# TRENDS IN AC DRIVE APPLICATIONS

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**Abstract** - As the technology of AC drives developed and matured, new applications are emerging. This paper looks at the application segments and evaluates drive growth potential for each of them. Drive characteristics which are critical for each application segment are identified and technical solutions are discussed

**Key words**: Motor Drives, Power Converters

## 1. Introduction

AC drives were traditionally first applied in process industries, such as cement, plastic, textile, etc. With development of various vector control methods, AC drives started also to replace DC drives in industries requiring high precision of speed control and good dynamic performance, such as machine tools, robotics, metal rolling, paper mill finishing lines, etc. These are all applications which must have adjustable speed, by the nature of the process. Induction motors are predominantly used, although at power below 10 KW, PM motors have been preferred in servo applications. That application has had spectacular growth over the last 20 years. For example, over that period, one manufacturer has approximately halved the time period for sale of each subsequent million units: from 9 years for the first million, 1984-1993, to two years for the 4th million(1). However, because AC drive penetration into these applications is almost 100%, (adjustable speed drives are provided to all applications where the speed has to be regulated), the future growth in this application segment is expected to essentially track the growth of the corresponding industries.

The second market segment has been slowly developing over the last 15 – 20 years and consists of drive applications to fans, pumps and compressors. (This market is sometimes referred to as Heating, Ventilation and Air Conditioning, or HVAC, although fan and pump applications are found also in process industries and power plants). The fluid flow in these applications can be achieved also using mechanical devices, so that a switch to AC drives is based primarily on the resultant energy savings. Depending on economic situation and the prevailing interest rates, a decision to use AC drives is normally made (in the USA) if the investment can be recovered through energy savings in 1.5 – 2 years. This has been almost exclusively a retrofit market, where the already installed induction motors are retrofitted with AC drives. However, more recently, new installations start with AC drives, sometimes opening an opportunity for a new motor selection.

Aside from some niche applications, these two segments account for a vast majority of AC drives sold presently, especially in the USA, where the railway applications for fast trains play much smaller part then in Europe and Japan. Table 1(2) gives an indication of the size and growth of the low voltage AC drive market over the last 11 years. (The values are approximate, due to the fluctuating currency exchange rates).

The biggest change in the application of AC drives will come from development of large consumer markets for products which incorporate AC drives. That market has been already growing in Japan, specifically in residential heat pumps, where out of the total market of 7 million units, (year 2000) 94% were with inverter control. The second, even larger world-wide consumer market for AC drives is in hybrid electric vehicles, an application again pioneered in Japan. Thus, we are at a threshold of consumer applications, with a very large growth potential

Table 1: World market growth of low-voltage adjustable speed drives bellow 160 KW(2) in billions of dollars.

| Market | 1991 | 2002 | Annual Growth |
|---|---|---|---|
| Europe | 0.616 | 1.512 | ~7.7% |
| North America | 0.560 | 1.008 | ~5.0% |
| Japan | 0.686 | 1.022 | ~3.4% |
| Rest of World | 0.378 | 1.344 | ~11.1% |
| **Total** | 2.24 | 4.886 | ~6.7% |

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and significantly different requirements then industrial applications of 5-20 years ago.

This paper presents a brief survey of the state of the art of present industrial drives and then examines the required characteristics of the AC drives in the two consumer markets.

## 2. State of the art, current industrial AC drives

Many good papers [(2)-(4)] have been recently written on the future of adjustable speed drives, so only some salient aspects and new points will be discussed here. More important, still outstanding application problems will be also considered.

The spectacular growth of AC drives over the last 10 - 15 years, coupled with a parallel reduction in their price reflects the maturation and stabilization of that industry. The last significant technology changes were conversion to IGBT power devices and digital control about 15-18 years ago. Current low voltage (to 575 V) AC drives have now standardized on a diode rectifier - DC link - IGBT PWM inverter topology. Power devices are used without snubbers; control is µP or DSP implemented, significantly increasing drive functionality and features. (In fact, the transfer of functionality from hardware to software not only resulted in application flexibility, but also contributed to reduction in drive size and cost and increase in drive reliability.

