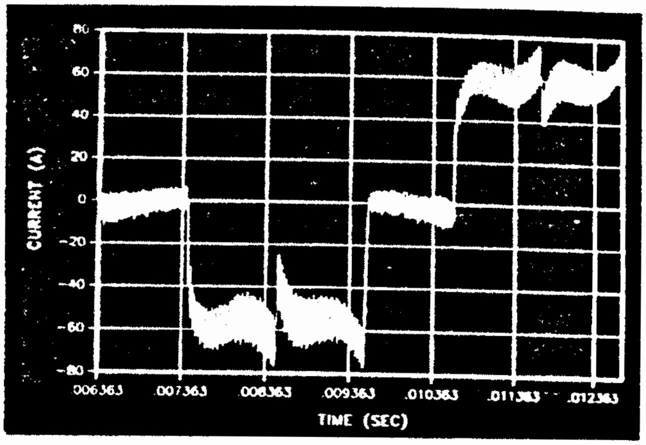


Figure 4

Figure 5 shows a nominal 50 kW motor and controller designed for application to an electric vehicle drive system. The motor weighs approximately 15 kg and is air cooled. The controller also air cooled and weighs 20.5 kg. Two of these motors are being used to power a hybrid electric minivan conversion currently being developed.

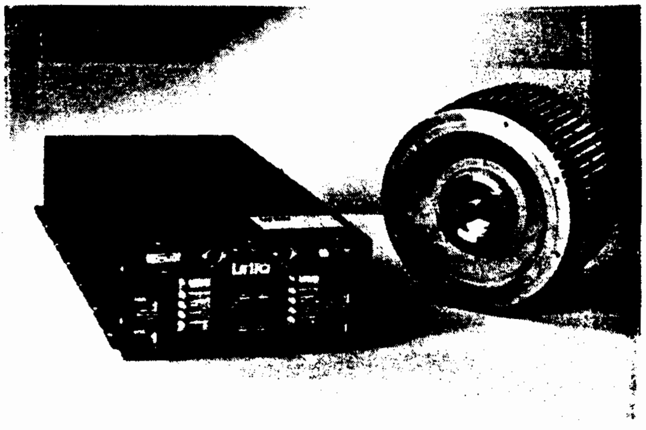


Figure 5

VEHICLE REQUIREMENTS

Typical road vehicle wheel torque versus speed characteristics are shown in Figure 6. The peak torque corresponds to that required for vehicle acceleration from a stop or low speed. The constant power region corresponds to acceleration requirements for merging and/or passing. The primary variable that defines the envelope of operation as shown in Figure 6 is vehicle weight. Values of peak wheel torque required are on the order of 500-600 Nm/1000 kg vehicle weight. In the region of constant power, 15 to 20 kW/1000 kg is typical. The power required for high speed operation (80-120 km/hr) is dependent primarily on aerodynamic drag and rolling resistance and is on the order of one-half of the constant power value.

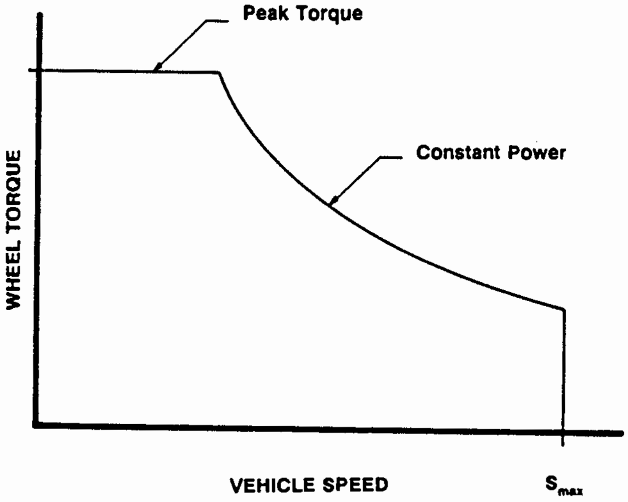


Figure 6

For a given vehicle, the engine or electric motor torque desired to achieve the required wheel torque depends upon the gear reduction between the prime mover and the wheels. The torque output versus speed curve of an internal combustion engine is relatively flat and with a single value of gear reduction cannot match the range of wheel torque requirements. Hence the need for multi-speed transmissions. For electric vehicles it is possible to consider a single ratio gear reduction, thus saving weight and increasing efficiency by eliminating the multi-speed transmission. Series or shunt wound brush commutated dc motors generally exhibit the desired torque versus speed characteristics and many successful electric vehicles have been built using such motors. However, these motors are quite heavy and are less inefficient than permanent magnet brushless dc motors or induction motors operating at high speed.

Following is a discussion as to how the benefits of high power density and high efficiency permanent magnet brushless dc motors can be realized in electric vehicle applications. Figure 7 shows a typical torque versus speed curve for a permanent magnet brushless dc motor. Note that the continuous torque line is relatively flat with stall torque being 40-50% greater than rated torque at high speed. Next, compare the available torque to the wheels from a permanent magnet motor with fixed gear reduction to the required torque based on an assumption that the motor and reduction design is such that the torque requirements are met at the half speed point. Such a curve would be as shown in Figure 8a. One can conclude that under the assumptions made, acceleration performance at lower speed would be marginal while at higher speeds more power would be available than needed for acceptable performance.

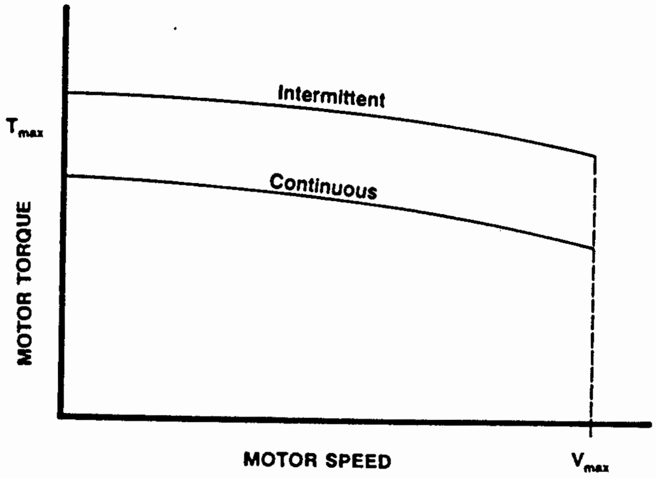


Figure 7

In a motor with a magnetic field that is constant, the available torque is directly proportional to the current delivered to the motor. Thus at low speed and for intermittent operation, it is possible for the permanent magnet motor of Figure 8a to meet vehicle requirements by increasing the size of the electronic controller and making more current available to the motor. The motor size may also be increased such that it is capable of satisfying torque requirements in continuous operation as opposed to intermittent operation. If one takes this approach as shown in Figure 8b, one now has a motor and electronic drive system that meets vehicle requirements but is considerably over sized for all other aspects of vehicle operation other than low speed acceleration. The cost of such a system is likely to be too high.

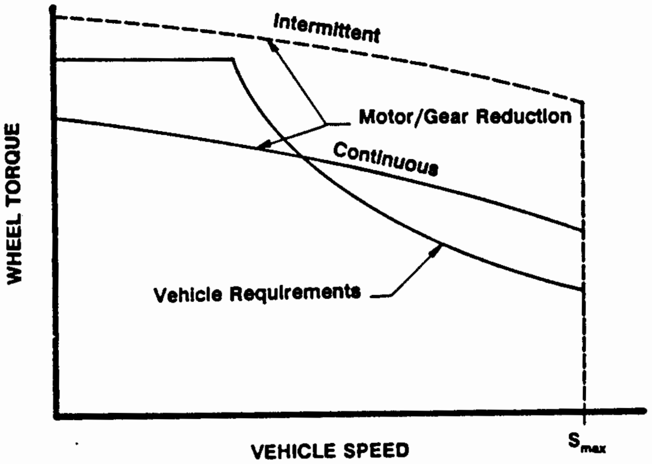


Figure 8a

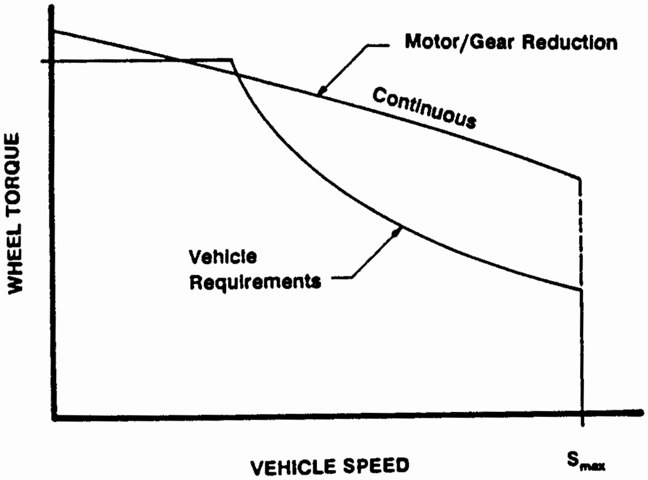


Figure 8b

There are several ways to get around this problem of low speed torque without increasing motor and electronic drive size, weight and cost. The most obvious solution is a multi-speed transmission. However, as suggested above, this is to be avoided if at all possible. Another approach is to use a continuously variable transmission or torque converter device. Technology in this area is lacking in terms of cost and efficiency. Unique currently is investigating two other techniques to increase the low speed torque capabilities of its permanent magnet motor for electric vehicle applications. The first approach involves use of field modification techniques. In this approach, the permanent field of the motor is altered by the use of an auxiliary field coil. At low speed, the total magnetic field can be increased to provide additional torque for constant current. For higher speed operation, the field is reduced and motor operates in a reduced torque overspeed condition.

Figure 9 shows the required wheel torque versus speed characteristic with a typical controller operating regime for a constant field permanent magnet motor and fixed ratio gear reduction. The upper limit of torque is determined by the maximum output current as shown by line I_{max}. The upper limit of speed is shown by V_{max} and is determined by the upper limit of system voltage. With these two curves we have now defined four regions of operation.

Region 1 defines an operating region that is within both the permanent magnet motor and controller continuous rating. The method of control in this region is pwm of the stator current. There is no field excitation in this region of operation. This is desirable for cruising below base speed as no power is wasted in the field coil. Region 2 is similar in operation but available power exceeds that actually required. Region 3 is the area where a combination of stator pwm and field strengthening is required to obtain desired torque. Region 4 is the overspeed region. In this region the stator pwm is reduced to zero and the field is weakened to increase and control speed.

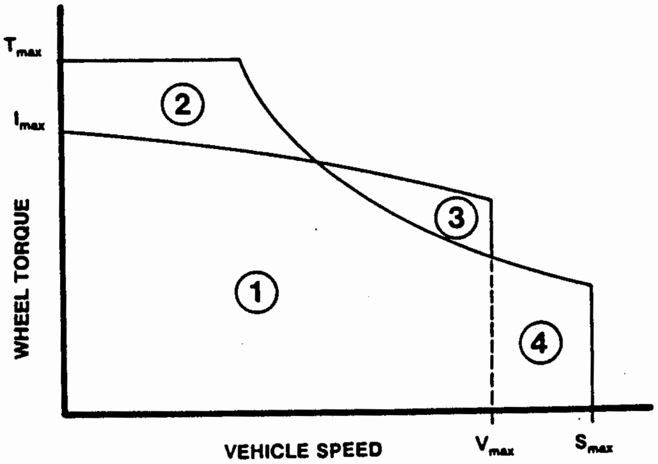


Figure 9

Practical implementation of the field modification concept has to accommodate changing conditions in the power system environment. Some sensitivities and their effects are:

Changing battery voltage	- V_{max} varies
Controller temperature	- I_{max} varies
Motor magnet temperature	- I_{max} and V_{max} vary

Overall control is accomplished by sensing operational changes in the stator controller rather than absolute speed and torque values. This is desireable because torque is a very difficult parameter to obtain by present means of sensing. Speed must be used to a certain degree to determine the direction of field current applied. For example, at low speed, continued application of accelerator signal will cause the field to strengthen (with a corresponding decrease in stator pwm to maintain applied speed) in order to deliver higher torque. In the overspeed region, increasing accelerator pressure requires a decrease in the field, but not so rapidly that torque cannot be maintained. Using inexact means of implementing control, and considering the possibility that efficiencies might improve and transitions from one mode to another may be smoother if the boundaries of control overlap or are smeared, the resulting control map looks like Figure 10.

Another approach which holds promise for matching the brushless dc motor torque speed curve to the vehicle requirements involves a motor winding switch. Unique's motors are constructed with six slots per pole. In a 3-phase wye wound motor that are two parallel winding slots per phase leg. These parallel slots may be externally connected in either series or parallel. The concept is illustrated in Figure 11. In series operation, the torque constant of the motor is doubled and the top speed halved. In parallel operation the torque constant is reduced by a factor of two and the top speed doubles. The torque versus speed characteristics of a switchable motor are shown in Figure 12. Note that in this instance, the current handling capability of the electronic controller need not be increased to obtain higher lower speed torque. The switchable motor increases in size slightly as the stator thickness must be increased somewhat because of the higher winding resistance during series operation. In actual implementation, the winding switch gives the driver of a vehicle the sense of a very sudden drop off of torque. The feeling is similar to that one would get in shifting from second gear to fourth or fifth gear in a conventional vehicle. This torque variation may be accommodated by electronic smoothing of the torque-speed curve. It is necessary to embed a current/torque-speed algorithm in the electronic controller to smooth the transition and provide the desired vehicle torque versus speed characteristic.

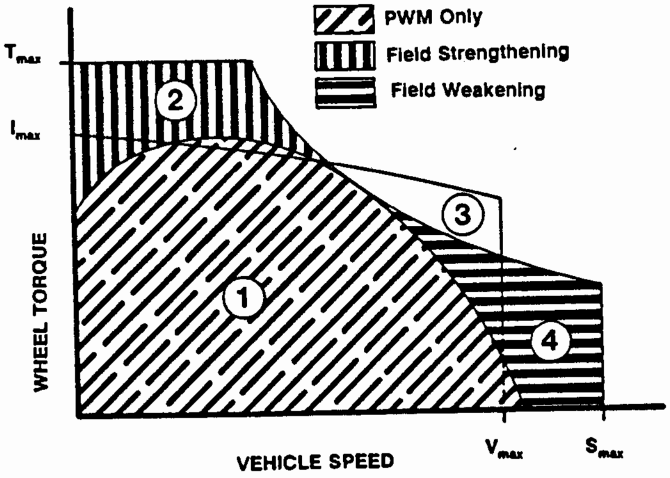


Figure 10

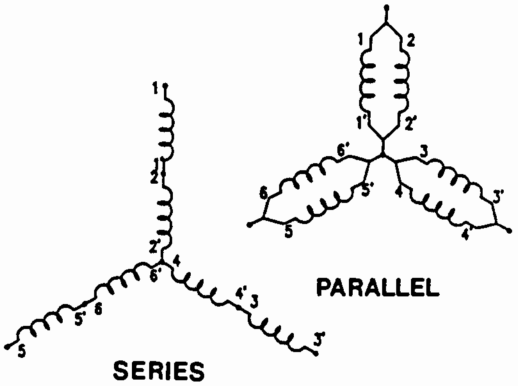


Figure 11

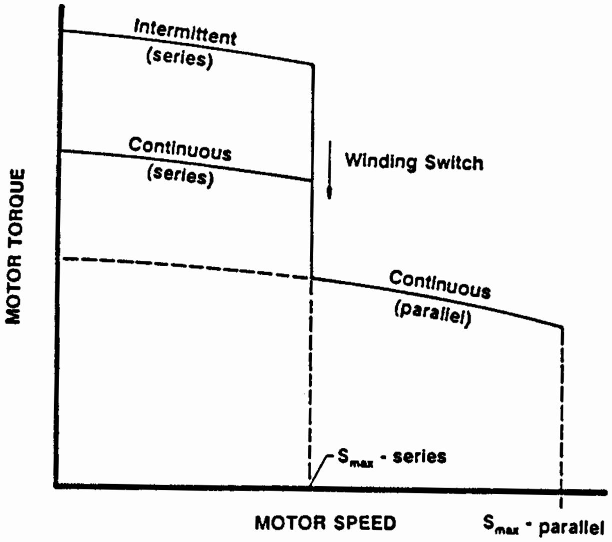


Figure 12

INTEGRATED MOTOR/TRANSAXLE

The compact size of the Unique motor permits its direct integration with a reduction gear and differential. Several approaches are possible. The Unique motor is hollow and depending on torque and gear ratio it may be possible to integrate the gear reduction directly into the body of the motor thus reducing overall size and system weight.

Typical gear ratios for electric vehicles will be in the 6 to 10:1 range depending on vehicle design and motor top speed. Except for relatively large diameter motors this may preclude packaging the gear reduction directly within the motor housing.

Figure 13 shows an integrated motor/transaxle which incorporates a 7500 rpm motor, a 7.5:1 gear reduction and a planetary differential which delivers the reducer output to both wheels of the vehicle by incorporating a hollow motor shaft.

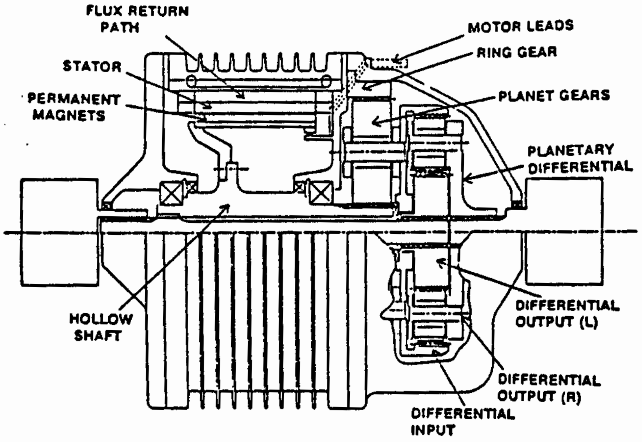


Figure 13

SUMMARY

Unique Mobility is optimizing it's advanced permanent magnet brushless dc motor technology for electric and hybrid electric vehicle application. The company is also exploring a wide variety of industrial applications for the technology.

The goal of achieving a cost effective brushless dc electric vehicle drive system which requires only a single stage of gear reduction requires adoption of new techniques to increase low speed torque. Means to achieve this currently being considered include field modification techniques and a two speed winding shift.

The motors can be integrated with gear reduction and differential to provide a lightweight, high efficiency completely integrated electric powertrain. Ultimately these technologies and other advances in the field will lead to an affordable electric transmission for vehicles. Unique's objectives in developing these concepts is to provide the basis for a commercially viable clean vehicle having greater range performance and economy than its fossil fueled counterparts.

Which Motor/Drive?

Fast microprocessors and digital signal processors are significantly impacting the control of inputs and outputs in the latest adjustable-speed drives.

Dan Jones

Incremotion Associates Inc., AIME Member

Today's adjustable-speed drives are more responsive to load changes, have wider speed ranges, and possess more accurate speed controls than previous adjustable-speed drive product families.

The availability of new power devices and permanent magnets is also providing the means to develop more powerful power bridges and motors that significantly outperform previous products. Reliable components at lower costs are impacting all types of adjustable-speed drive technology today. The electronic drive is significantly improving motor performance, but there are intrinsic performance parameters that limit motor performance.

Let's review motor and drive performance of the following four major motor drive technologies from the perspective of the motor:

- AC induction motor with PWM VVI controller
- AC induction motor with flux vector controller
- Brush DC motor with SCR controller
- Brushless DC motor with PWM vector controller

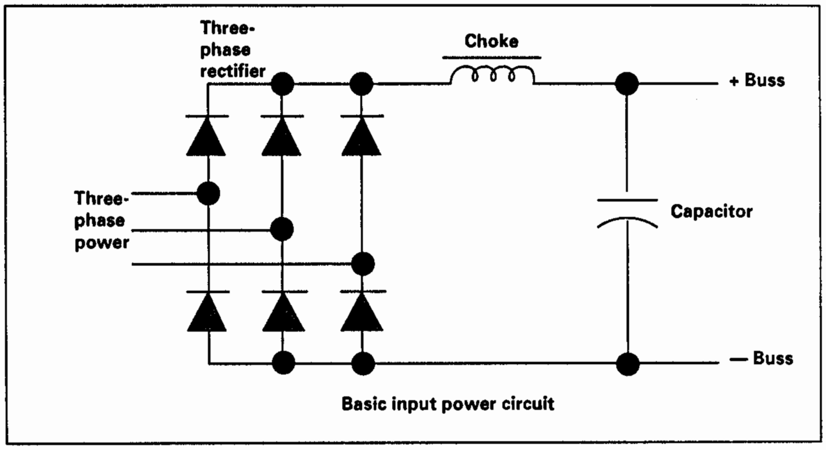
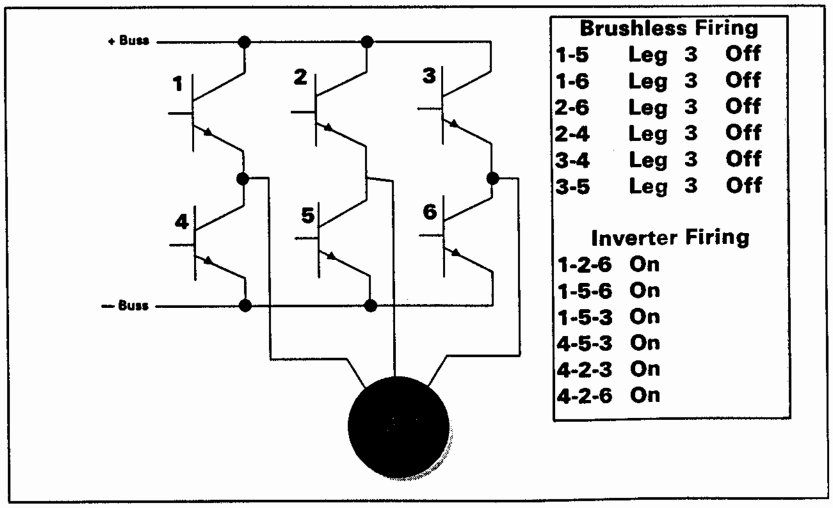


Figure 1. Basic input power circuit for brushless DC controller showing filter choke



Brushless Firing		
1-5	Leg 3	Off
1-6	Leg 3	Off
2-6	Leg 3	Off
2-4	Leg 3	Off
3-4	Leg 3	Off
3-5	Leg 3	Off

Inverter Firing	
1-2-6	On
1-5-6	On
1-5-3	On
4-5-3	On
4-2-3	On
4-2-6	On

Figure 2. Commutation comparison of brushless and inverter-type controllers

Workhorse

The AC induction motor is the most commonly used motor in the U. S. for a wide range of applications. Developed in the 1880s by N. Tesla, the AC induction motor speed does not directly track the input frequency, but exhibits a small speed fall off designated slip. This slip (speed drop-off) causes the induction motor shaft speed to typically drop 2% to 5% as higher loads are encountered until the induction motor reaches an unstable region and breaks down or drops to zero speed.

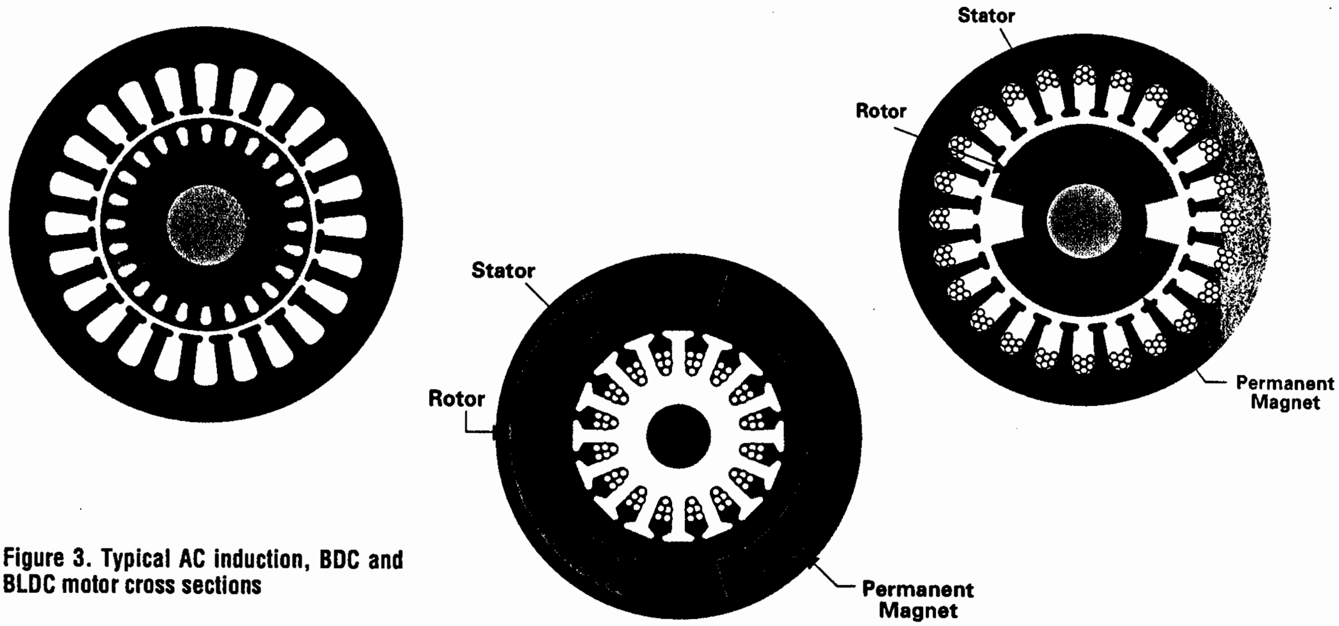


Figure 3. Typical AC induction, BDC and BLDC motor cross sections

The PWM-type inverter and, more recently, the flux vector inverter are the best representatives of today's AC induction adjustable-speed drives. The PWM inverter (typically a VVI type) produces a three-phase sinusoidal current, I, output at frequencies typically controlled from 3 to 120 Hz, holding the excitation voltage at a constant ratio relative to frequency. Above 60 Hz, this constant ratio decreases with increasing frequency. This constant ratio must also be increased at low input frequencies (up to 5 Hz) to correct for motor low-speed losses.

The VVI AC controller directs the motor to run at a shaft speed, but any load changes will change the AC motor shaft speed. This adjustable-speed drive system depends on the AC motor's self-regulation capability, because there is no actual feedback device to detect and correct any changes in shaft speed. Changing the frequency and the motor terminal voltage allows the AC induction to operate effectively over a 10:1 speed range and maintain good torque load regulation down to speeds approaching 300 rpm. This simpler and lower-cost adjustable-speed drive system is used in many less demanding applications, but it cannot compete with the high performance requirements usually obtained by brush-type DC adjustable-speed drives.

The AC flux vector controller shares the same power conversion hardware, but it works on a completely different control principle. In vector control devices, the rotor flux is produced dynamically via a fast software algorithm by using the instantaneous current in the stator. The software algorithm creates the ever-changing current vector (magnitude and phase angle) as a function of rapid changes in load, temperature, voltage, speed, motor inductance, resistance, etc.

A feedback device is used on most AC vector adjustable speed drives to provide the necessary speed signal to create excellent accuracy and dynamic response. Typically speed ranges of 500:1 with 0.01% speed regulation are readily acheivable with position feedback based on AC-vector-controlled systems.

Today, more powerful predictive software control algorithms employing faster digital signal processors (DSPs) and microprocessors have eliminated the need for a feedback device at the expense of a portion of the vector control's high performance and dynamic response. One can expect the sensorless vector control to slowly extend its dynamic performance range as the control devices (DSPs and microprocessors) improve. None of these AC control techniques can improve the intrinsic power efficiency of the AC motor at rated speed and load conditions.

The brushed DC motor was invented in 1856 by Wemer Von Siemens in Germany. Adjustable speed by armature voltage control (Ward-Leonard System) was first used in the 1930s in an AC motor–DC generator system. The DC generator's DC output was varied by using a rheostat to vary the DC motor's wound field excitation. This adjustable DC voltage was then used to power the armature circuit of another DC motor.

The shaft speed of a DC motor is a direct function of the applied armature voltage. The torque produced by a DC motor will vary directly with armature current. These two simple performance characteristics make the DC motor a popular and cost-effective method of achieving adjustable-speed drives for constant torque industrial applications.

Permanent magnet (PM) brushed DC motors created the element of linear current vs. linear torque performance and simple load control for the subfractional to 25 hp market. This was critical when PM brushed DC motors became popular in the early 1980s in adjustable-speed drive applications. Field control algorithms for larger brushed DC-driven adjustable-speed drives (greater than 15 hp) have improved controllability for these larger DC motors. Speed ranges of 1,000:1 are typical for base brush DC-motor-driven sytems.

DC motors are very power efficient (87% to 92%) in the 7-hp to 100-hp performance range. Why change to other adjustable-speed drive technologies? Unfortunately, SCR power devices drive the brushed DC motor by varying the point on the AC voltage waveform at which armature current begins to flow. Low and middle output voltage conditions result in low power factor values and a large waste in electrical power utilization. The biggest single factor against brushed DC motors is the use of mechanical brushes to transfer electrical power from the input terminals to the motor armature. Brush wear causes large maintenance costs and, many times, reliability problems.

BLDC

The brushless DC (BLDC) motor first appeared in the U.S. in 1962, when T. Wilson and P. Trickey developed a "DC machine with solid-state commutation" for a defense application. It initially evolved into low-precision, high-performance, adjustable speed and positioning motor drives for computer peripherals (disk drives, tape drives, and printers). Compact actuators use BLDC motors to drive aircraft control surfaces and robotic arms in special hostile environmental applications where brushes could not be used. The concurrent developments of high-voltage power transistors, rare-earth magnets, and Hall-effect-activated switches in the '70s and '80s propelled the BLDC motor into the industrial servo market for machine tools and other factory-floor applications.

The first large permanent-magnet BLDC motor was a 50-hp BLDC motor for adjustable-speed drive applications in the plastics industry in the late 1980s by Bob Lordo of Powertec, a division of Pacific Scientific Co. This company continues to manufacture large horsepower permanent-magnet BLDC motors driven by solid-state controllers (rectifiers and inverters). Present BLDC technology reaches 600 hp (450 kW) power levels.

The brushless DC controller uses a diode-based rectifier to convert high-voltage three-phase AC power into DC power as shown in Figure 1. A large input choke is used to provide high power factor and to further reduce input current distortion effects. AC line harmonic distortion as low as 2% is readily achievable when a properly sized choke (inductor) is used. Figure 2 compares the firing sequences for a three-phase AC inverter and for a BLDC "H" bridge driver. The feedback device (encoder or resolver) always selects or commutates two switches to provide voltage to the windings in the H-bridge configuration (e.g., switches 1 and 5). One upper switch and one lower switch are always energized for each phase. Current flows from one switch through the other switch. In BLDC motors, two of three phases are usually energized.

AC inverter excitation (see Figure 2) powers all three phases simultaneously while the brushless DC bridge driver leaves one phase turned off during the normal excitation (commutation) pattern. This rest period for a single brushless DC motor phase reduces the bridge driver's operating stress, which is the most common cause of failure of power devices in AC drives.

The BLDC motor possesses a much different structure than the brushed DC motor, as shown in Figure 3. The magnets are located on the moving rotor, and an electronic commutator (in the form of a magnetic Hall or optical actuated set of electronic switches) is used to commutate or switch on and off the stator windings in the proper sequence and position. One of the limiting factors for accepting BLDC technology is its higher unit cost, usually caused by using expensive rare-earth magnets to achieve high motor torque performance. Powertec has achieved higher motor torque through judicious design of the rotor magnetic structure using lower-cost ferrite magnets and an optimization of the stator winding copper fill. The AC induction motor shares a similar stator winding pattern with the BLDC motor but uses a squirrel cage rotor structure to achieve the traditional AC motor torque vs. speed performance.

The brushless DC motor possesses a number of outstanding performance advantages over the brushed DC and AC induction motors. They include the following:

- Highest power efficiency
- Highest response to load changes (highest T/J)
- Smallest size for a specific power rating
- Highest peak torque capability
- Lighter weight

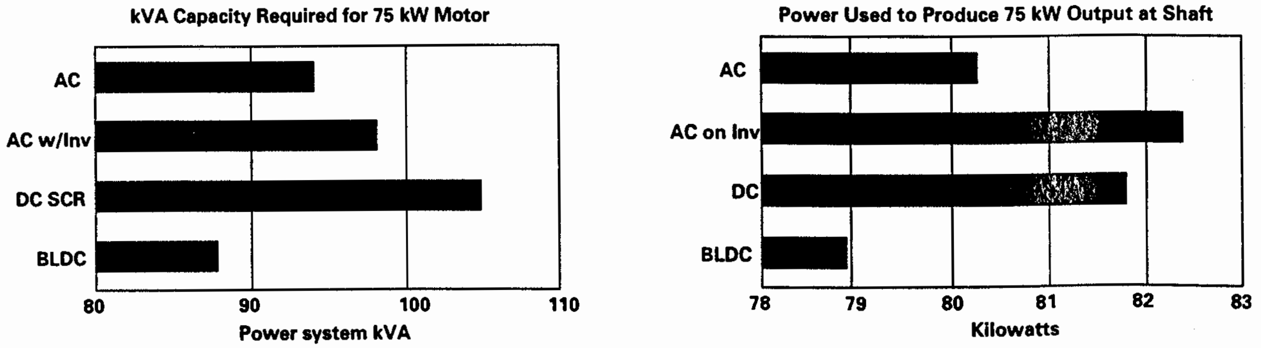


Figure 4. The left demonstrates that the KVA requirements are less for BLDC motors. The right details power used.

A four-pole ceramic magnet structure is used for the smaller frame sizes 0.5 hp to 50 hp (0.37 kW to 37 kW) at 1,750 rpm, while an eight-pole ceramic magnet structure is used for the larger frame sizes 50 hp to 600 hp (37 kW to 450 kW). High-strength glass-epoxy bands are used to restrain the rotor magnets at speeds well beyond its rated speed values. Many BLDC motor designs are capable of peak torques of over 400%. Both single- and dual-circuit wye and delta hookup configurations are available. This permits four different voltage and torque constants from one stator winding, and four different motor base speeds are available.

The BLDC motor's size and mounting dimensions are smaller, but are selected to match standard NEMA frame sizes and mounting dimensions and comply with national and foreign third-party safety standards. Special attention was paid to motor thermal characteristics by using a patented (Powertec) finned extruded or cast aluminum housing that has both internal and external cooling fins.

Most common NEMA and EEC motor enclosures are available, such as drip-proof fully guarded (DPFG-IP22), drip-proof blower ventilated (DPBV-IP22), totally enclosed nonventilated (TENV-IP44), totally enclosed fan cooled (TEFC-IP44), and totally enclosed pipe ventilated (TEPV-IP54).

The controller utilized PWM technology, incorporating third-generation IGBTs. The switching frequency of 1.8 KHz in older BLDC products has been raised to 2.5 KHz for the larger units and up to 10 KHz for the smaller units. Temperature-sensing circuits actively control heat sink fans and motor-cooling devices and protect both the motor and the power bridge. Speed regulation of the BLDC-motor-based adjustable-speed drive was chosen to be absolute. A digital phase lock speed control loop was selected, and an encoder was used as the feedback device. The resulting speed regulation is 0%. Since digital control techniques are used, multiple-axis master/slave adjustable-speed drives are readily attainable. The communications protocol used to interface to a PC is the RS-232 available port which is on most BLDC adjustable-speed drives.

The typical industrial 100-hp (75-kW) brushless adjustable-speed drive in early 1995 exhibited the following performance:

- Speed regulation 0%
- Speed range 100:1
- Constant torque range 100:1
- Two-quadrant/four-quadrant operation
- Power factor 0.90
- High dynamic response
- One minute on duty cycle torque 160%

The most recent generation of PM-BLDC adjustable-speed drives exhibit significant performance improvements.

Comparison

The U.S. industrial factory is searching for more efficient and cost-effective methods to reduce its ever-spiraling electric energy costs. The latest adjustable-speed drives provide great opportunities for saving electric power in U.S. industry. It also requires that these adjustable-speed drives display great control flexibility. But which motor technology and associated adjustable-speed drive provides the best performance capabilities?

The AC induction motor hooked up directly across the power line can be considered the baseline technology. The other three technologies will be evaluated.

Figure 4 displays the performance of these four motor technologies with a 75 kW (100-hp) output. The kVA (kilovolt-ampere) input power requirements show that the high torque and high response brushed DC motor, SCR driven, consumes the most power, and the BLDC motor, IGBT driven, consumes the least. Note that the inverter kVA losses cause the AC induction motor/drive to consume about three kVA more than the AC induction motor directly across the line.

The actual power used in the four motor-driven adjustable-speed drives is shown in the right plot in Figure 4. The BLDC motor consumes less than 106 hp (79 kW) in generating 100 hp (75 kW) output.

The inverter-driven AC induction motor (e.g., PWM VVI) needs 110.5 hp (82.41 kW) input power to generate 100 hp (75 kW) output. Note the AC motor, line driven, has the second best input power consumption performance. That is only at the rated torque and speed point. Decrease the load (and reduce the output power) and the AC motor, line driven, will still consume the same input power. The inverter and associated controller adjusts the AC motor's input voltage and current to optimize motor power consumption over a wide range of loads and speeds. The left of Figure 5 displays the actual AC line currents that are

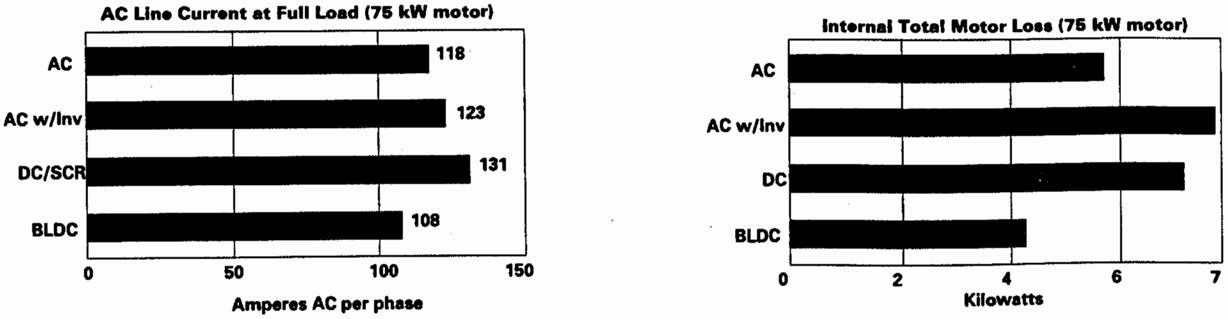


Figure 5. BLDC motors require less current at full load and exhibit less total motor loss.

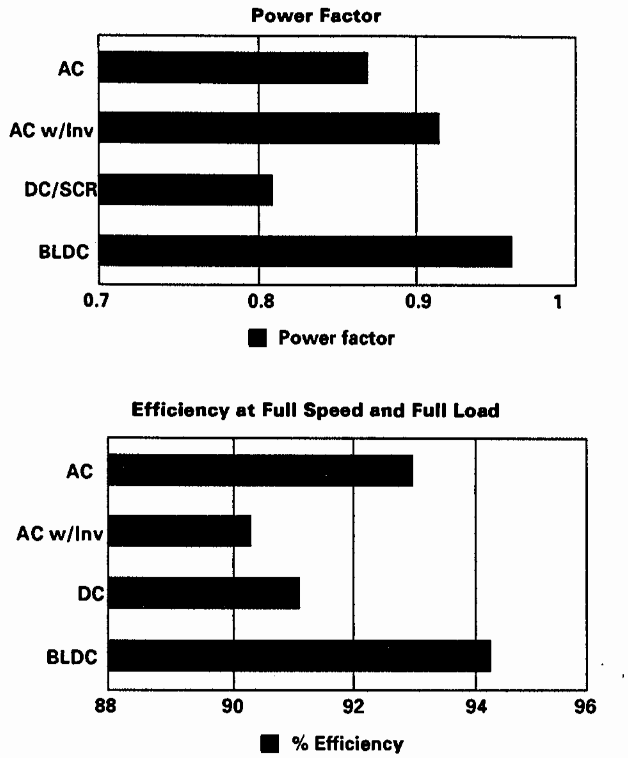


Figure 6. BLDC motors have the advantage for power factor and efficiency.

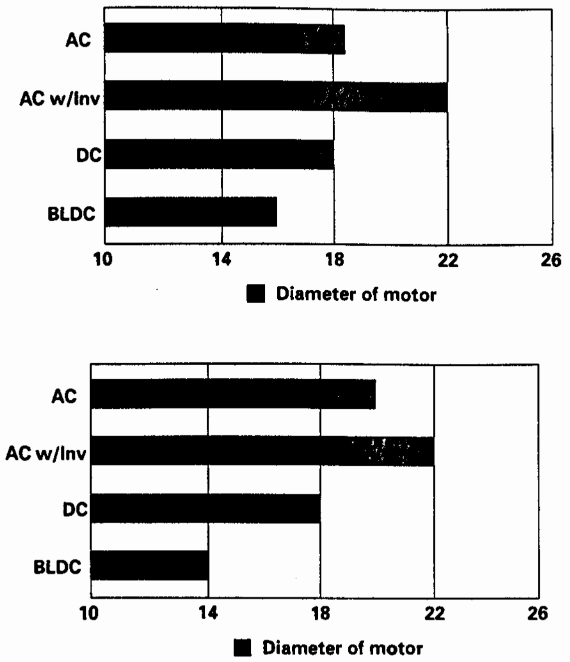


Figure 7. The BLDC's efficiency means that it can be produced in smaller form factors.

measured for the four motor technologies. The more efficient 100-hp (75 kW) BLDC motor draws the least AC line current at 108 amps per phase. The 100-hp (75-kW) brushed DC draws the most current at 131 amps per phase. The right of Figure 5 shows the various motors' internal total motor losses. The BLDC motor possesses the lowest internal losses and the inverter-driven AC motor the highest.