Although the drive technology is becoming mature, the development continues, mostly directed to some form of cost reduction. Some of the most important current trends in low voltage AC drives are:

1. Continuing expansion of various forms of sensorless vector control to General Purpose (GP) drives, replacing previous V/Hz control (with or without slip compensation). The main reasons for this change are increasing performance requirements of GP drives, which still do not need servo grade characteristics and need for improved efficiency, resulting from better motor flux control. Current performance allows for ±10% torque regulation accuracy [(5)]. This trend will continue, as new research results are transferring to industry, eventually permitting a position sensorless control [(6)].
2. Continued inclusion of PLC functionality in drives, further increasing the drive application flexibility in process automation.
3. Continued development of motors with integrated power electronics [(7-8)], increasing the rated power from less then 10 HP to several hundred HP. The three main reasons for integrating electronics in the motor are reduced wiring, contained electro-magnetic interference (EMI) and easier application. One such motor for servo applications is shown in Fig. 1.
4. Gradual commercial justification of PWM controlled rectifiers, which help meet the current harmonic standards, EN-61000-3-2 in Europe and IEEE-519 in the USA, with smaller filters then those needed with diode rectifiers. The introduction of PWM rectifiers may permit elimination or a drastic reduction of the electrolytic DC link capacitors[(9-10)], thus improving the drive reliability while reducing its size.
5. Introduction of liquid cooled drives, with closed-circuit for (typically) de-ionized water being either part of the drive, or drive having a cold plate, which is cooled by cabinet installed liquid cooling. The obvious objective is to reduce the drive size, saving some of the precious cabinet space. The same trend towards reduced foot print can be also seen in packaged drives, which are taking the shape similar to servo drives [(5)].

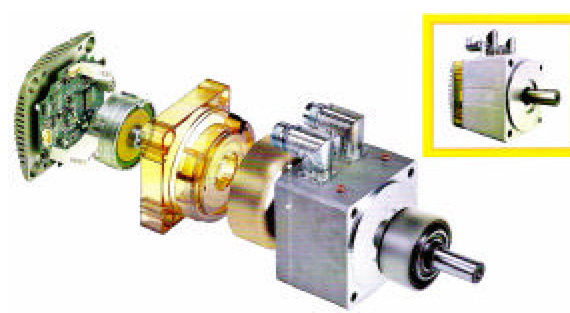

Fig. 1: Example of a servo motor with integrated electronics, containing inverter, 16-bit absolute encoder, communication, RFI filter, etc. The motor develops 2.5 – 6 Nm, 3000 RPM. The yellow piece provides a temperature shield between motor and electronics. Courtesy of Phase Motion Control S.r.l

6. Continued transition from fixed to floating point DSPs, permitting higher flexibility, faster software developments and easier maintenance.
7. Use of direct drives with linear motors in various machine tool applications, having traverse speeds exceeding 0.5 - 1.0 m/sec. (This is considered to be the limiting speed for ball screw coupling). Direct drives offer also reduced speed ripple and better precision. On the other hand, with a direct drive, one loses the benefit of gearing and torque multiplication, requiring a larger motor for a given final output torque. An example of a linear PM motor is shown in Fig. 2.
8. Expansion of the application range of PM motors to much higher power, as high as 500 hp. The main reason for this trend is dramatically reduced motor size and a significant increase in its efficiency. The motor size is further reduced by liquid cooling of the motor. The price difference compared to induction motors is smaller then expected and is often justified by better PM motor characteristics. Table 2 shows representative efficiency, power/weight and power density numbers for large PM and high efficiency induction motors. Figures 3-5 show representative large PM motors.

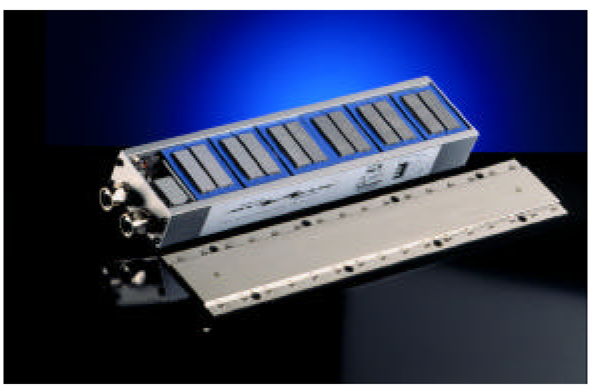

Fig. 2: Linear PM motor, with continuous trust of 400 N, peak trust of 1000 N, speed of 5 m/sec, for Cartesian robot applications. Courtesy of Phase Motion Control S.r.l

Table 2: Representative motor characteristics

| Power Range 100-500 HP | Efficiency | HP/in$^3$ | HP/lb |
|---|---|---|---|
| PM motors | 95 - 98% | 0.15–0.2 | 1.5 – 1.7 |
| Induction motors | 90 – 93% | 0.05–0.08 | 0.21 - 0.44 |