Power factor is the ratio of real input power drawn to the apparent power drawn by the motor from the power line. The ideal power factor is 1.00 over a wide range of speeds and loads. The top of Figure 6 displays the power factor at a rated load and speed. The BLDC motor features the highest power factor (0.91) and the brushed DC motor, SCR driven, the lowest. The bottom of Figure 6 illustrates the four motors' power efficiency rating at full load and full speed. Again, the BLDC motor leads the other technologies with the highest power efficiency, and the AC motor inverter is driven with the lowest. Figure 7, top and bottom, shows the motors' outside diameters and their representative NEMA frame sizes. The smaller motor frame size of the BLDC motor is more efficient and more thermally stable than the other motor technologies. The inverter-driven AC induction motor possesses the largest frame size. Two different 100-hp (75-kW) NEMA motor enclosures are represented in the two Figure 7 plots.

Summarizing, the BLDC motor and PWM bridge driver consistently out-performs the AC induction motor with PWM VVI controller and the SCR-driven brushed DC motor. The AC motor hooked directly across the power line is used as a comparison baseline. However, there is one motor/drive technology that was not a part of the initial comparison charts: the AC induction motor with flux vector controller.

Flux vector or just vector-controlled AC motors with inverter drives possess significant performance improvements over the other AC inverter-driven motor/drive systems. The creation of the current vector and the implementation of a temperature compensation algorithm produce a high-performance AC vector control system. A feedback device is needed to achieve wide range capabilities of 500:1, speed regulation of 0.01%, and four-quadrant operation. The vector-controlled AC induction adjustable-speed drive will develop a higher power factor (see the top of Figure 6) and a lower KVA (see the top of Figure 4). Vector control techniques do not improve the AC motor's intrinsic power efficiency or overall internal losses.

The brushless DC (BLDC) motor possesses superior performance to all present motors in both precision adjustable speed and positioning systems. Usually acquisition costs are higher for the BLDC-motor-driven systems. But, it has been amply demonstrated for two decades that low precision BLDC motors are very cost-effective. One has only to look at the small spindle motors in Winchester disk drives (over 50 million built in 1995 alone) to show that control electronics tightly integrated to the BLDC motor yields a cost-competitive system.

One can expect adjustable-speed drive technology to continue to employ more processor power, user-friendly menu-driven adjustable-speed drive control and application-specific algorithms in the future. **MC**

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Advancements in Electric Propulsion Systems at BMW

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ABSTRACT

At the 1991 international automobil show, IAA in Frankfurt, Germany, BMW presented it's E1, the first specially designed electric car for urban traffic. Up to now, the car and it's components have been further developed and improved. This paper gives a short outline of the concept of the car and describes the state of the development. Special information is given about the electronic drivetrain system and the recent advances of controller developments. Additionally, technical potentials are discussed and the advances are shown on the drivetrain of the BMW E2 study.

INTRODUCTION

Alternative vehicle concepts are widely viewed as a potential solution to the pressing traffic problems of this day and age - increasingly dense traffic, atmospheric pollution and noise emissions. Minimum emissions approaching zero can only be achieved by those vehicle concepts which are radically optimised in terms of energy consumption.

Electric vehicles are at present the only feasible solution for satisfying legal requirements for emissions-free local operation. Moreover, they offer the advantage that the infrastructure for generating and distributing the energy for their operation already exists. This eliminates the need for high investment in the planning and implementation schedules for the development of a supply network; the process of generating electrical energy remains independent of any specific energy carrier.

VEHICLE CONCEPT

The vehicle known as the E1 is a 2+2 city vehicle with two doors and a tailgate lid (Fig. 1). The E1's size has been chosen to be well equipped for city driving [1]. Principle vehicle data is given in Table 1. The E1 is propelled by a rear-mounted motor driving the rear wheels. The motor/transmission unit has been integrated into the rear axle. The NaS high-energy battery manufactured by ABB has an energy content of 19 kWh, operates at a voltage level of 120 Volt and can achieve a maximum output of 22 kW. The assembly's weight, including management system and oil/water radiator, is 200 kg. Together with the battery located ahead of the rear axle, the favourable axle load distribution of some 60 % of the vehicle's weight resting on the rear axle in all load conditions has been achieved. The battery's location beneath the rear seat means that not only is the available space utilised very efficiently, but the battery is also well protected in the event of a crash.

The E1's body is of a hybrid design, consisting of a supporting aluminium frame structure and a plastic outer skin. The passenger compartment is very strong, with large-dimensioned cross members and posts. The E1's bumper concept is designed to withstand minor collisions without incurring any damage. To provide optimum protection for the occupants, the vehicle has an integral seat-belt system with Eurobags for driver and front passenger, and a continuous knee-bar; effective side crash protection is provided by continuous reinforcing cross-members in the seat areas and between the A- and B-posts, and by a door barrier.

The two-stage folding rear seat keeps the interior versatile, as a result of which the luggage compartment volume can be increased from 260 litres to 900 litres. The vehicle is simple to load and unload with its level luggage-compartment floor, low loading edge and large tailgate.

The E1's suspension has also been purpose designed. The rear axle layout is that of the central-link axle, already familiar from the Z1 and new 3 Series. It was optimised and redesigned in accordance with the concept requirements of an electric vehicle. Lightweight solutions were chosen and realised by the use of aluminium for most parts of the axles, such as wheel carriers, control arms, or spring struts. Different sizes of wheels have been chosen for the front and rear (14-inch at front, 16-inch at rear). On the one hand, this decision is based on the styling requirement to create a

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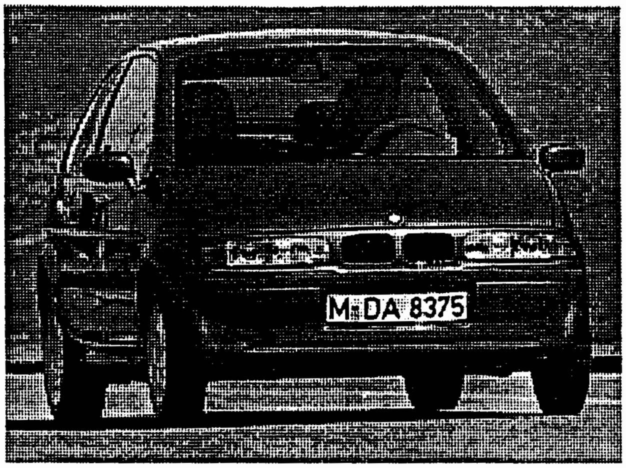

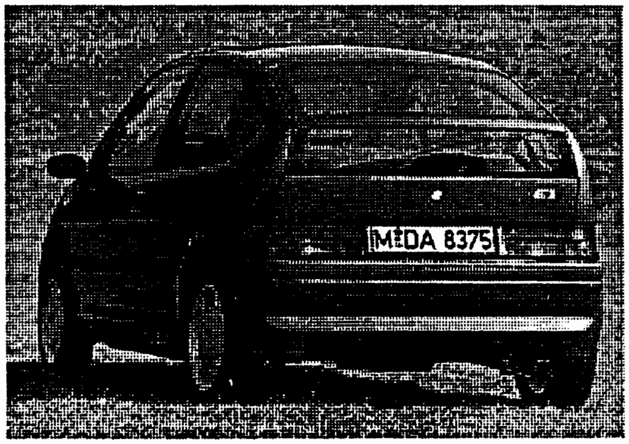

Fig.1: The BMW E1

Vehicle data		BMW E1
Unladen weight	kg	880
Max. payload	kg	300
Length	mm	3460
Width	mm	1648
Height	mm	1500
Wheelbase	mm	2325
Drag coefficient		0.32
Luggage compartment volume	l	260 - 900
Max. power output	kW	32
Max. starting torque	Nm	150
Track, front and rear	mm	1420
Turning circle	m	< 9
Battery type		NaS
Battery capacity	kWh	19.2
Recharging time (normal)	h	6 - 8
Recharging time (rapid charger)	h	app. 2
Performance		
Top speed	km/h	120
Acceleration 0 - 50 km/h	s	6
Acceleration 0 - 80 km/h	s	18
Max. gradient	%	35
Action radius (City - driving)	km	app. 150 - 200

Table1: Vehicle data of BMW E1

dynamic appearance, and on the other hand the smaller front tyres permit a wider steering angle, and therefore a smaller turning circle, without impinging on the passenger compartment. In a concerted effort to save energy, the vehicle has been equipped with optimised tyres for minimum rolling resistance . These narrow tyres achieve an average rolling-resistance coefficient of 8 per thousand, a reduction of approx. 30 % on conventional tyres.

A brake servo proved unnecessary in view of the vehicle's low weight. An electrically-operated hand brake automatically locks the rear axle whenever the vehicle is parked. In view of the E1's operating spectrum, no spare wheel is needed; breakdown tyre inflating bottles are carried for eventual puncture repair.

DRIVETRAIN

At the very heart of the E1's drive system is a brushless DC rotating-field motor with a rated output of 32 kW and starting torque of 150 Nm [2]. The motor radiator and the control electronics are cooled with water. The motor has a hollow rotor shaft accommodating one of the output shafts from the single-stage planetary gear train flanged to the side of the motor, with integral differential.In view of the motor's high starting torque and the wide speed range, only one transmission stage is required. The available travel stages - forward, reverse, neutral and park - are shifted with a small selector lever and shown on a display in the instrument cluster.

Three stages have so far been completed in the development of the overall drive control system, and of the controller in particular. The first stage was the use of an air-cooled, analog controller in an experimental vehicle

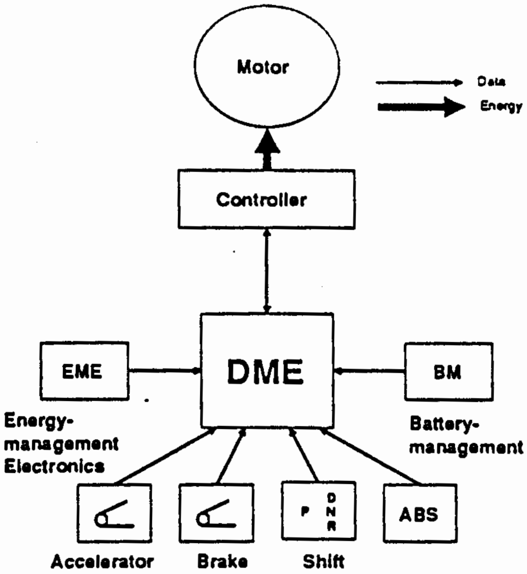

Fig.2: Drive management system

specially designed for testing the driveline. The additional energy required to cool the controller had to be taken from the car's battery, thus reducing its maximum range. No energy loss occurs in the E1's water-cooled controller, which represented the second development stage. Moreover, thermal energy transferred to the water circuit can be used to heat the passenger compartment. An all-digital drive control system represents the latest state of the art. The characteristics of the various controller concepts already realised and the way they function are described below.

The key traction control element is a digital drive management system (DME) which controls and monitors the interaction between motor controller, battery management and energy management electronics. The battery management system's main tasks are to monitor power drawn from the battery during operation, to check battery temperature and to initiate battery cooling if necessary. Energy management electronics monitor and control all the vehicle's electrical devices (bus system) and carry out diagnosis checks. Drive management is based on the vehicle's dynamics and permits acceleration, refinement, energy consumption and range to be influenced. Input values are the position of the selector lever (forward, reverse, neutral, park position), the accelerator and the brake pedal, information on current driving conditions (ABS signal, monitoring regenerative braking) and the output variables of battery and energy management (e.g. battery temperature, number and magnitude of consumers currently in operation). The aim of drive management is to reproduce typical BMW characteristics, such as driving dynamics and comfort, in the electric car. Fig. 2 shows the basic structure of the drive management system.

Electronics are used to satisfy the driver's requirements by bringing about an appropriate rotational movement of the motor shaft. Taking account of driving speed, the position of the accelerator pedal is converted into a torque reference value. This serves as an input variable for the motor controller, which in turn informs the DME of current motor temperature (overload protection) and speed of rotation.

Communication with the motor controller is by means of a digital interface. The analog motor controller is responsible for torque control, the final output stage control function and the final output stage itself (Fig. 3). Dividing the E1's drive control system into an analog motor controller and digital drive management electronics offers the following advantages:

- the vehicle's driving dynamics are independent of the motor's control system
- vehicle response can be altered easily by means of software implementations

These advantages, however, are accompanied by certain disadvantages:

- due to its analog design, the controller is difficult to modify
- due to electrical radiation (EMC), it is susceptible to faults and internal values can be affected by crosstalk
- the design of analog circuits becomes more complex as their size increases

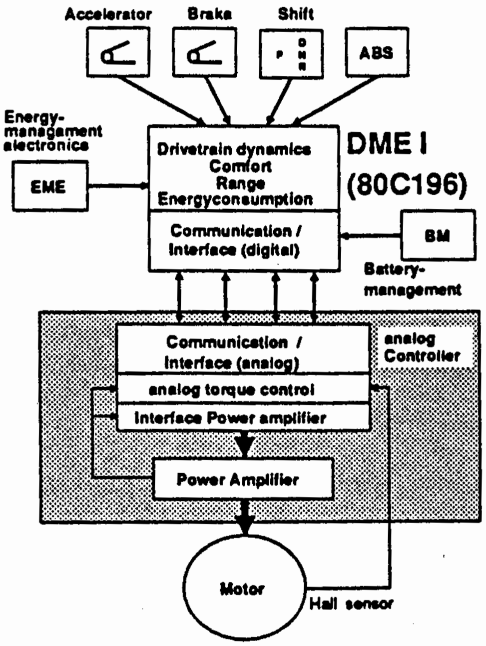

Fig.3: Drive management system with analog controller

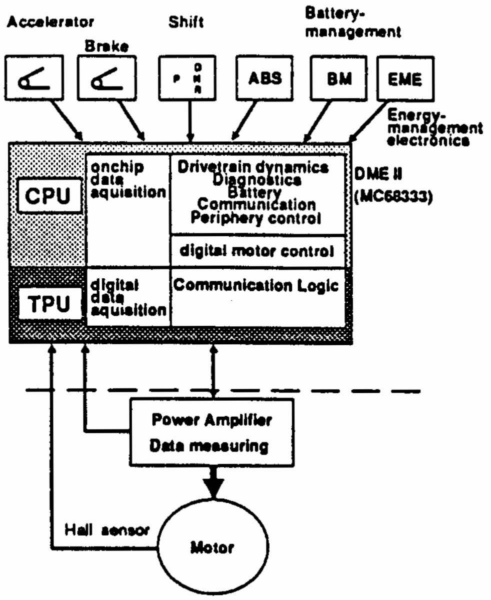

Fig. 4:Fully digital drive management system

- analog circuits are sensitive to temperature changes; this has an adverse effect on control circuits, commutation and communication with the drive management system
- there is no diagnosis facility, e.g. interrogation of a fault memory.

For these reasons, work is currently being carried out on a fully digital version of the drive management unit and the controller.

Drive management electronics (DME), torque control and the control function for the power circuit are being integrated into a single unit. Implementation of DME and controller takes place in a 32-bit Motorola MC 68333 micro-controller. The final output stage is separate and galvanically isolated (Fig. 4). It is therefore possible to combine all the logical control functions into a single piece of equipment. The control algorithms are implemented in high-level language C, so that individual modules can be serviced much more effectively. The fact that there are no longer any controlling or regulating electronics in this section makes the circuit neater and reduces the weight and volume of the electronic components.

The control function's time response is clearly laid down by the software and is realised by a separate TPU (timer processing unit) in the processor. The TPU guarantees exact timing and thus the transient behaviour of the signals. It can be programmed in Micro Code / Assembler, thus providing sufficient flexibility for adapting it to other motors and power circuits.

The modular design of the drive management system makes it possible to implement and test new driveline versions at short notice. More powerful motors for enhanced driving dynamics can be tested relatively easily by adjusting the separate final output stage to suit the new conditions. Thanks to this modification, the same drive management system can be used to test other battery types (NaS, NiCd, NiMH). Batteries with relatively high operating voltages, the advantages of which include lower current intensity, can also be tested. This promises to enhance the efficiency of the entire driveline.

OUTLOOK

The BMW E1 represented the first step towards a purpose-designed electric vehicle. This model has proven its functionality, but still has much scope for optimisation. The BMW E2 unveiled at the Greater Los Angeles Motor Show in January 1992 represents a further step in the same direction (Fig. 5).

This vehicle, modelled by BMW's Californian design studio Design Works, sought to accommodate American tastes and specific road traffic requirements in the Los Angeles area:

- Fast-flowing traffic on the Freeways means that an electric car needs better acceleration.
- The relatively constant cruising speeds of 55 to 65 m.p.h need to be maintained on slight inclines so that an electric car does not obstruct other traffic.
- The larger distances covered in America necessitate a much higher operating range. A reference distance of 160 km is under discussion.
- Climatic conditions in Southern California render an air conditioning system imperative on electric vehicles too, but the power consumption of this item will noticeably curtail the maximum operating range.
- The parking space problem is by no means as acute in American cities as in Europe.

With the exception of the last topic, all the points listed mean that a larger battery with a higher energy capacity and higher output is needed. An NaS battery with an operating voltage of 180 V, an energy capacity of 28.8 kWh and weighing 265 kg is therefore scheduled for use in this vehicle. The vehicle's length needs to be increased slightly to accommodate the marginally larger battery. In principle, the suspension layout and driveline correspond to the BMW E1, with the suspension components adapted to the modified requirements. Table 2 shows principal vehicle data for the BMW E2.

Fig.5: The BMW E2

Vehicle data		BMW E2
Unladen weight	kg	915
Max. payload	kg	300
Length	mm	3800
Width	mm	1700
Height	mm	1455
Wheelbase	mm	2525
Drag coefficient		0.32
Luggage compartment volume	l	> 260 - 900
Max. power output	kW	32
Max. starting torque	Nm	150
Track, front and rear	mm	1435
Turning circle	m	< 9
Battery type		NaS
Battery capacity	kWh	28.8
Recharging time (normal)	h	9 - 12
Recharging time (rapid charger)	h	app. 2
Performance		
Top speed	km/h	120
Acceleration 0 - 50 km/h	s	< 6
Acceleration 0 - 80 km/h	s	< 13
Max. gradient	%	33
Action radius (City - driving incl. air conditioning)	km	app. 160 - 230

Table2: Vehicle data of BMW E2

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AN OVERVIEW OF THE DOE ELECTRIC AND HYBRID PROPULSION SYSTEMS PROGRAM

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ABSTRACT

The Department of Energy continues to focus its efforts on the technologies that are critical in making electric and hybrid vehicles competitive with conventional vehicles in cost, performance, and reliability. The successful penetration of electric and hybrid vehicles in the U.S. vehicle population is necessary if these vehicles are to contribute significantly to solving a number of national problems, including dependence on foreign oil, poor air quality, and the negative balance of trade. DOE continues to work with industry in addressing the critical technical barriers and is coordinating its efforts with other federal agencies engaged in similar research and development activities through the Interagency Coordination Task Force on Electric and Hybrid Vehicle Technologies. This paper provides an overview of the DOE program.

INTRODUCTION

The successful penetration of electric and hybrid vehicles (EHVs) into the U.S. vehicle fleet would allow the transportation sector to partially meet its demand for energy with electricity. Dependence on petroleum fuels would be reduced, since only about four percent of electricity in the United States is generated from petroleum. EHVs will not only reduce reliance on petroleum and result in more efficient energy use in the transportation sector, but will also help to reduce severe urban environmental pollution problems. Emissions from on-board fuel combustion are partly (in the case of hybrid vehicles) or fully (in the case of electric vehicles) removed from the street level and, in most cases, from the urban area. In fact, electric vehicles will be essentially non-polluting if they use electricity generated from non-fossil fuels. Even in areas where electric power generation is almost exclusively from fossil fuels, the substitution of electric vehicles for gasoline-fueled vehicles would result in net reductions of carbon monoxide, hydrocarbons, and nitrogen oxide emissions. In economic terms, large national gains could result from creating and expanding domestic and international markets for domestically-produced electric and hybrid vehicles. However, they still need to be developed and made competitive with conventional, gasoline-powered vehicles in terms of cost, performance, and safety.