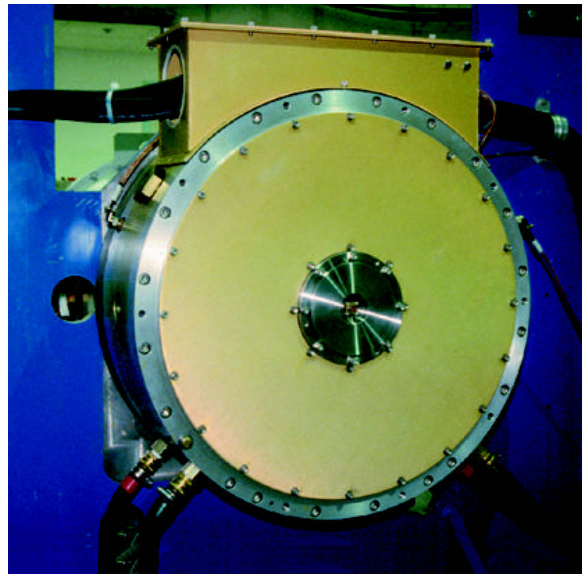

Fig. 3 1000 HP, liquid cooled PM motor, 96% efficiency, 4,000 RPM, 36 poles, 780 lb, continuous torque at stall: 2660 N-m. Courtesy of DRS Electric Power Technologies, Inc.

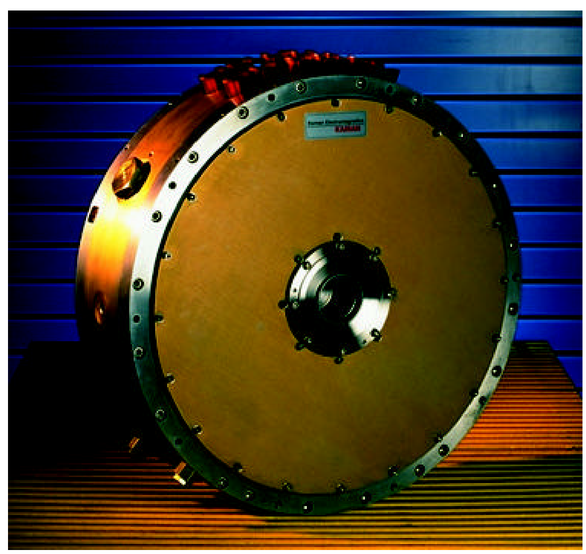

Fig. 4: 450 HP, axial flux, liquid cooled PM motor, with 28 poles, maximum speed of 3600 RPM, 2000 Nm continuous torque at stall, 395 lb, 95% efficiency. Courtesy of DRS Electric Power Technologies, Inc.

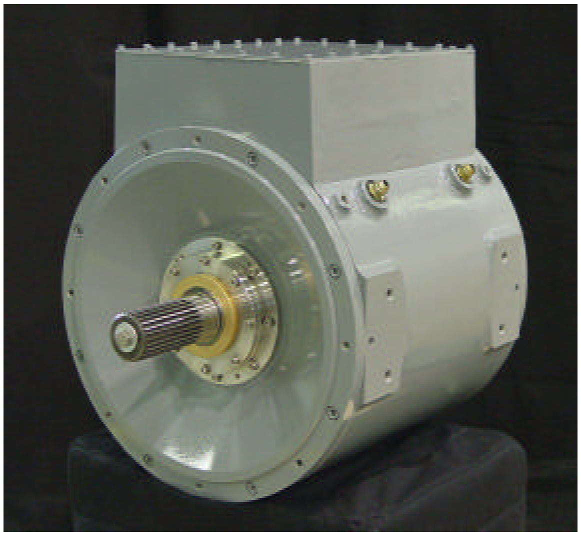

Fig. 5: 500 HP PM motor, introduced as competition to induction motors, with clearly visible liquid cooling connection points. It has 20 poles, 95% efficiency and weights 500 lb. Courtesy of DRS Electric Power Technologies, Inc.

The large PM motors (such as those shown here) are typically used in applications requiring high torque, especially at low speed, compact size or high efficiency. This means high torque vehicle drives, mining, large air-conditioning compressors, oil and gas drilling, mobile generators, cranes, wind turbine generators, etc. On the other hand, the PM motors either need a shaft position sensor or sensorless control, which usually cannot provide the full available torque at standstill.