THE DOE ELECTRIC AND HYBRID PROPULSION SYSTEMS PROGRAM

Recognizing the large potential for energy, environmental, and economic benefits to the Nation, DOE is devoting considerable resources to an Electric and Hybrid Propulsion Systems Program focused on developing critical component and vehicle system technologies that will enable industry to:

- Commercialize a 100-mile range electric vehicle in the near-term (1993-1996);
- Commercialize a 250-mile range electric vehicle and demonstrate an unlimited range, ultra-low emission hybrid vehicle in the mid-term (1996-2000); and
- Commercialize cost-competitive, zero-emission vehicles with range and performance equivalent to conventional gasoline-powered vehicles in the long-term (2000-2005).

Specific program objectives are based on achieving steady improvements in key technologies, such as batteries, fuel cells, and propulsion systems, thus enabling industry to provide commercially acceptable vehicles that will capture a larger market share as the technological progress is achieved.

Fuel Cells R&D. DOE is working closely with industry to develop commercially viable, fuel cell propulsion systems for light-duty and heavy-duty vehicles. More specifically, the current focus is on: developing and demonstrating the phosphoric acid fuel cell in an urban transit bus as a near-term application (by 1995); developing the methanol-fueled, proton-exchange-membrane (PEM) fuel cell as a mid-term option for passenger vehicles; and providing fuel flexibility by developing advanced reformers (to convert hydrocarbon fuels to hydrogen for use by fuel cells) and by developing improved hydrogen storage systems for on-board vehicle use with fuel cells.

Of the fuel cell technologies, the phosphoric acid fuel cell is the only one suitably developed for transportation applications at this time. An urban transit bus was selected as the initial test vehicle because it can readily accommodate the packaging of the first generation fuel cell powered propulsion system. The development of a phosphoric acid fuel cell propulsion system for a small urban bus follows the schedule shown in Exhibit 2. This effort is co-sponsored by the Department of Transportation/Federal Transit Administration and California's South Coast Air Quality Management District.

In Phase I, two industrial teams demonstrated the feasibility of the concept by building and testing a laboratory brassboard power system half the size needed for the bus. Phase II of this project, a 25 percent cost-shared contract awarded by DOE to H-Power Corporation, includes fabrication and delivery of three 29-ft, 25-passenger urban buses, and the design for a full-size 40-ft urban bus. The first test bed bus will be delivered in October, with two more to follow in FY 1994. All of these vehicles will then be subjected to rigorous test and evaluation.

The proton-exchange-membrane (PEM) fuel cell, when fully developed, will offer significant advantages over the phosphoric acid fuel cell including reduced size and weight, faster start-up, and potentially lower cost. A fully integrated PEM fuel cell propulsion system will have the potential to meet the size and weight requirements for use in automobiles, vans, and light trucks. The schedule for the development of the PEM fuel cell for light-duty vehicles is shown in Exhibit 3. As the prime contractor for phase I, General

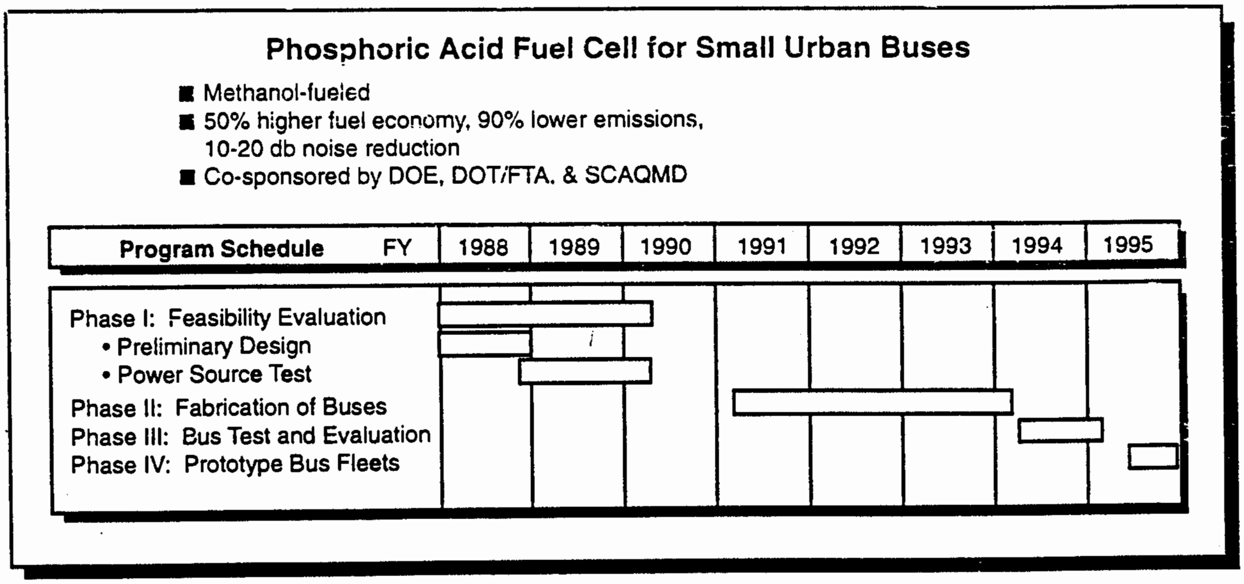


Exhibit 2. Phosphoric Acid Fuel Cell for Small Urban Buses

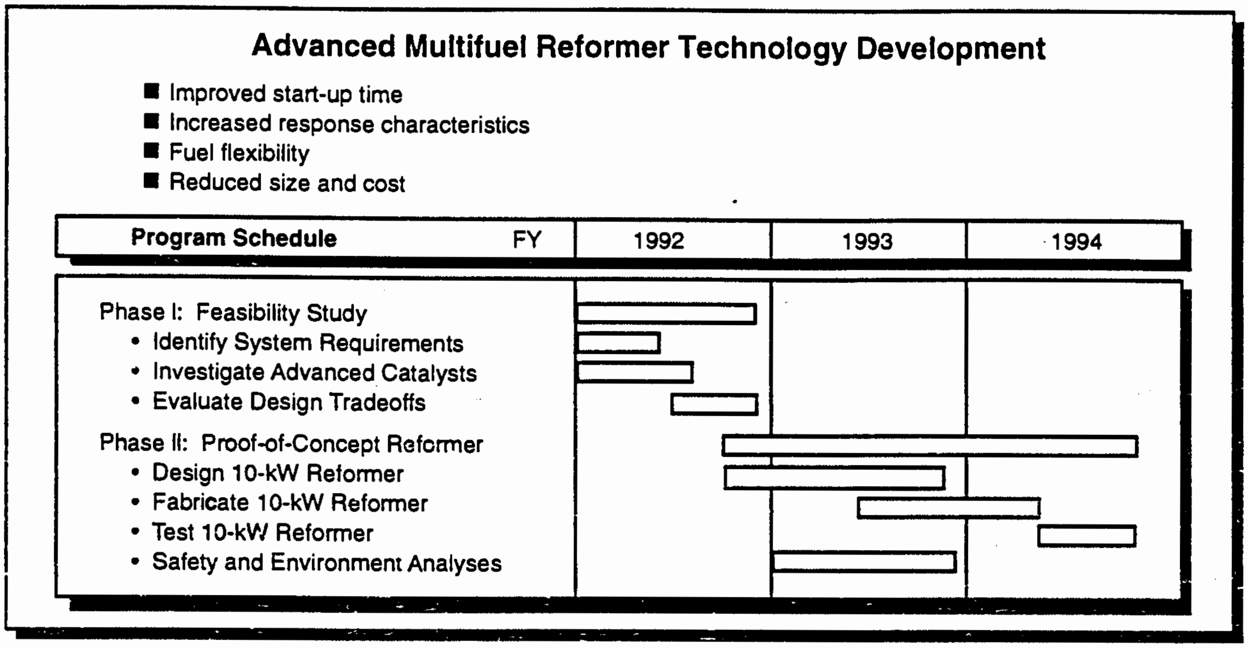
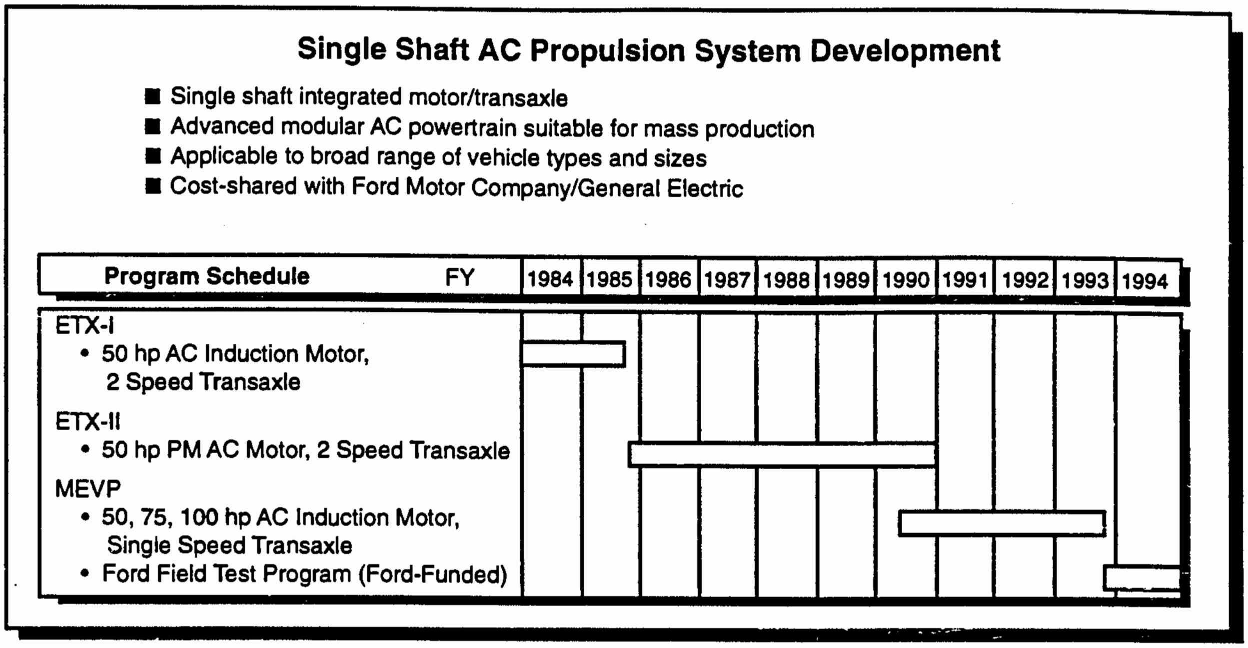


Exhibit 4. Advanced Multifuel Reformer Technology Development

<u>Propulsion Systems R&D</u>. Focus of this effort has been in the development of a modular electric vehicle propulsion system and a new initiative in FY 1993 for the development of a hybrid vehicle propulsion systems.

Through a series of projects conducted jointly with Ford Motor Company and General Electric since 1984 (see Exhibit 5), DOE has advanced the state of alternating current (AC) powertrain technology to the point at which it can provide the basis for competitive electric vehicles as soon as an adequate battery technology becomes available. A prototype advanced modular AC powertrain suitable for mass production has been developed (Exhibit 6) and project completion is expected in FY 1993 with the delivery of the prototype system in a test bed van to DOE for testing. Field testing of production modular AC powertrains will be performed and funded by Ford Motor Co. in FY 1994 and beyond.

The Hybrid Vehicle Program was recently initiated as a five-year, cost-shared cooperative program which will involve industry teams to develop and demonstrate hybrid/electric propulsion systems for light duty vehicles. These systems will satisfy EPA Tier II emissions standards, improve fuel economy by as much as 100 percent, and offer performance characteristics that are competitive with those of conventional vehicles in all other aspects. The systems will incorporate high-power batteries and heat engine technologies developed by DOE and industry programs. Industry teams have been identified by DOE through the competitive procurement process and as of August 1993, a contract with General Motors Corporation was signed September 30, 1993, negotiations on a second contract is underway. The schedule for the hybrid vehicle research and development program is shown in Exhibit 7.



Single Shaft AC Propulsion System Development

- Single shaft integrated motor/transaxle
- Advanced modular AC powertrain suitable for mass production
- Applicable to broad range of vehicle types and sizes
- Cost-shared with Ford Motor Company/General Electric

Exhibit 5. Single Shaft AC Propulsion System Development

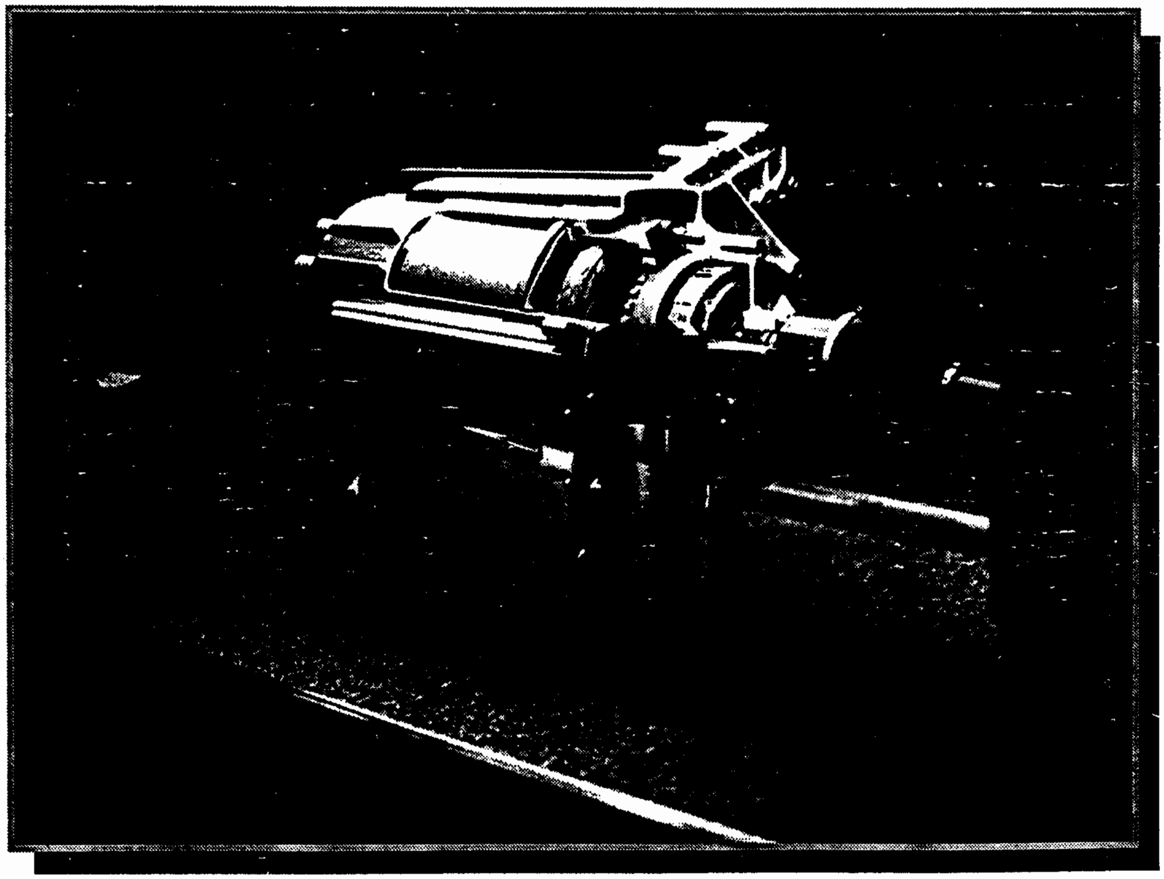


Exhibit 6. Prototype Modular Electric Vehicle Propulsion System

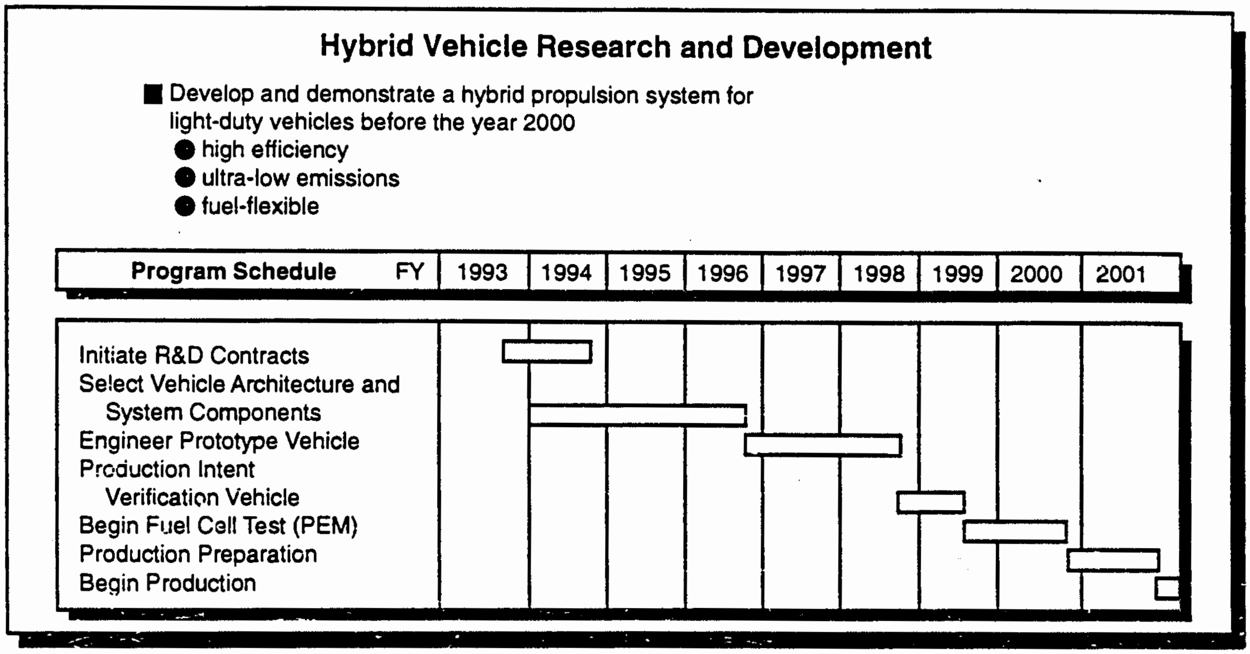


Exhibit 7. Hybrid Vehicle Research and Development

PROGRAM IMPLEMENTATION

The Electric and Hybrid Vehicle Program emphasizes the involvement of industry in the successful implementation of its research and development. Industry participation and input is solicited in the planning process to identify and review critical technical barriers and technology requirements. This involvement assures that the DOE program funds are directed to problems and issues industry deems a priority. The technical program focuses on the critical technologies identified through industry and government collaboration; the technical agenda is executed jointly between industry, national laboratories, and universities; and research activities are conducted through a cooperative endeavor involving industry, private research and development laboratories, universities, and federally funded laboratories. This cooperation affords considerable opportunity for interdisciplinary review of technology needs, definition of problems requiring solutions, and for ready transfer of research results to the technology users.

Exhibit 8 shows the level of coordination between the DOE Program and the private and public R&D for electric and hybrid vehicle program activities. In 1993, the Interagency Coordination Task Force on Electric and Hybrid Vehicle Technologies was organized to coordinate and integrate the programs and policies of Federal agencies involved in developing, testing, and promoting electric and hybrid vehicles and associated technologies. Over ten Federal agencies are currently represented on the Task Force, with DOE playing a coordinating role. The Task Force meets at least once every quarter to review and discuss the agencies' programs, progress, and opportunities for coordination.

CONCLUSION

DOE has ensured that its activities are focused and continue to focus on the technical issues that are critical in making electric and hybrid vehicles commercially viable by actively soliciting private sector input during the formulation of its research and development agenda. DOE also ensures that duplication of efforts is minimized by coordinating with other Federal agencies conducting similar activities in electric and hybrid vehicles technologies development. The experience of the DOE Electric and Hybrid Propulsion Systems Program in dealing with the U.S. Advanced Battery Consortium in developing a critical technology such as the advanced battery systems should also serve DOE well, especially in the recently announced partnership between government and industry to develop a new generation of vehicles.

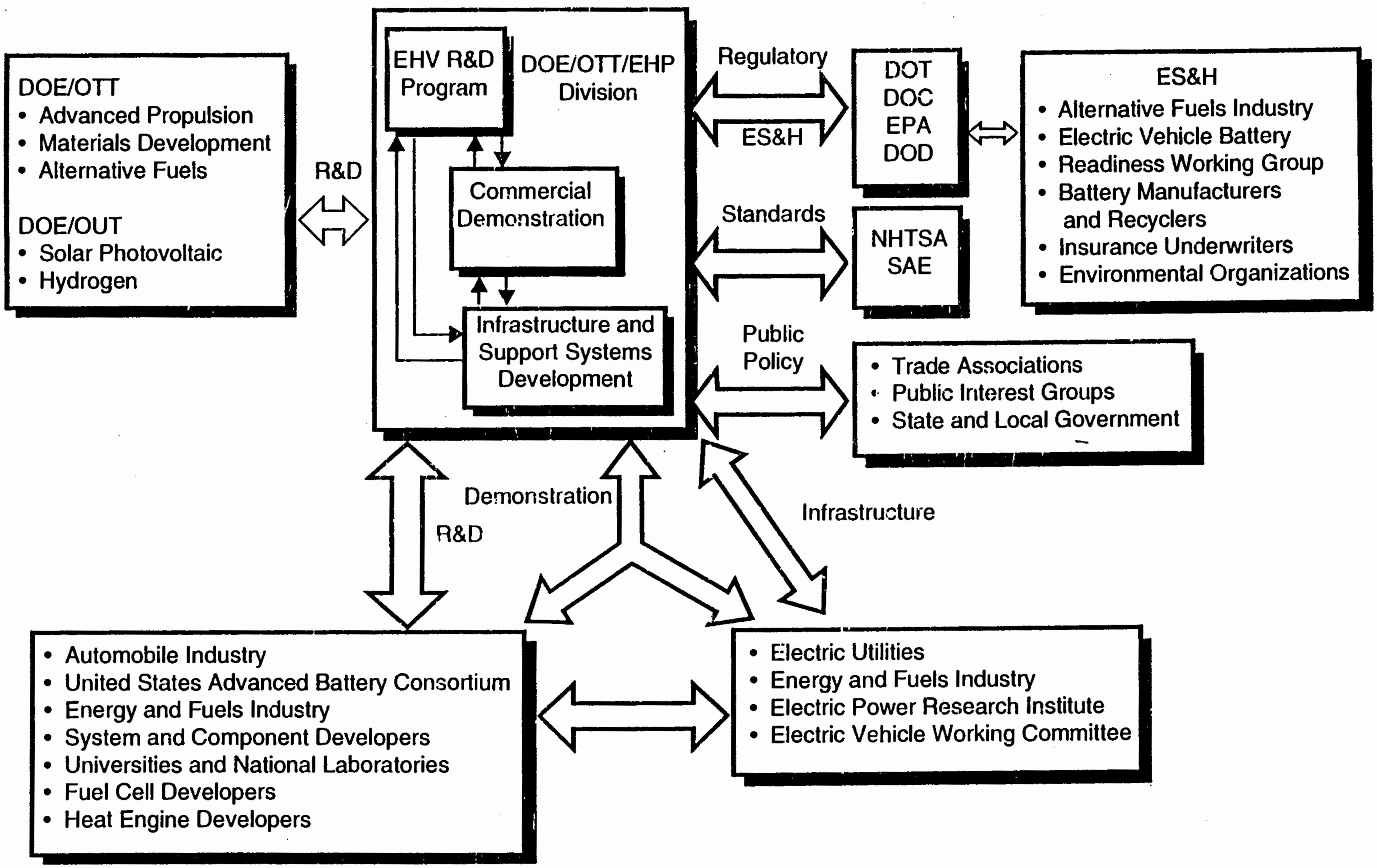


Exhibit 8. Federal and Non-Federal Coordination of DOE/EHP Program Activities

Technology Trends in Microcomputer Control of Electrical Machines

BIMAL K. BOSE, SENIOR MEMBER, IEEE

Abstract—Computer automation of factories, homes, and offices is ushering a new era of industrial revolution. Our automated factories, homes, and offices of the future will significantly advance our industrial civilization and profoundly influence the quality of human life on this planet. Microcomputer-based intelligent motion control systems which constitute the workhorses in the automated environment will play a significant role in the forthcoming era.

Electronic motion control technology has moved a long way since the introduction of power semiconductor devices in the mid-1950's. In course of its dynamic evolution during the last three decades, the area of motion control has grown as diverse interdisciplinary technology. The frontier of this technology has taken a new dimension with the advent of today's powerful microcomputers, VLSI circuits, power integrated circuits, and advanced computer-aided design (CAD) techniques.

The paper gives a comprehensive review of state-of-the-art motion control technology in which the salient technical features of electrical machines, power electronic circuits, microcomputer control, VLSI circuits, machine controls and computer-aided design techniques have been discussed, and wherever possible, appropriate trends of the technology have been indicated.

I. Introduction

MICROCOMPUTER-based intelligent motion control systems are playing a vital role in today's industrial automation. In an automated industrial environment, a hierarchical computer system makes decisions about actions based on a preset strategy, and a motion control system, as a workhorse, translates these decisions into mechanical action.

Today's motion control is an area of technology that embraces many diverse disciplines, such as electrical machines, power semiconductor devices, converter circuits, dedicated hardware signal electronics, control theory, and microcomputers (Fig. 1). More recently, the advent of VLSI/ULSI circuits and sophisticated computer-aided design techniques has added new dimensions to the technology. Each of the component disciplines is undergoing an evolutionary process, and is contributing to the total advancement of motion control technology. The motion control engineer today is indeed facing a challenge to keep abreast with this complex and ever-growing multidisciplinary technology.

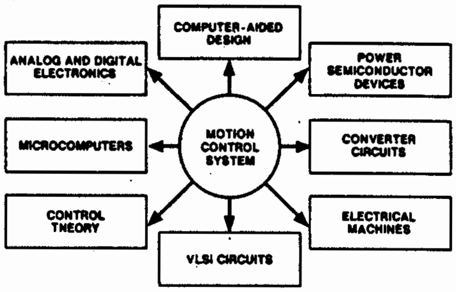


Fig. 1. Motion control system—An interdisciplinary technology.

Motion control is a new term defined by the present generation of engineers. It is an offspring of electrical machine drives technology, which has grown at a rapid pace over the last two decades. The era of electronic motion control essentially started with the advent of power semiconductor devices in the late 1950's, though hydraulic, pneumatic, and other mechanically driven actuation systems were known for a long time. Gradually, the use of integrated signal electronics simplified the electronic control hardware. The introduction of microcomputers in the early 1970's profoundly influenced motion control systems, not only by simplifying the control hardware, but by adding intelligence as well as diagnostic capability to the system.

We have seen an explosive growth in the application of motion control systems during recent years. Mechanical motion control systems found widespread acceptance in industry since the invention of the steam engine started the first industrial revolution in the eighteenth century, when mass industrial manufacturing replaced manual labor. Since then, the evolution of motion control engineering has been influenced by the development of electrical machines, vacuum tube electronics, gas tube electronics, saturable reactor magnetics, solid-state electronics, and control theory. The advent of computer technology and microelectronics during recent years has brought us to the doorstep of a second industrial revolution. Today, a tremendous momentum has developed for computer automation of our factories, homes, and offices. The principal motivation for this automation is improvement of productivity and and quality and minimization of less predictable human elements; and these motives in turn are being inspired by international competition. Computer-aided design (CAD) and computer-aided manufacturing (CAM) are playing increasingly important roles in factory automation. The concept of computer-integrated manufacturing (CIM), in which business decisions are translated to designs, which are then translated to manufacturing through a hierarchy of

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computers and motion control systems, will become a reality in the near future.

A motion control system, as mentioned before, is the workhorse through which higher level computer decisions are translated into mechanical actions. Motion control applications in industry include robots, numerically controlled machine tools, general-purpose industrial drives, computer peripherals, and instrument type drives. In the home, applications include home appliance drives for washers, dryers, air-conditioners, blenders, mixers, etc. In a typical computer-controlled manufacturing system on a factory floor, as illustrated in Fig. 2, there are three layers of control. The master control (usually a minicomputer) operates the entire network. It includes parts transportation and material handling on machine tools by robots. The direct numerical control (DNC) unit, usually a second minicomputer, collects programs for the microcomputers which directly control the machine tools. The computerized numerical control units (CNC), in addition, contain diagnostic programs that can detect mechanical and electronic malfunctions in a machine tool and report them to central controllers. The data entry units allow communication between the operator and the DNC computer.

In motion control systems, the application of robots is of significant interest today. The robot essentially symbolizes the challenge of synthesizing all state-of-the-art component technologies shown in Fig. 1. The modern industrial robot was introduced by Japan in 1980, and since then, it has evolved from performing simple tasks, such as handling and transferring, to performing sophisticated work including welding, painting, assembling, inspection, and adjustment. In Japan, the world leader in factory automation, almost two hundred thousand robots are in operation today. This is about 60 percent of all industrial robots in the world. One noticeable trend is the growth of robot use in non-manufacturing fields, for example, nuclear power generation, medical service and welfare, agriculture, construction, transport and warehousing, underwater work, and space exploration. More intelligent robots that will mimic the brain and muscles of human beings will be put to work in the future, for factory, home, or office automation.

The application of motion control has growth at a phenomenal rate in the computer peripheral industry. For example, in the U.S. alone, electronic printers, disk drives and tape drives used 24 million motors in 1983, and this figure is expected to rise to a staggering 80 million by the year 1988. It has been estimated that an average American home uses 50 motors in all the household appliances, and this amounts to a staggering 12.5 billion motors in all U.S. homes. Eventually, all these motors will be controlled by microcomputer. In an automated home of the future, all the motors will have a central home computer-based control through an integrated power-and-signal wiring system. Similar integrated motion control concepts will be applied to automobiles, airplanes, and so on.

This report is intended to review the technology trends of motion control that relate to electrical machines, power semiconductor devices, converter circuits, microcomputers, VLSI circuits, control of machines, and computer-aided control design techniques. Particular emphasis will be paid to intelligent motion control based on microcomputers. Again, motion control systems that use small machines will be our main theme of discussion. The literature on motion control has grown enormously, and proliferated so diversely that it is impossible to deal with all the aspects of the technology. Therefore, only the salient features will be highlighted.

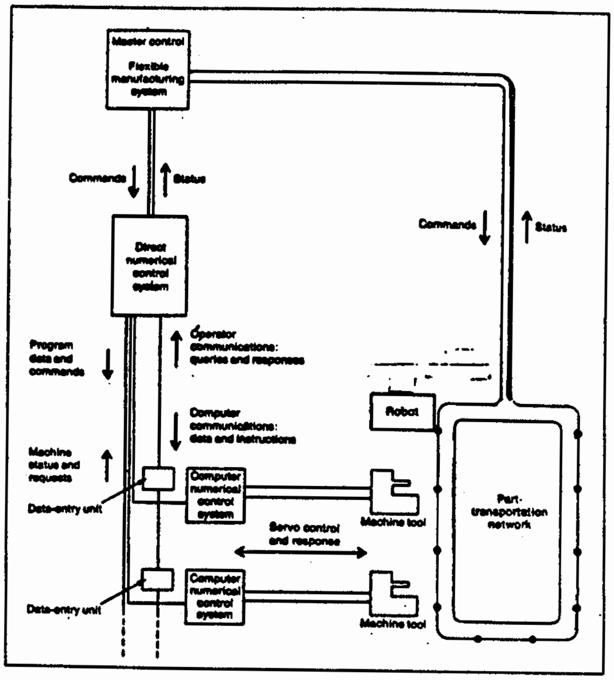

Fig. 2. Computer-controlled manufacturing system, showing interface with motion control systems.

II. ELECTRICAL MACHINES

An electrical machine is an electromagnetic energy conversion device that translates its input electrical energy into output mechanical motion. Electrical machines have been available for nearly a century,[1] and during this period the world's leading universities, research laboratories, and industries have made extensive studies of them. The evolution of machine technology, unlike that of electronics and computer science, has been long and slow, and we have not seen any dramatic invention in this area for a long time. The first machines were bulky, expensive, and had poor performance. Better understanding of machine principles coupled with evolution of new and improved materials has contributed to the improvement of machine design. The advent of modern digital computers and more recently the theory of finite element design have helped in further design optimization.

In motion control applications, the prime competitive candidates in electrical machines are dc machines, induction machines, synchronous machines (in brushless dc form), step motors, and switched reluctance machines. Recent literature on motion control has extensively discussed the behavior of these machines. To a unified machine analyst, the generic behavior of all the machines is the same. A dc machine is essentially an ac machine internally, where commutators and

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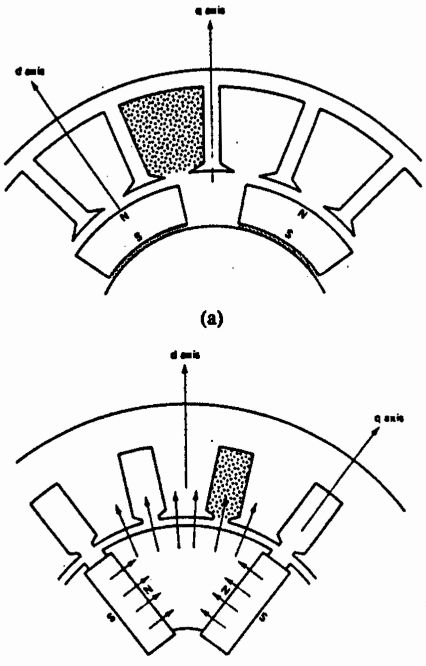
[1] This year the Polytechnic di Torino, Italy, is celebrating the hundredth anniversary of induction machines.

brushes function as elements of a position-sensitive mechanical inverter. Here, the orthogonal disposition of field mmf and armature mmf is the prime reason for enhanced speed of response. This type of machine has been traditionally favored in electronic motion control applications, and by far the majority of industrial drives today use this type of machine. Although its control principle and converter equipment are somewhat simple, a dc machine, in general, is bulky and expensive compared to ac machines. In addition, the principal problem of a dc machine is that its commutators and brushes make it less reliable, and unsuitable to operate in a dusty or explosive environment. A dc machine definitely needs periodic maintenance. High reliability and maintenance-free operation are prime considerations in industrial motion control systems.

For these reasons, we are beginning to see a tremendous surge in the application of ac machines in motion control systems. Historically, ac machines, such as the induction and synchronous types, have been favored for constant-speed applications. In the last two decades, ac motion control technology has grown by leaps and bounds. Traditionally, the induction machine, particularly the cage type, has been the workhorse in industry because of its ruggedness, reliability, efficiency, and low cost. Although ac machines are simple, the cost of conversion and control equipment is generally high, which makes the total drive system expensive.The scenario has been changing recently, however, because of the advent of the integrated converter and microcomputer-based controllers. One reason for the control complexity of an ac machine is its complex dynamic behavior, which must be taken into consideration in feedback control systems. An ac machine is basically a nonlinear multivariable system with coupling between direct and quadrature axes, and its dynamic model is usually specified by a state-space equation in a synchronously rotating reference frame.

An induction motor always operates at a lagging power factor because its rotor field excitation has to be supplied from the stator side. In a permanent magnet synchronous machine, however, the field is established by the magnets. The stator will supply reactive current only (leading or lagging), if mismatch between supply voltage and induced voltage demands it. The concept of a brushless or commutatorless dc motor using a synchronous machine was developed by Ohno *et al.* [8]. A dc machine is a synchronous machine internally with magnets on the stator and armature on the rotor (commutators and brushes serve as the rotor position commutated inverter, as mentioned before). The same operation mode is possible if magnetics are transferred to the rotor, and the stator which contains the armature winding is supplied with ac power through an electronic inverter. The inverter commutation or gating signals must now be derived from a rotor position encoder to maintain absolute synchronism between magnet fluxes and stator winding induced fluxes. The reward of eliminating mechanical commutators and brushes is offset to some extent by the penalty of an absolute position encoder in the rotor and an expensive electronic inverter with the complex control. Besides in this new configuration, a dc machine-like transient response may not be straightforward.



(a)

(b)

Fig. 3. Profile of permanent magnet machines. (a) Surface magnet machine. (b) Interior magnet machine.

It is important to mention that PM machines have essentially two different configurations. The conventional surface magnet machine (Fig. 3(a)) is essentially nonsalient (it has a large airgap) and is popularly used in a brushless drive. The large airgap again weakens the armature reaction effect, and therefore the operation is essentially restricted to a constant torque region. Recently, synchronously machines have been introduced with interior or buried magnets (Fig. 3(b)), which, because of their narrow airgap, overcome the above drawback of surface magnet machines. A buried magnet machine is essentially a hybrid machine in which torque is contributed by the reluctance component as well as the field component. The evolution of magnet materials is contributing to the size reduction of PM machines. Fig. 4 shows characteristics of several viable magnet materials. Ferrite material, which is low in cost and has excellent demagnetization linearity, is traditionally used in PM machines, but the machine tends to be bulky because of low remanence. Cobalt-samarium has a higher energy product and excellent temperature insensitivity, but its high cost restricts its use for specialized applications. The neodymium–iron–boron magnet, which has been introduced only recently (June 1983), has maximum remanence and coercive force force, and because of its reasonably low cost, shows great promise for future applications. This material, however, has some temperature sensitivity which must be taken into consideration during machine design.

In incremental motion control applications, the most widely used class of machines is step motors. While the machines discussed so far are characterized by continuous motion, step motors are characterized by discrete steps of motion and respond directly to digital command pulses. Step motors have been available for nearly half a century, but much attention has been focused on them recently because of the surge of

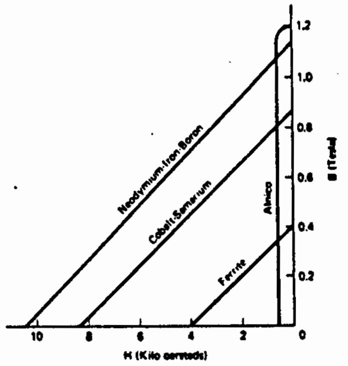
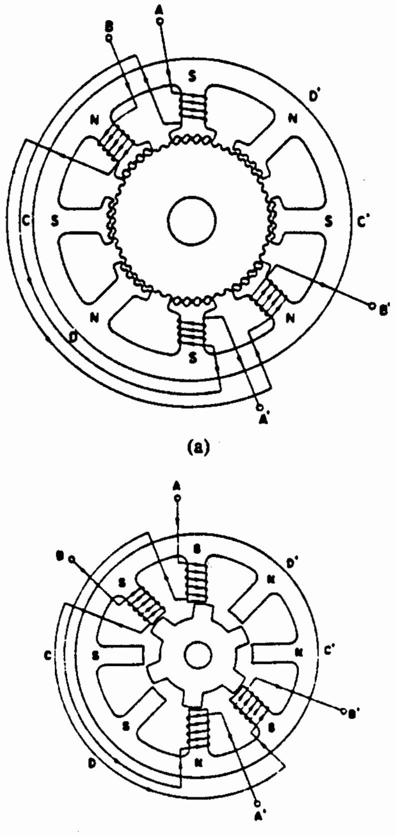


Fig. 4. Permanent magnet characteristics.

applications in the incremental motion control industry. Basically, step motors have characteristics similar to synchronous machines and are constructed in PM hybrid form or variable reluctance form. An example of a variable reluctance step motor with 1.8° step movement is shown in Fig. 5(a). A step movement of the rotor corresponds to the effective angular rotation of stator poles created by the stator winding mmf's. The inherently simple and economical construction of this "brushless" machine coupled with its simple open-loop control makes it extremely popular in the motion control industry. However, a number of performance penalties must be paid for these good features. Besides limited angle resolution, the open-loop synchronous machine-like operation gives load-dependent position accuracy, underdamped step response, high loss, and a tendency to lose synchronism as speed is increased. However, these characteristics are not limitations in application such as printer and disk drives and remote indicators, where these machines are most popularly used. As the market for motion control systems grew, the proponents of step motors came out with sophisticated controls using position encoder signals to solve some of the above problems. With these modifications, however, the appeal of inherent simplicity and economy is lost, and the margin of difference between step motor drive and brushless dc drive is narrowed. In summary, the points in favor of the closed-loop controlled step motor in comparison with the brushless dc motor include the following.

1) Below a few hundred watts of power, a PM step motor is cheaper than a PM synchronous motor, mainly because the former needs only one magnet, whereas the latter needs four (four poles).
2) A large holding torque and a high stiffness near the detent position are inherent in a step motor, whereas in the brushless dc motor the feedback mechanism (which may be sluggish) is responsible for establishing the above parameters.
3) A step motor requires a simple incremental position encoder, whereas a brushless motor needs an absolute position encoder.

The switched reluctance machine (SRM), the principle of which has been known for over a century, has seen a revival of interest in recent years for small-machine drives. Basically, the SRM is a variable-reluctance, continuous-movement machine (Fig. 5(b)), which is structurally identical to the single-stack, reluctance-type step motor. In this machine, continuous movement is regulated by current magnitude control and rotor synchronized commutation of stator phases, where commutation signals are derived from an absolute position encoder. The control is analogous to that of a concentrated winding brushless dc machine, and speed can be smoothly increased beyond the constant torque region. One drawback of this machine is its large pulsating torque, which makes it difficult to apply in position servo drives. Pulsating torque compensation has been proposed through such schemes as pole shaping, current command profiling and adaptive feedback control, and these show good promise.