**Remaining Problems**

Although AC drives have evolved to advanced level of maturity and although their acceptance is universal, there are still technical problems which hinder drive applications. Three most important problems are listed here, in descending order of importance:

1. Motor bearing and insulation problems. These problems, as well as some of the solutions have been well documented (11-16). While the failure mechanism is complex, the winding insulation problem is essentially, caused by fast IGBT switchings (high dv/dt) and long motor cables, while the bearing failures are caused by high dv/dt, capacitive coupling between stator and rotor and high frequency common mode voltages. Of these two, insulation problem is much better understood and can be normally solved. The bearing problem is much more complex and is still a cause of significant number of motor failures, impacting the drive reliability. It is interesting that PM motors do not show bearing failure problem, possibly because of the large equivalent air-gap and thus weak stator-rotor capacitive coupling.
2. EMI and line-side harmonics. Although very much related, these two phenomena are not identical. EMI includes not only line harmonics, but also the effects of inverter switching and specifically differential and common mode noise. These problems have been also well documented (17-20). Their solutions are also well known, especially regarding line harmonics and involve either filters or PWM rectification with some high frequency filtering. While still more expensive, the PWM rectification is gradually becoming almost competitive with the traditional diode bridge solution at powers bellow ~100 KVA. But, either solution lowers the drive efficiency (2). The EMI is more difficult to control, especially in common mode and knowledgeable selection and placement of filters becomes very important (18).
3. Acoustic noise. The availability of fast IGBTs has almost solved the noise problem, as the switching frequency is pushed outside of the audio range. In cases where this is not practical, the alternate approach is to vary the switching frequency over each fundamental cycle (21), so that the acoustic energy is spread over the frequency spectrum, creating a form of “white noise”. In both cases, the price for reducing the acoustic noise is also reduced drive efficiency.

## 3. Consumer Applications

Two most significant applications of AC drives to consumer products are in residential heat pumps and in passenger automobiles. Both markets are huge and their full development will affect also the technology of industrial AC drives. In Japan, the inverter driven residential heat pumps represent already a mature product[20]. In fact, 94% of all heat pumps sold in Japan in a year 2000 had an inverter. Table 3 gives the evolution of the use of adjustable speed drives in Japanese heat pumps [20], showing already a mature market. In a process of increasing the market share of inverter driven pumps, significant advances were made in reducing the EMI, the acoustic noise and above everything the inverter cost, while increasing the inverter reliability.

There are several reasons which explain why Europe and America have not followed the Japanese trend in use of variable speed heat pumps. One is that both have, in general, less temperate climate then Japan and that heat pumps are not so widely accepted, as in Japan. Another one is that the power rating of central air-conditioning in the USA is several times higher then the rating of split systems typically used in Japan, so that the inverter cost is also much higher. Yet another reason is that the energy cost in the USA is lower then in Japan, reducing the incentive to switch to inverter driven compressors. One could continue listing these reasons, not all of which are convincingly valid. Hopefully, with changing economic conditions, the rest of the world may start to enjoy the same comfort offered by inverter driven heat pumps.

Table 3: Residential heat-pump units sold in Japan with percentage of those with an inverter drive.

| YEAR | HEAT PUMP UNITS SOLD IN JAPAN (MILLIONS) | % HAVING INVERTER DRIVE |
|---|---|---|
| 1990 | 6.1 | 45% |
| 1991 | 7.0 | 55% |
| 1992 | 6.0 | 61% |
| 1993 | 5.1 | 60% |
| 1994 | 7.1 | 60% |
| 1995 | 7.7 | 68% |
| 1996 | 7.9 | 72% |
| 1997 | 7.0 | 75% |
| 1998 | 6.6 | 91% |
| 1999 | 6.6 | 95% |
| 2000 | 7.0 | 94% |

The use of inverter driven motors in the automotive applications was also pioneered in Japan, but that trend is spreading throughout the world. From drive design point of view, the main challenge is to provide the required drive reliability in the presence of extreme temperature changes and vibrations. That reliability has to be an order of magnitude greater then the reliability of standard industrial drives, currently around 0.5 – 1%. The system challenge is to control the drive EMI so that the inverter operation is not a source of noise disturbance. But the overall challenge is to reduce the drive cost, so that the premium for hybrid vehicles becomes acceptable. (The increasing fuel prices are helping there!)