(a)

(b)

Fig. 5. Profiles of step and switched reluctance machines. (a) Variable reluctance single stack step motor (1.8° step). (b) Switched reluctance machine.

III. Power Converters

An electronic power converter translates the control signal at the input to the power actuation signal for the machine. The modern era of electronic motion control technology came into existence because of the advent of power semiconductor devices. These devices have grown in power rating and performance by an evolutionary process in the last two and a half decades. The improvement of device model, computer-aided simulation and design techniques, and semiconductor processing improvement have contributed to performance enhancement. Silicon is the principal material and will remain so in the foreseeable future. Phase-control thyristors were first introduced in the late 1950s; they found ready acceptance in rectifier controlled dc machine drives and variable-voltage constant-frequency controlled induction machine drives. The devices that are primarily important for small machine control applications are power transistors and power MOSFET's.

Bipolar Darlington transistors have been established as power switching devices for the high end of motion control converters. Second breakdown effects were the prime killers of power transistors for a long time. Today, these phenomena are understood better, and devices and circuits are being designed for better reliability and higher utilization factor.

Power MOSFET devices were introduced in the late 1970's, and these devices have found a tremendous growth of applications in converters up to several hundred watts. This frontier is expanding with the introduction of higher power devices in the market. Unlike the bipolar transistor, the MOSFET is a majority voltage-controlled device. Its second breakdown effect is minimal. One great demerit of the MOSFET is its high conduction drop; this drop increases with higher voltage rating and operating temperature. The on-resistance of the device has been improved over the last several years, but there seems to be a fundamental limit for silicon. While the conduction loss of the MOS device is high, its switching loss is almost negligible. In sinusoidal-output inverter applications, the PWM frequency can be extended to a high value so that conduction loss is offset by an improvement of the machine harmonic loss.

Very recently, we have seen the emergence of several hybrid power semiconductor devices. An example is the insulated-gate transistor (IGT), which is also known as the GEMFET or COMFET. It is essentially a MOSFET-driven bipolar transistor, and, therefore, combines the advantages of both the devices. It has the high input impedance of the MOSFET but the low conduction drop of the bipolar device. The switching speed is slow because the minority carrier storage and the second breakdown effect of the bipolar device are retained. The device has thyristor-like reverse voltage blocking capability. IGT's have been introduced in the 500-V 50-A range, and soon this range will be extended. Another hybrid device worth mentioning is the MOS-controlled thyristor. The device, as the name indicates, is designed in such a way that a MOSFET can control the turn-on and turn-off operations of a thyristor.

The converter in a motion control system is expensive, primarily because of the high cost of discrete power devices. The bulk of device cost is due to packaging complexity. The trend toward integration in low power signal electronics is being applied to power circuits also. Hybrid integration of half-bridge of full-bridge converters with or without control electronics has been available for some time. A more significant change is in monolithic integration of power circuits with embedded signal electronics. Such a circuit not only reduces cost and size, but eliminates EMI and interface problems. Further, integration of power devices and control electronics is so-called "smart" power devices brings in easily the additional functions, such as temperature control and overvoltage and overcurrent protections. This would not be possible with discrete power devices. The principal technical hurdles in this area are isolation between high-voltage devices and low-voltage circuits, and efficient thermal management. The birth of power integrated circuit (PIC) technology has brought us to the doorstep of what we call the "second electronic revolution." The first electronic revolution started with the integration of small signal electronics. Power IC's are already appearing in the low end of motion control applications. Eventually, as the technology advances, these will appear in our home appliances, automobiles, robots, and other factory floor drives. Researchers in this area are optimistic that eventually PIC's will incorporate sensing signal processing, and will directly interface speed and position encoders. Hall sensors, temperature sensors, and so on. If sensing, power control, and signal processing can be combined, a standalone, single-chip system that will interface with a central microcomputer can be constructed, and mounted on the drive machine directly.

Computer-aided power circuit design techniques have evolved over a number of years. Compared to trial-and-error design with the help of a breadboard, computer-based design systems are very convenient for design optimization. Because of its switching elements, a converter is essentially a discrete time system. Therefore, it can be simulated on a digital computer as a time-varying network topology, i.e., in each switching state of a converter, a linear state-space equation can be described and solved by Fortran-like programs. Alternately, the network can be described as a graph by nodes and branches, and programs such as SPICE II (University of California, Berkeley) can be used. CAD techniques for signal electronics (both logic and analog) and control systems have reached a stage of maturity, and therefore the problem of how to integrate various design and simulation tools of an integrated power system remains. Fig. 6 illustrates a CAD of a converter circuit with conversions and links to the various programs [18]. In the beginning, the user defines a circuit schematic from given specifications and requirements by preliminary analysis and design. The P-CAD (Personal CAD Systems Inc.) programs capture the schematic, extract the netlist, and produce the SPICE input file. The SPICE-NIP translator converts the SPICE input file into the NIP (nodal description input program—California Institute of Technology) input file. The function of NIP is to generate (from a nodal description input file) the state-space equations, output equations, and feedback/feedforward equations associated with linear switched networks that a converter goes through in each switching cycle. The SCAP (switching converter analysis program—California Institute of Technology) program generates a state-space-averaged model of the converter that can be used to study steady-state and frequency-response behaviors. SIMNON (nonlinear simulation program—Lund Institute of Technology, Sweden) accepts the state-space equations from NIP through a translator and permits the simulation of time domain behavior SIMNON will be further discussed in Section VI. After optimizing the converter design with several iterations, the program can be integrated with controller simulation and/or used to generate the layout of a power integrated circuit.

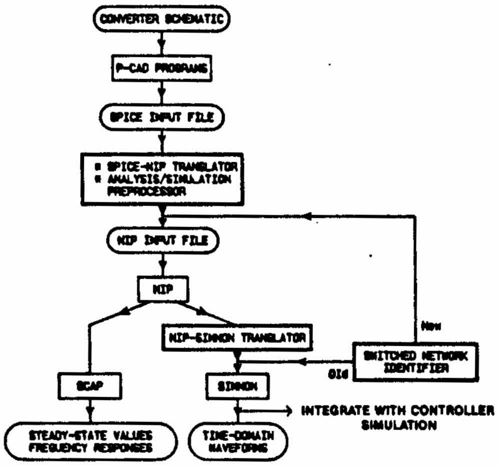


Fig. 6. CAD of a converter from a schematic entry.

IV. Control of Electrical Machines

The advent of gas tubes, such as thyratrons and ignitrons in the 1930's, and then, magnetic amplifier or saturable devices in the 1940's gave birth to the first generation of motion control systems using dc machines. Advancement of feedback control theory in post World War II years intensified evolution of the technology, but modern motion control technology was truly born with the advent of power semiconductor devices. In a feedback control system, the machine as well as the converter are elements in feedback loops, and therefore their dynamic models should be taken into consideration. A dc machine, particularly a small machine with a permanent magnet field, can be modeled as a linear second-order system between applied armature voltage and speed-neglecting armature reaction, saturation, temperature, and brush nonlinearity. However, a converter-machine system with digital control is a discrete time system because of the sampling effect. It is convenient to analyze, simulate, and design such a system on a computer.

Control of a dc machine is considerably simpler than that of an ac machine. A dc machine can be interfaced with utility ac supply through a phase-controlled converter, and the output (speed, position, or torque) can be regulated by controlling the converter firing angle. A universal motor can be controlled by anti-parallel thyristors or triac devices. A high-performance dc servo, in which dc power is obtained from a rectified ac supply or from a battery and then controlled by a pulsewidth modulated chopper, is shown in Fig. 7. The addition of inner current control (which is indirectly torque control) and speed control loops not only expand the system bandwidth but help in limiting the excursion of the state variables.

Control of an ac machine with a feedback loop is considerably more complex, and this complexity increases as higher performances are demanded. The main reason for this complexity is that ac machine dynamics are more complex; they must be represented by nonlinear multivariable state-space equations. For example, an induction motor model can be represented by a sixth-order state-space equation, where voltage and frequency are inputs to the stator and the outputs may be speed, position, torque, flux stator currents, or a combination of them. The additional reasons for complexity in ac drives are intricate feedback signal processing and the requirement for complex control of the variable-frequency power supply.

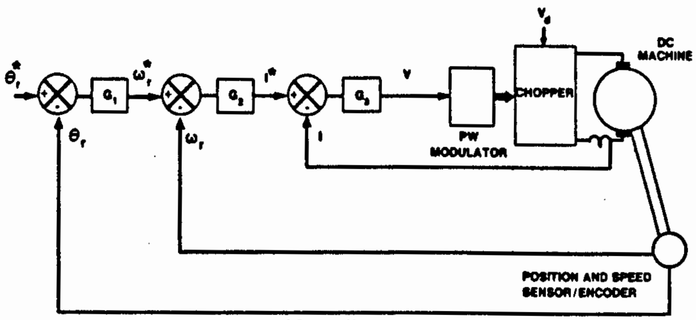
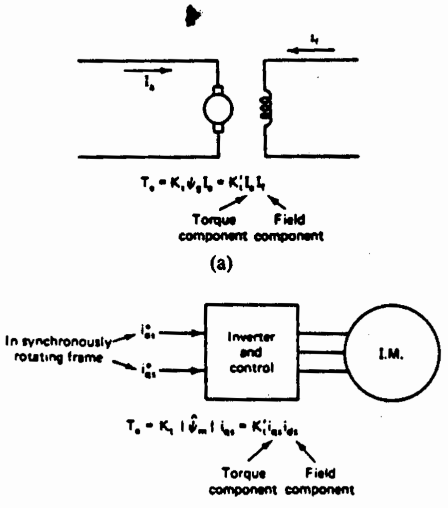


Fig. 7. Control block diagram of a dc machine.

Many different control techniques of varying degrees of complexity have appeared in the evolution of ac drives. The acceptance of a particular method depends on the nature of the application. A simple and economical method of control of an induction motor is to vary the stator voltage at utility frequency through a phase-controlled anti-parallel thyristor or a triac converter. Such a scheme, though inefficient, is used in blower and appliance drives. A simple open-loop volts/Hz control method has been popularly used for a long time. It will continue to be used in the future for low-performance, low-power, and cost-effective industrial drives. Feedback flux control, torque control, slip control, angle control, etc., have been used extensively where better performance is demanded. The penalty in such feedback controls is the difficulty of feedback signals synthesis using distorted ac voltage and current waves. Problems arise in such a "scalar" control method, because of the nonlinearity of the machine model and the inherent coupling effect between the direct (d) and quadrature (q) axes. The poles and zeros of machine transfer functions vary at each operating point. The control can be optimized at a certain operating point, but the performance will deteriorate if the operating point shifts. Besides, the coupling effect causes sluggish transient response.

The field oriented or vector control techniques are now being accepted almost universally for control of ac machines. Such control methods were developed in Germany in the early 1970's. Blaschke [21] introduced the direct or feedback method of vector control and Hasse [22] invented the indirect or feedforward method. But the world ignored these techniques because of the complexity of their implementation. With the advent of the microcomputer era, such control complexity is no longer a problem.

The vector or decoupling control considers the generic analogy between ac and dc machines (Fig. 8). The underlying principle of vector control is to eliminate the coupling problem between the *d* and *q* axes; then an ac machine will behave like a separately excited dc machine. The fundamentals of vector control implementation with the machine model in a synchronously rotating reference frame are explained in Fig. 9. The phase and coordinate transformations within the machine are cancelled by two stages of inverse transformation in the control so that i_{ds}^* and i_{qs}^* currents correspond to i_{ds} and i_{qs},



(a)

(b)

Fig. 8. DC machine and induction motor analogy in vector control.

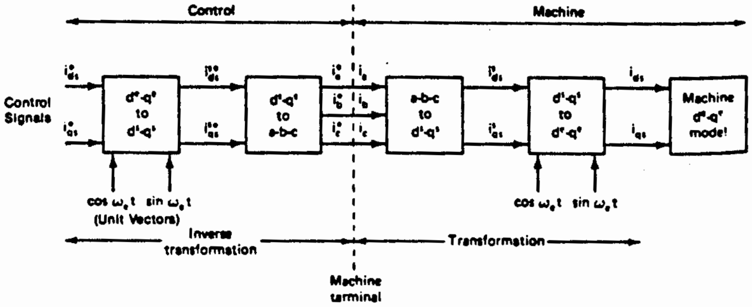


Fig. 9. Vector control implementation technique with d^e-q^e machine model.

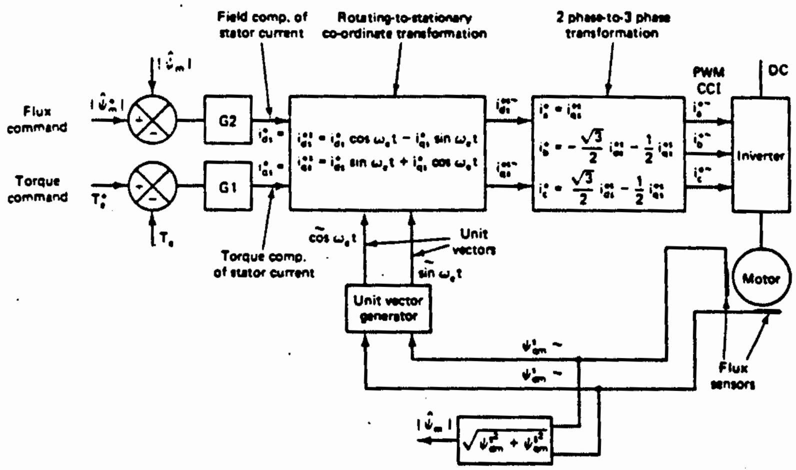


Fig. 10. Direct or feedback method of vector control of induction motor.

respectively. The converter dynamics and sampling delays are omitted for simplicity. The unit vectors cos $\omega_e t$ and sin $\omega_e t$ assume alignment of i_{ds} (field component) with the flux and i_{qs} (torque component) orthogonal to it, in order to have dc machine-like decoupling. The vector control not only gives the advantage of fast transient response, but also eliminates the conventional stability limit of the induction motor. The torque relation becomes linear with i_{qs}, and the drive can be easily designed for four-quadrant operation. Of course, the price to be paid for all the benefits is complex coordinate transformation, phase conversion, and intricate feedback signal processing.

Blaschke's direct method for a PWM voltage-fed inverter with current control is illustrated in Fig. 10. The principal control parameters i_{ds}^* and i_{qs}^*, which are dc quantities, are converted to a stationary reference frame with the help of unit vectors as shown. These are then converted to phase current commands for the inverter. The unit vectors are generated from d and q components of airgap flux with the help of the phase-locked loop so that cos $\omega_e t$ and sin $\omega_e t$ are cophasal to

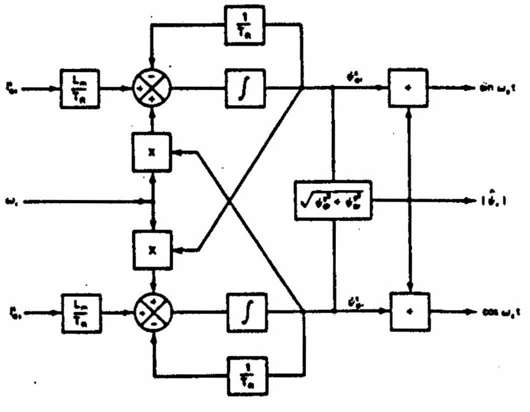
ψ^s_{dm}, and ψ^s_{qm}, respectively. The flux components can be measured directly by Hall-effect sensors or flux coils, or can be estimated from stator voltage and current signals with the help of a partial observer. Blaschke has shown that rotor fluxes instead of airgap fluxes, as shown in Fig. 10, should be used in order to avoid undesirable stability problems. It is possible to reconstruct rotor fluxes from airgap fluxes with the help of stator currents.

The direct method of vector control as discussed above can operate typically above 10 percent of the base speed, because of the difficulty in accurate flux signal synthesis at low speed. In fact, the flux signal obtained by direct integration of stator voltages can be used only in a higher speed range. The resulting coupling effect, although small at higher speed, may become significant as the speed is reduced. In applications such as servo drives, the drive system must operate at truly zero speed with best possible transient response. The accurate stator drop compensation near zero speed is very difficult. Blaschke derived flux estimation equations which use speed and stator current signals. These equations are valid at any speed (including zero speed), and can be given as follows:

$$\frac{d\psi^s_{qr}}{dt}=\frac{L_m}{T_R}i^s_{qs}+\omega_r\psi^s_{dr}-\frac{1}{T_R}\psi^s_{qr} \tag{1}$$

$$\frac{d\psi^s_{dr}}{dt}=\frac{L_m}{T_R}i^s_{ds}+\omega_r\psi^s_{qr}-\frac{1}{T_R}\psi^s_{dr} \tag{2}$$

where $T_R = L_r/R_r$ is the rotor circuit time constant, and all other parameters are in standard symbols. The estimation block diagram for unit vectors and rotor flux from these equations is shown in Fig. 11. Note that the estimation is machine parameter dependent; the rotor resistance variation due to temperature and skin effect, and the inductance variation due to saturation, are all important.



$$\frac{d\psi_{qr}^s}{dt}=\frac{L_m}{T_R}i_{qs}^s+\omega_r\psi_{dr}^s-\frac{1}{T_R}\psi_{qr}^s$$

$$\frac{d\psi_{dr}^s}{dt}=\frac{L_m}{T_R}i_{ds}^s+\omega_r\psi_{qr}^s-\frac{1}{T_R}\psi_{dr}^s$$

Fig. 11. Unit vectors and rotor flux estimation from speed and stator currents.

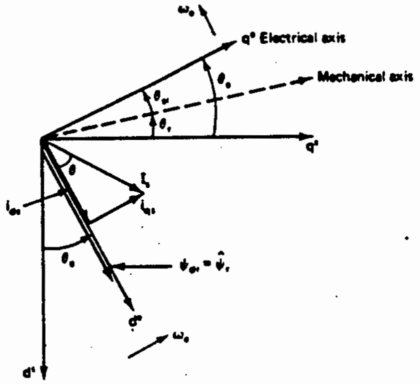


Fig. 12. Phasor diagram for indirect vector control.

Hasse's method generates unit vectors indirectly from rotor position and feedforward slip signal, the control method otherwise remaining the same as before. Fig. 12 explains the indirect vector control principle with the help of a phasor diagram, and Fig. 13 shows a position servo implementation using this method. In order to satisfy the criteria of decoupling control, the following equations can be established from the rotation frame equivalent circuit [1]:

$$\omega_{sl}=\frac{L_mR_r}{L_r|\hat\psi_r|}i_{qs} \tag{3}$$

$$\frac{L_r}{R_r}\frac{d\hat\psi_r}{dt}+\hat\psi_r=L_m i_{ds}. \tag{4}$$

In Fig. 13, the i^*_{ds} signal for the desired rotor flux $\hat\psi_r$ is determined from (4). The i^*_{qs} signal, which is proportional to torque, is derived from the speed control loop. The set value of slip ω_{sl} is related to current i_{qs} by (3). The slip angle vectors sin θ_{sl} and cos θ^*_{sl}, which determine the desired electrical axis with respect to rotor mechanical axis, are generated from i^*_{qs} in a feedforward manner. The rotor position vectors are then added with the slip angle vectors to generate the desired unit vectors for coordinate transformation. Since induction motors can locate the field flux at any position, an absolute shaft position encoder is not needed. In fact, the rotor speed can be added directly with the slip signal, and then unit vectors can be synthesized by a VCO, counter, and SIN/COS waveform generator. Both the indirect method and the direct method are dependent on machine parameters. The dominant parameter to be considered is rotor resistance, which has been estimated on-line by various techniques giving improved performance in decoupling control. Fig. 13 can be modified to incorporate control in the field-weakening region as shown in Fig. 14. Below base speed, the machine operates at constant flux, and, therefore, operation is identical to that in Fig. 13. Above base speed, $|\hat\psi_r|$ is weakened to be inversely proportional to speed so that the drive system remains under the vector control mode. Note that here flux is controlled in an open-loop manner by solving (4).

Control of synchronous machine drives is, in many ways, similar to control machine drives. Synchronous machines may have essentially two different modes of operation. One is the open-loop true synchronous machine mode, where a simple volts per hertz method of control locks the machine speed with

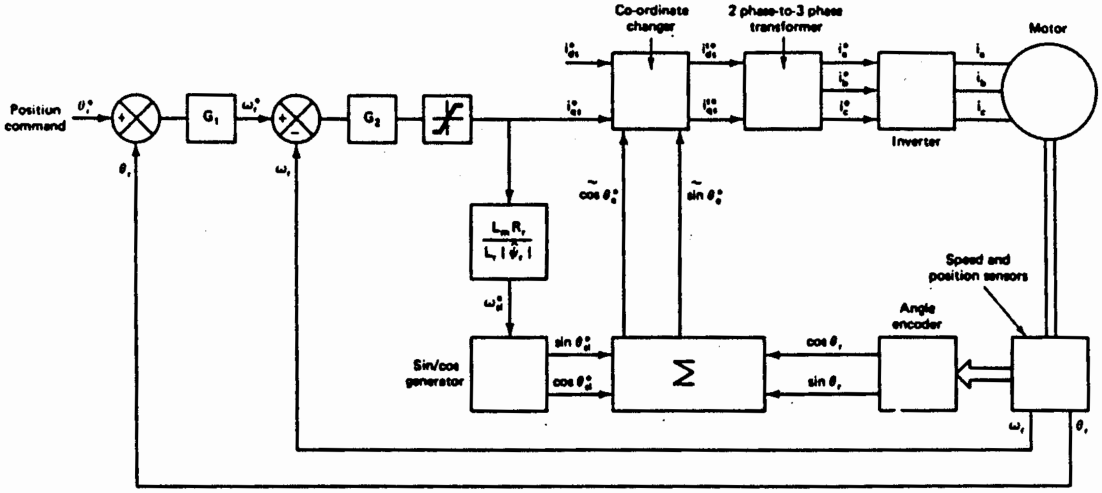


Fig. 13. Induction motor position servo using indirect or feedforward method of vector control.

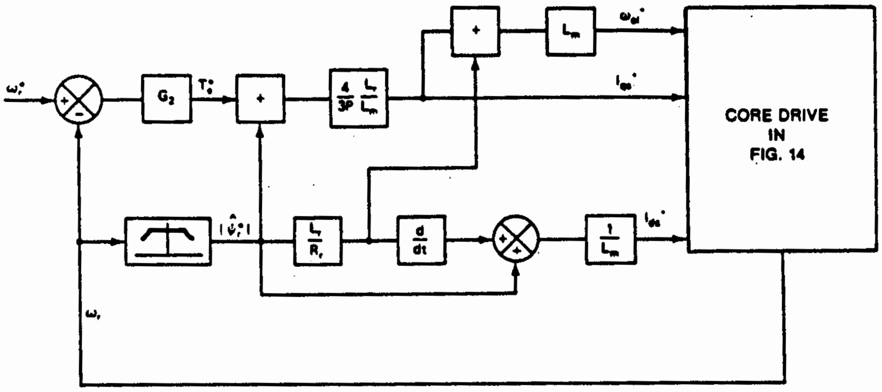


Fig. 14. Indirect vector control principle in field weakening constant power region.

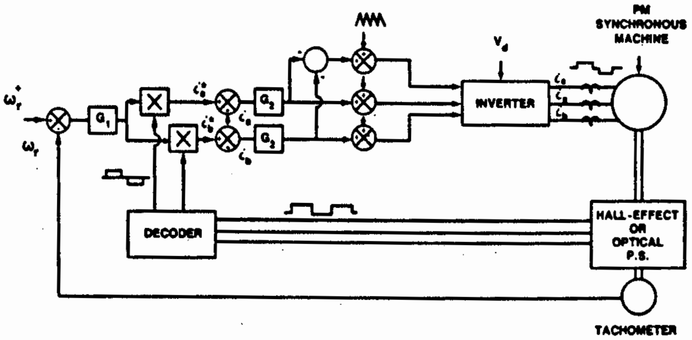


Fig. 15. Control scheme of trapezoidally wound PM (surface) machine in brushless dc motor mode.

the frequency of an independent oscillator. This method of speed control is popular in multiple reluctance or PM machine drives where close speed tracking is essential in such applications as a fiber-spinning mill. The other is the self-control mode, in which variable-frequency inverter control pulses are derived from an absolute position encoder. A self-controlled machine, as mentioned before, is known as an electronically commutated motor (ECM), brushless dc motor (BLM), or commutatorless brushless motor (CLM).

Fig. 15 shows a control scheme of a brushless dc drive using a trapezoidally wound surface-type PM machine. Since the induced phase voltages of the machine are trapezoidal in shape, it can be shown that a six-step line current wave in phase with the induced voltage wave will maintain constant developed torque. A Hall-effect or optical encoder properly aligned on the shaft with respect to rotor poles generates three-phase, 180° square pulses, which are shaped to six-step waves by a decoder as shown. The speed loop generates the current magnitude command, which is multiplied by the decoder output to generate phase current command waves. The current control loop generates the voltage command, which is pulse-width modulated (PWM) by a fixed frequency triangular carrier wave. The simplicity of the machine, the position sensor, and the control electronics makes this type of brushless drive very popular in industrial motion control systems. However, the drive has a pulsating torque problem because of the mismatch of current switching instants and the machine counter emf wave. Besides, an extra tachometer is needed for a speed control system as shown in the figure.

For a sinusoidally wound PM machine, the inverter can synthesize sine wave line current, and then the pulsating torque problem does not arise. Since in a surface magnet machine the armature reaction effect is very weak, the stator current phasor can be positioned orthogonal to the magnet flux

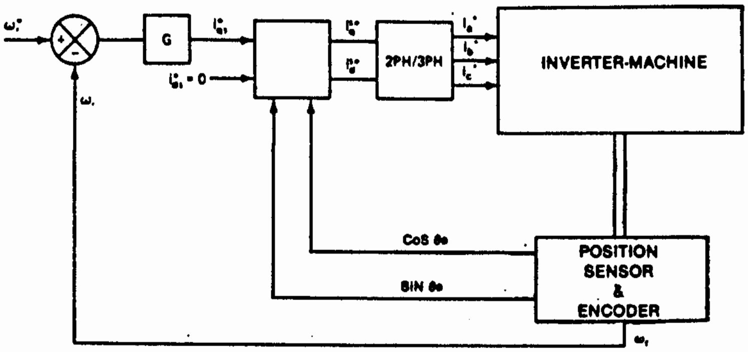


Fig. 16. Vector control scheme of sinusoidal PM (surface) machine in brushless dc motor mode.

(i.e., in phase with counter emf) with the help of an absolute position sensor. Such a decoupling or vector control method, as discussed before, will give true dc machine-like response from a sinusoidal brushless dc motor. Fig. 16 shows a speed control system using such a control scheme. This scheme can be derived from the induction motor vector control method shown in Fig. 13 with the modifications $\omega_{sl} = 0$, $\theta_r = \theta_e$, and $i_{ds}^* = 0$. Since the rotor establishes the airgap flux, the stator need not supply any reactive current. Generally, an expensive position resolver is required in such a control scheme. If a resolver/digital converter is used with an analog resolver, then its outputs can be used not only for vector transformation, (i.e., commutation), but for speed and position control loops as well.

A simple open-loop step motor control scheme (Fig. 17) consists of sequence logic, a power converter and the machine. The sequence logic receives a step input pulse train and direction signal from the host controller, and these are then translated into sequential drive signals to the converter such that the machine stator poles advance by a step in response to a step input pulse. With a step input of constant frequency, the machine runs in the specified direction with the corresponding number of steps per second. In such a "time-dependent commutation" (unlike the position-dependent commutation in a brushless dc machine), the step motor behaves as a synchronous motor, and, therefore, oscillatory response and loss of synchronism are possible, as indicated before. There is also a possibility that the machine may miss step pulses. These disadvantages can be eliminated by a closed-loop control using an incremental position encoder (Fig. 17). Adding the complexity of closed-loop control, step motors have been used for more accurate position control, much higher and smoother speed, and greater versatility in many other aspects. A commonly used closed-loop control, where the phase switching angle is rotor-position-synchronized with advance angle excitation as a function of speed, is shown in Fig. 17. Schemes have been proposed in which rotor position is estimated by observer techniques.

It was indicated before that the switched reluctance machine (SRM) is nothing but a variable reluctance step motor with different controls. An SRM is a continuously controlled machine in which holding torque is established by feedback method. An absolute position encoder is essential for an SRM to provide rotor position synchronized excitation to the stator windings. Fig. 18 shows an SRM position servo with an inner speed control loop. An inner high bandwidth torque loop can be provided to compensate pulsating torque at low speed. An absolute position encoder generates commutating signals for converter switches. The machine operates with full performance in all four quadrants. In the forward motoring mode, the stator phases are turned on at an advance angle (θ_0) with respect to positive inductance slope so that full active stator current can be established. The torque is then controlled by chopping the level of current I. Beyond the constant torque region, chopping control is lost, and then turn-off angles can be controlled in the constant power region.

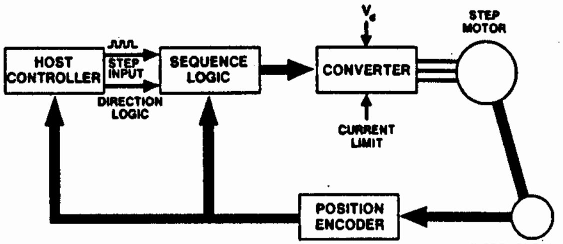


Fig. 17. Step motor control system.

There has been a recent interest in applying modern control theories to motion control systems. The theories have been advanced since the 1960's, but in general, they have not found practical applications. They were initially applied to aerospace systems and general process control applications, but the advent of inexpensive and powerful microcomputers has made it possible to apply them to time-critical motion control systems as well. Although dc drives are receiving most of the attention, ac drives are being considered as well. Applying modern control theory to motion control systems in general is difficult because of large time-critical computation requirements.

Optimal control theory, such as Pontryagin's minimum principle, or the dynamic programming technique, which is based on extensive iterative computation, can be generally applied to a single optimal profile of the drive system. The optimal precomputed profile can be generated, for example, on the basis of minimum time of transit or minimum energy consumption subjected to a number of control constraints. Such optimal control principles are extremely difficult to apply in general motion control systems.

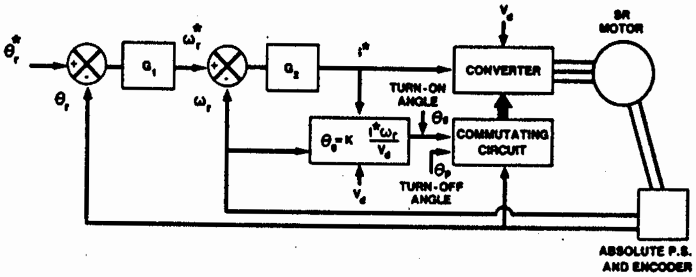


Fig. 18. Position servo using switched reluctance machine.

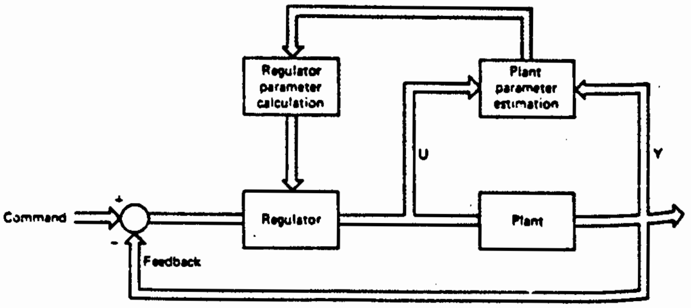


Fig. 19. Self-tuning regulation of drive system based on on-line parameter estimation.

The applications of adaptive control theories, still just beginning, are growing at a rapid pace. They are extremely useful in systems such as robots and machine tool drives, where the system has to be robust, on insensitive to parameter variations. A conventional PI (proportional-integral) or PID (proportional-integral-derivative) controller with fixed parameters cannot generate optimal response in a plant parameter varying system. In self-tuning adaptive control, the controller parameters are tuned to adapt to plant parameter variations. Such a general control scheme is indicated in Fig. 19. The plant parameter estimation algorithm solves the plant model in real-time and updates the plant parameters on the basis of recursive least square identification techniques. A tuning algorithm then adjusts the regulator parameters based on plant parameters. The tuned system may have pole-assignment control, but dead-beat, state-space, or design of time-series control can also be used. The regulator parameters may be updated at a slower rate than the main control loop sampling rate if the plant parameters vary slowly (which may not be necessarily true). For successful operation of the global system, stability is essential.

In a model referencing adaptive control (Fig. 20), the plant response is forced to track the response of a reference model irrespective of plant parameter variation. The reference model with fixed parameters is stored in microcomputer memory, and therefore the response of the plant becomes insensitive to parameter variation. The speed command ω_r^* generated by the position control loop in Fig. 20 is applied in parallel to the reference model and plant controller. The reference model output ω_{rm} is compared with the measured plant speed ω_r, and the resulting error signal e actuates the adaptation algorithm. The feedforward and feedback gains K_f and K_B, respectively, of the plant controller are iterated by the adaptation algorithm so as to dynamically reduce the error e to zero. The plant can track the reference model without saturation, provided the parameters in the reference model are defined on a worst-case basis. Therefore, the desired robustness of the control system is obtained at the sacrifice of optimum response speed. In general, the structure of the reference model and the plant should be the same, and the parameters should be compatible for satisfactory adaptation. The global stability of the system can be analyzed by Popov's hyperstability theorem.

A model referencing adaptive control system with a PI controller that is based on an on-line search strategy is shown in Fig. 21. For example, the plant under consideration may be a vector-controlled induction motor, where rotor resistance variation causes a coupling effect and torque sensitivity with I_{qs}^* changes. The parameters of PI torque controller can be adapted to compensate the plant parameter variation, so that the system tracks the reference model. The controller parameters K_1 and K_2 are varied by trial-and-error so that the error between actual and desired responses remains bounded within a hysteresis band. Again, the reference model is to be determined on the basis of worst-case parameters of the plant so that the torque loop can physically track the reference model.

A sliding-mode or variable-structure control technique has been applied successfully to both dc and ac drive systems. Basically, it is an adaptive model-referencing control (MRAC), but is easier to implement by microcomputer than the conventional MRAC system. The sliding mode control is ideally suitable for position servo, such as robot and machine tool drives, where problems related to mechanical inertia variation and load disturbance effect can be eliminated. The control can be extended to multiple drives where close speed or position tracking is desired. In sliding mode control, the "reference model" or a predefined trajectory in the phase is stored in a microcomputer, and the drive system is forced to follow or "slide" along the trajectory by a switching control algorithm, irrespective of plant parameter variation and load torque disturbance. The microcomputer detects the deviation of the actual trajectory from the reference trajectory and correspondingly changes the switching topology to restore tracking. Fig. 22 shows sliding mode control applied to a vector-controlled induction motor drive system, and Fig. 23 shows the sliding trajectory for both forward and reverse motions in phase plane. The sliding trajectory of the reference contour defines acceleration (δ_1), constant speed (δ_2), and deceleration (δ_3) segments which are beyond the drift band, so that the system always remains controllable. The actual sliding curve that follows the defined trajectory is given by a zigzag line in the direction of the arrow. The phase plane trajectory

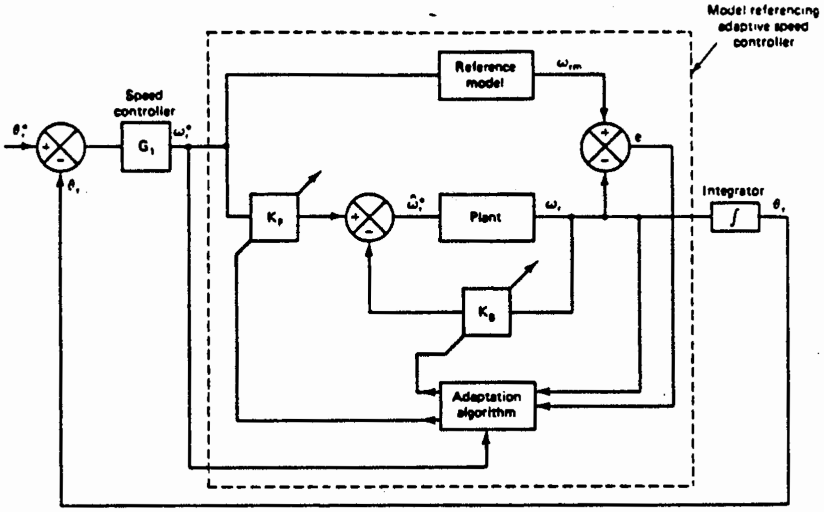


Fig. 20. Model referencing adaptive control (MRAC) system.

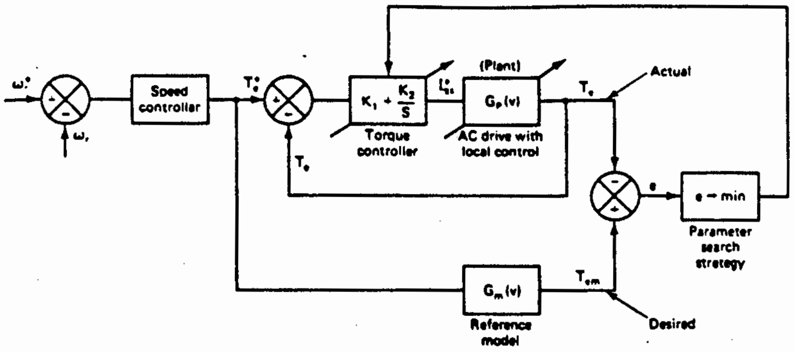


Fig. 21. Self-optimizing controller based on search strategy.

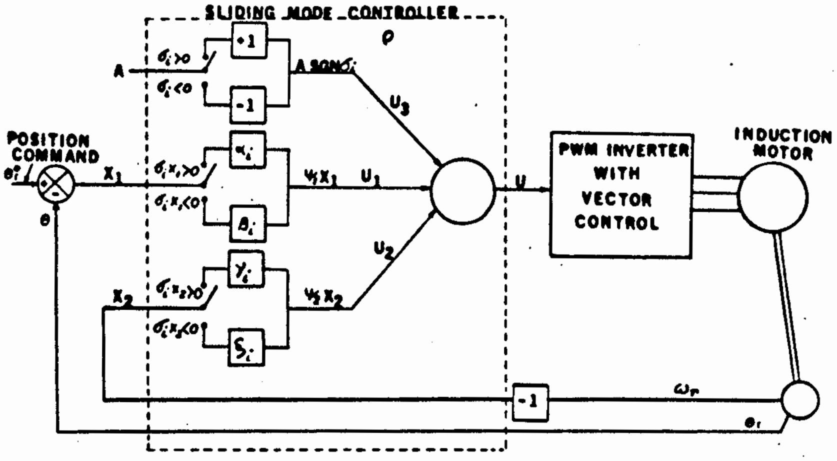


Fig. 22. Sliding mode control of induction motor.

can easily be translated into a corresponding time domain response. In a sliding mode controller, the position loop error (X_1), its derivative (X_2), and a constant A are transmitted through single-pole double-throw (SPDT) switches and the respective gains to constitute the effective control input U. The position of SPDT switches is determined by the operating point with respect to the defined trajectory. The jitter in the response can be regulated by good resolution of signals, small sampling time of computation, and high switching frequency of the inverter.

V. MICROCOMPUTER CONTROL

The advent of microcomputers has brought a new dimension in motion control technology. The impact of this evolution is as significant as the advent of power semiconductor devices in the 1950s. It is interesting to see that both ends of the spectrum

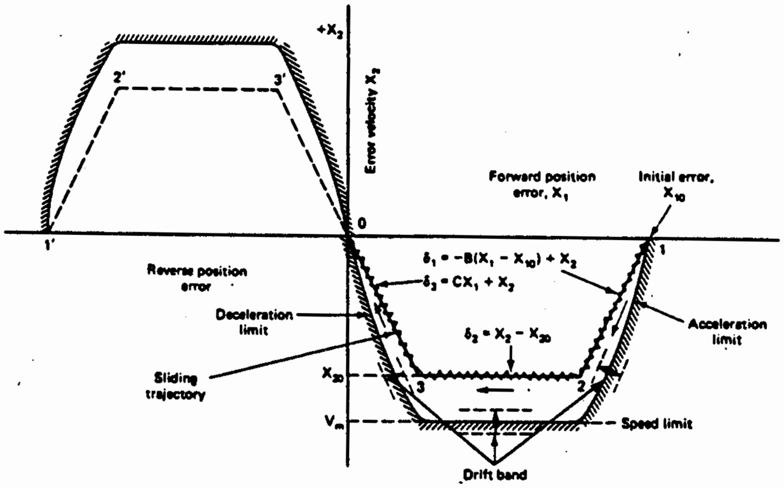


Fig. 23. Sliding trajectory in phase plane.

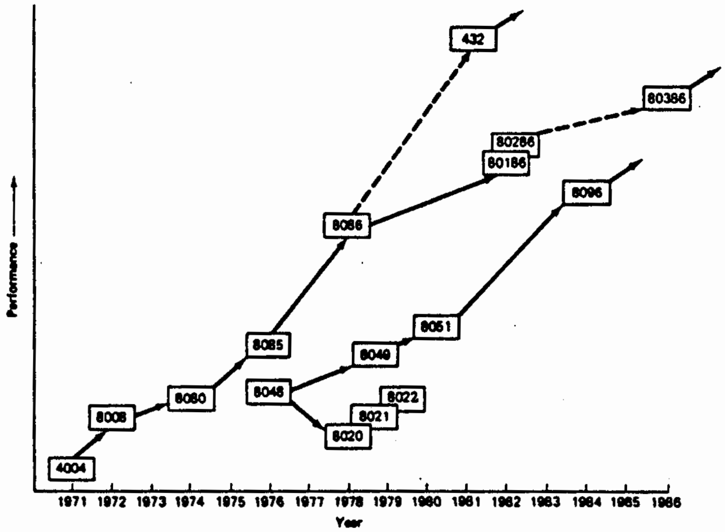


Fig. 24. Intel microprocessor evolution.

are digital: power semiconductors provide the muscle, whereas microcomputers provide the brain. Microcomputers have now found universal acceptance in motion control systems.

The advantages of microcomputers, seem obvious. They provide significant cost reduction in control electronics, improve reliability, and eliminate drift and electromagnetic interference (EMI) problems. They also permit design of universal hardware and flexible software control. Software can be updated or altered as the system performance demands change. "Micro" has the powerful capability of complex computation and decision-making. With the present trend toward computer-automated factories, microcontrol provides a compatible communication link in the computer hierarchy.

Microcontrol has the disadvantage of signal quantization and sampling delay. It is sluggish compared to dedicated hardware. In motion control, micro has time-critical functions which are unheard of in general process control applications. Of course, computation speed can be enhanced by parallel processing, use of more dedicated hardware, and assembly language programs.

Since the introduction of microcomputers in 1971 by Intel Corporation, the technology has gone through an intense evolution in the last two and a half decades. Intel microcomputers have dominated in motion control systems; other key competitors in the market are Motorola, Zilog, Texas Instruments, and National Semiconductor. Fig. 24 shows an overview of Intel microcomputer evolution. Here, the performance can be considered as a weighted average of bit size, components, improvement of hardware and software features, and so on. The 8080 is, in fact, the first generation microcomputer, which was once the industry's most commonly used micro. The evolution indicates two general directions: the multi-chip and single-chip families. Both 8- and 16-bit microcomputers are widely used, but as the price is coming down and system functions are increasing, the 16-bitters are finding more acceptance. A very dominant member of the Intel family is the 16-bit, single-chip 8096 microcontroller, which is designed for real-time control applications. The key features of the 8096 are summarized in Table I; Fig. 25 shows its architecture. It has a built-in A/D converter that can accept unipolar signals and a PWM output that can be used for

TABLE I
KEY FEATURES OF INTEL 8096 MICROCONTROLLER

- 8K-byte on-chip ROM
- 232-byte register space (RAM)
- 10-bit, eight-channel A/D converter
- Five 8-bit I/O ports
- Full-duplex serial port
- High-speed pulse I/O
- Pulse-width-modulated output
- Eight interrupt sources
- Four 16-bit software timers and two 16-bit hardware timers
- Watchdog timer
- Hardware (microcoded) signed and unsigned multiply/divide

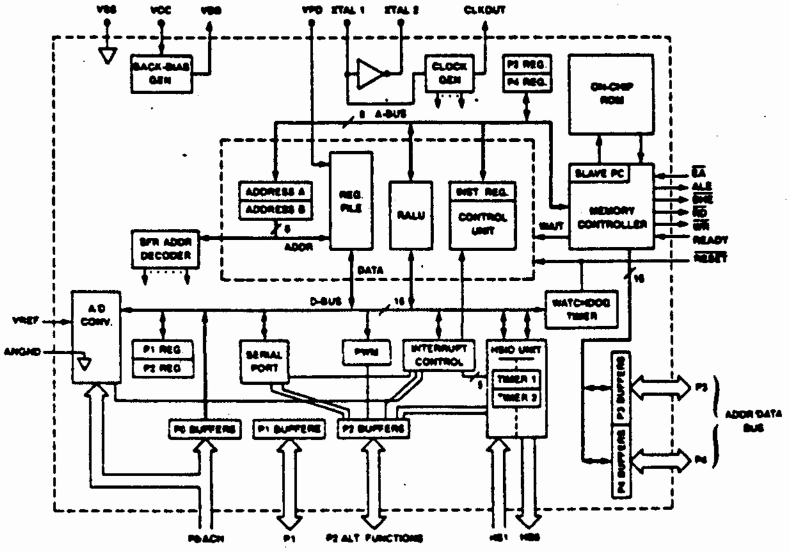


Fig. 25. Architecture of Intel 8096 microcomputer.

D/A conversion. With a 12-MHz clock frequency, the 8096 can do 16-bit addition in 1.0 μs and a 16 × 16 multiply or 32/16 divide in 6.5 μs. The other interesting features are high-speed trigger inputs (HSI's) and high-speed outputs (HSO's). The HSI's look for transition of input lines and record the times at which external events occur. The HSO's trigger external events at preset times and therefore can be used to generate interrupts at preset times. This microcomputer is expected to find wide applications in motion control.

TABLE II
KEY FEATURES OF TMS32010 DIGITAL SIGNAL PROCESSOR

- 160-ns instruction cycle
- 144-word on-chip data RAM
- 1.5 K-word on-chip program ROM-TMS320M10
- External memory expansion to a total of 4 K words at full speed
- 16-bit instruction/data word
- 32-bit ALU/accumulator
- 16 × 16-bit multiply in 160 ns
- 0 to 15-bit barrel shifter
- Eight input and eight output channels
- 16-bit bidirectional data bus with 50 megabits/s transfer rate
- Interrupt with full context save
- Signed two's complement fixed-point arithmetic
- NMOS technology
- Single 5-V supply
- Two versions available
  - TMS32010-20—20.5 MHz clock
  - TMS32010-25—25.0 MHz clock

Digital signal processors are high-speed microcomputers than generally act as peripheral components to a central processor and help in processing I/O signals. A very dominant member in this family is the TMS32010, which was introduced by Texas Instruments several years ago. The key features of this chip are given in Table II. The 16-bit microcomputer has 160 ns instruction cycle time (32010-25), which includes 16 × 16-bit multiply instruction. More recently, a CMOS version (320C25) has been announced in which the speed has been enhanced to 100 ns. Faster program execution has been possible in the TMS320 family by using what is called modified Harvard architecture, which permits overlap of instruction fetch and execution of consecutive instructions. In addition, the chip uses a dedicated hardware multiplier and barrel shifter. The TMS32020, which represents a considerable enhancement of its predecessor, the TMS32010, contains 544-word on-chip RAM, 128 K-words of ROM, sixteen input and output channels, three external interrupts, and one hardware timer.

We are beginning to see the emerging growth of 32-bit microcomputers in the market. Though National Semiconductor originally introduced 32-bit architecture four years ago, the age of the 32-bit machine truly started with the introduction of Motorola's 68020. At present, the other prominent members of the 32-bit family are Intel's 80386, Zilog's Z8000, AT&T's WE32100, and National's NS32C532. In terms of data processing capability, microcomputers can now successfully complete with mainframes and minicomputers. An interesting architecture of 32-bit machine is RISC (reduced instruction set computer) architecture which, because of its simplicity and single-cycle per-instruction operation, can considerably enhance the capabilities of microcomputers. The Inmos "Transputer" family are the first commercially available RISC machines. An example is the 32-bit T414 (1.5 micron, 200,000 transistors), which runs at 10 MIPS (million instructions/s) with memory transfer rate up to 25 MHz. The 32-bit machines will initially make inroads for data processing applications, but as prices come down, they will be considered for real-time control. Besides high-resolution signal processing, they will be useful in high-performance control systems using modern control theories.

As semiconductor processing technology improves, it will be possible to integrate more devices in a chip, and therefore to achieve more functional integration in a microcomputer. At present, the speed of microcomputers is limited because they operate in an inherently sequential manner. Using VLSI techniques, systems can be built in which many elements work in parallel on the same problem, thus allowing an enormous increase in processing speeds. In such a parallel computing system,[2] a large number of processors are arranged in a rectangular grid, with each processor able to communicate with its nearest neighbors on the grid, and, using a global communication system with any other processor in the machine. The machine operates in a single-instruction, multiple-data mode, which means that all component processors execute the same instruction at the same time. Super microcomputers based on parallel machines will be very expensive initially for real-time control applications.

What role can the microcomputer play in digital motion control systems? Practically all the control functions discussed so far can be implemented by microcomputer. The application areas may include gate-firing control of phase-controlled converters, closed-loop control, nonlinearity compensation, digital filtering, programmable delay, sequencing of control modes, programmable set point commands, system signal monitoring and warning, and data acquisition. Microcomputers have been used for optimal PWM wave generation of an inverter. Powerful micros are permitting vector control and optimal and adaptive control in motion control systems with intricate signal processing. The cost of a drive system can be reduced by using cheap sensors and by reconstructing precise signals with the micro's intelligence. In many cases, sensors can be completely eliminated, or redundant sensor information can be provided by observer computation. System reliability can be enhanced by micro-assisted fault-tolerant control. As the micro's speed and functional integration improve, it will be used in real time or quasi-real time for simulation of motion control systems. Artificial intelligence, another area where the microcomputer will find applications will be discussed later.

The micro will play an increasingly important role in system tests and diagnostics. The data from a system under test can be captured and processed to determine efficiency, power factor, etc. A personal computer is an important tool in such an application. Automated tests can be performed on a system, and structure and parameters can be identified. System diagnostics can be designed on either an on-line or an off-line basis. On-line diagnostics indicate the healthiness (or sickness) of system operation and give warnings if problems arise. Off-line diagnostics help in troubleshooting a system and minimize plant outage time. Diagnostic programs can be very user-friendly, and can be exercised by unskilled technicians.

Programmable controllers (PC's are finding increasing applications in today's factory floor environments. A PC is basically a general-purpose microcomputer controller that can be programmed for any application. Originally, it was intended to be an electronic replacement of industrial relay panels. Interestingly, the development of this application led to the invention of the microcomputer. From their initial applications in on-off sequencing of motors, solenoids, actuators, etc., PC's have evolved into intelligent workhorses with such advanced capabilities as data acquisition and storage, report generation, execution of complex mathematical algorithms, servo motor control, stepping control, axis control, self-diagnosis, system troubleshooting, and talking to other PC's and mainframe computers. The reasons for the proliferation of PC's on the factory floor are low off-the-shelf hardware cost, ease of programming and reprgramming by an ordinary electrician, system reliability, and ease of maintenance.

The supremacy of the microcomputer has been challenged recently by semi-custom or custom-VLSI circuits. Typically, a chip containing 100,000 or more devices is defined as a VLSI chip. All the peripheral chips of a micro can be integrated into a single chip, or both micro and peripheral chips can have a large single VLSI chip replacement. The advantages of VLSI design are low cost at high volume application, improvement of speed, reliability, and lower power consumption. The semi-custom design in VLSI is shown increasing popularity. The dominant member in this group is the gate array system, which is based on logic system synthesis using identical NAND or NOR gates. The chip may have analog devices to give more functional capability. The design and fabrication of gate array systems are highly computer-aided. Reasonably simple logic functions can be directly translated to gate-array design through what is known as a "silicon compiler." A programmable gate array permits flexible logic system design which can be erased and reprogrammed like an EPROM. In a standard cell VLSI design, individual cell or device parameters may be specified to gain tighter performance control of the circuit. The standard cell approach of semi-custom design normally permits large system design using logic analog, ROM, RAM, and even complete microcomputer function.

VI. COMPUTER-AIDED CONTROL SYSTEM DESIGN

CAD tools are playing an increasingly important role in motion control system design. It is convenient to design and simulate a newly developed control system on a computer before building a breadboard. The traditional paper-and-pencil

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[2] The CRAY2, generally acknowledged as the fastest supercomputer currently available, has four processors that execute up to a billion operations per second.

design of a control system and then trial-and error experiment in the laboratory may be very time-consuming, expensive, and frustrating, especially if the control system is complex and a lot of uncertainty is involved in performance. Both analog and digital computers have been used in the past for system design and simulation. In a hybrid computer, the control system can be appropriately partitioned for analog, logic, and digital simulation. Digital computers have found preference in recent years, and more and more powerful and user-friendly CAD programs are appearing in the market. By way of illustration, two general groups of CAD programs will be briefly reviewed.

The VAX-based federated CAD system [39] essentially consists of several independently developed subsystems tied together (Fig. 26) by a system supervisor and unified data base. The objective is to provide the user with a unified system that spans the entire control design problem: modeling, design, and simulation. In a federated system, the subsystems are loosely coupled, and each subsystem can be used as a standalone program. The additional advantages are that component programs can be added, deleted, or altered without affecting the main system. The first package, called IDPAC, is used for data analysis and identification of linear system. It can manipulate and plot data, and make correlation analysis, special analysis, and model identification. The next package, CLADP, permits frequency domain design methods. These include Bode, Nyquist, and root-locus design. The SSDP is a state-space design package that provides time domain design techniques. The MATLAB, which stands for "matrix laboratory," is used to solve matrix-related problems. The SIMNON is a Fortran-based simulation program for nonlinear dynamic systems. Both continuous and discrete time systems can be simulated on a VAX using SIMNON. The simulation of a discrete time system with prescribed sampling time is of particular importance to a microcomputer-based control system. SIMNON accepts descriptions of a dynamic system in state-space form; i.e., a continuous system is described by differential equations and a discrete time system by difference equations. For simulation, a large system is normally resolved into small interconnected subsystems. A connecting system routine links the subsystems by I/O signals. SIMNON can interface specially formatted FORTRAN to expand its capabilities.

CTRL-C, developed by Systems Control Technology, is an interactive computer language for the analysis and design of multivariable linear control systems and signal processing. Systems may be described in state-space, transfer function, or continuous or discrete-time forms. Transformations between representations are simple and straightforward. A powerful matrix environment provides a workbench for system simulation, signal generation, matrix analysis and graphics. The ACSL is a continuous system simulation language that can be used for simulation of nonlinear dynamic systems, both in continuous and discrete time form. It can be integrated with CTRL-C (Fig. 27) to form a complete CAD design and simulation package. Both the programs are Fortran based, and the completed package is available for VAX and other computers.

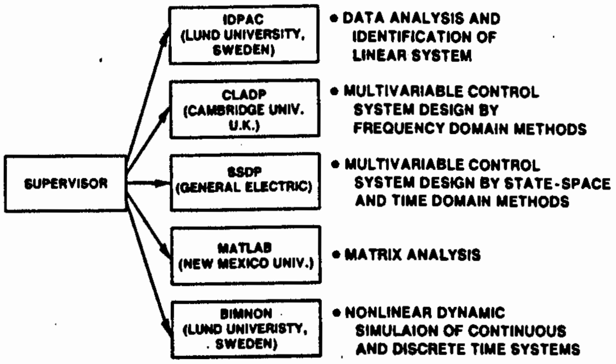

Fig. 26. Federated CAD of control system.

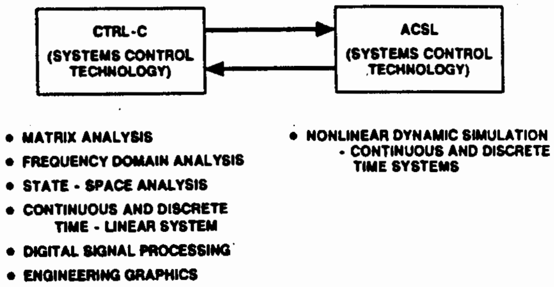

Fig. 27. CTRL-C/ACSL CAD system.

The tools for design of control systems can be divided into two categories: computer-aided control system design (CACSD), which is based on a mathematical model of a system, has been discussed above; the other is hardware/software architecture simulation for microcomputer-based control systems. An example in the latter category is HCSE (Hierarchical Control System Emulation), which was originally developed by Bolt, Beranek and Newmans, Inc. [42] for the National Bureau of Standards to support the development of their Automated Manufacturing Research Facility. The VAX-based HCSE simulation tool set permits emulation of a multiprocessor/multitasking system in the form of finite state machine (FSM) [47]. As mentioned before, only the hardware/software architecture is considered in the emulation without regard to actual implementation in hardware and software. The controller emulation in HCSE can be linked with plant simulation in SIMNON to evaluate design tradeoffs. When performance criteria are established, prototype hardware and software can be designed.

Computer-aided system design tools are in the process evolution and will undergo many changes in the future. The personal computer is expected to play an increasingly important role in this area. As microcomputer speed improves and memory becomes cheaper, more time-critical controls will be implemented in high-level languages. Eventually, the simulation software will be down-loaded directly to prototype microcomputer memory and use as real-time control software.

VII. Artificial Intelligence in Control

A significant advance has been made recently in control and CAD techniques by the introduction of artificial intelligence, or expert systems. Artificial intelligence involves programming a computer so that it can mimic human thinking. An expert system essentially tends to mechanize the expertise of a human being. A human expert has knowledge, an experience base, and the power of reasoning, judgment, and intuition. In a sense, conventional computer programs have some degree of artificial intelligence: they make decisions on questions which have clear-cut "yes" or "no" answers. But human thinking is often qualitative, involving ideas such as "large," "small," or "medium." Fuzzy logic[3] and fuzzy set[4] theories have been developed for computers to quantify and objectively evaluate the subjective ambiguity of human thinking.

There is now a tremendous surge of activity in expert systems applications. These include robotics, industrial process control, computer-aided design and diagnostics, medical diagnosis and prescription, medical knowledge automation, chemical and biological synthesis, mineral and oil exploration, space defence, air-traffic control, VLSI design, speech understanding, and knowledge-based management. An expert system can help in designing control structures and parameters for a desired performance goal. For example, a pole-placement design of a multivariable control system can be obtained automatically if a plant model and the desired set of poles are furnished to the computer. Expert-system-based diagnostics can locate faults in a complex control system with extensive man-machine dialogues. Such troubleshooting methods have already been used for diesel electric locomotives and jet engines. Expert systems are also being used for real-time control applications. In such a system, a controller can tune itself as it monitors the process and learns the dynamics of the operation, much as an experiences human operator would do. An example of such an auto-tuning regulator is the Foxboro Model 760, which can control a system that is not well understood and difficult to model. It is essentially a microcomputer-based PID controller with some 200 production rules. The self-tuning method is a pattern recognition approach that allows the user to specify desired temporal response to disturbances in the controlled parameter or in the controlled set point. The controller than observes the actual shape of these disturbances and adjusts its PID values to restore the desirable response.

A typical architecture of real-time expert control system is shown in Fig. 28. The plant under consideration may be unknown or difficult to model. A set of sensors measures the important variables that characterize the state of the process, and the pattern recognizers extract the features to detect important events. The rule base contains the knowledge of expert operators or designers and of the overall control strategy for all the regimes. The "meta control" can select the control strategy and define the control parameters. The speed of computation, system stability and robustness are serious issues in expert system control, and generally it requires extensive computer simulation study before actual implementation.

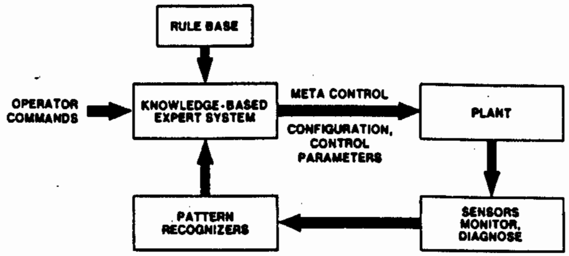

Fig. 28. Architecture of real-time expert control system.

VIII. CONCLUSION

This report has presented a comprehensive review of technology trends in microcomputer control of electrical machines. Although microcomputer control and computer-aided design techniques are our main themes of discussion, motion control as multidisciplinary technology has been reviewed in the broad perspective of electrical machines, power semiconductor devices, converter technology, microcomputers, and VLSI circuits. The concepts discussed in this report are valid not only for small machines, but for large machines as well.

Before concluding, I think that it is relevant to give some thought to the consequences of the "new" industrial revolution. Will it create more affluence for a privileged segment of society—thus furthering the gap between haves and have nots? Will it create a massive unemployment problem? Will the material prosperity deprive us of peace and tranquility and fill us with hypertension and restlessness, and consequently, aggravate the problems of our society? Will technological accomplishments bring more power rivalry in the world and bring us closer to war, and eventually destroy us with the results of our "accomplishments?" I think that we—the engineers, the creators of this technological society—should involve ourselves in answering these questions and help in shaping the future of our society.We, the human beings of this planet, are collectively responsible for our destiny. If accomplishments in technology have adverse influence on the society, that is not a justification for halting the march of technology.

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[3] Fuzzy logic is a kind of logic using graded or qualified statements rather than ones that are strictly true or false. The results of fuzzy reasoning are not as definite as those derived by strict logic.

[4] Fuzzy sets that do not have a crisply defined membership, but rather allow objects to have grades of membership from 0 to 1.

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