The approach in the USA is a little different then in Japan, to the extend that the hybrid systems have been first developed for buses and heavy vehicles, with hybrid passenger cars being introduced now and over the next 2 years. Fig. 6 shows 5th generation inverter package, developed for hybrid buses. The inverter operates with 5 KHz switching frequency and provides vector control to an induction motor. The communication is via CAN bus, SAE J1939 protocol. The unit's weight is 135 lbs, the water flow is 15lpm@70$^0$C, the input DC voltage can vary between 500 and 900 V and the total losses are about 7 KW. The package is designed to withstand continuous vibrations with 5g and momentary shocks of 40g. With the cover removed, the package from Fig. 6 is shown in Fig. 7. The control and signal electronics are on the bottom of the package, as shown in Fig. 8. The inverter package shown in Fig. 6 is also used with fuel cell powered buses, Fig. 9, which shows the inverter placement, providing an idea about the environmental conditions. (The inverter is exposed to splashing from the road and has to be adequately packaged). The inverter of Fig. 6 represents the current technology, the development of which started in 1991 with a DC chopper drive. Over 1000 units were supplied during that period. The key problems solved over that period were reduction of the inverter package size (essentially by going from air to liquid cooling), protection from the environmental conditions (by providing IP 67 package) and


Fig. 6: 220 KW water cooled inverter drive for hybrid buses, using induction motor. Control and signal connection is at the bottom (square covers). The cooling water is supplied through the two yellow connectors. On the top are three motor connectors, two (black) connectors for external braking resistor and two connectors for ± DC link. Courtesy of Saminco, Inc.

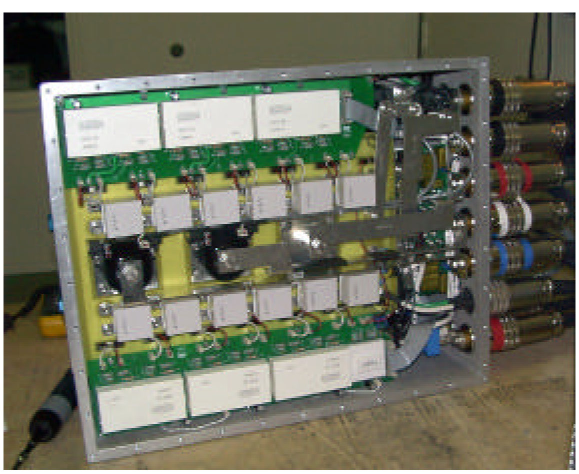

Fig. 7: The inverter package shown in Fig. 6, with the top cover removed. The connecting cables are visible on the far right. Courtesy of Saminco, Inc.

containment of the generated EMI, coming primarily from the inverter-motor connection cables. Based on the gained experience, this manufacturer is planning for the 6$^{th}$ generation to have inverter integrated with the motor, thus eliminating the power cables. It is interesting that the new Ford Escape, which offers a hybrid solution and which became available at the end of 2004, also has the drive integrated with the motor, giving elimination of cables and HV connectors as the main reason[(23)].

Fig. 8: The bottom side of the package shown in Fig. 6, with the cover removed. The capacitor cooling bays are on the top and the bottom of the photo. Courtesy of Saminco, Inc.

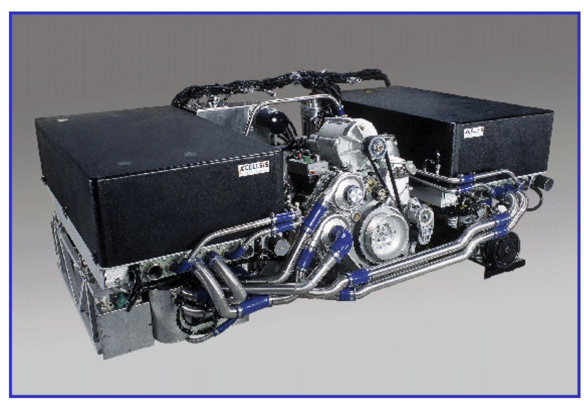

Fig. 9: Fuel cell drive for an all electric bus. The fuel cells are in two black boxes on the top. The inverter package (Fig. 6) is below the black box on the left. The oil-cooled motor is to the right of the inverter, exactly were the Diesel engine would be. Courtesy of Saminco, Inc.

Table 4[24] shows an overview of the hybrid vehicle programs of the world's main automotive manufacturers. (Table 4 addresses only vehicles with split hybrid architecture. For that reason, Honda, which uses parallel architecture, is not shown in Table 4).

Fig. 10 illustrates the input split system, characterized by having the engine power as input to the power split device, which is normally a planetary gear. Essentially, the speed and torque of the electric motor determine the mechanical output from the planetary gear. The result is that the engine operates at essentially constant speed, while the torque transmitted to the wheels is regulated by the speed of the electric motor.

Fig. 11 shows the concept of the compound split, which is characterized by having the engine power as the input to the first power split device AND output to the wheels is via the second power split device. This architecture, developed by GM offers added flexibility in selecting modes of hybrid operation.

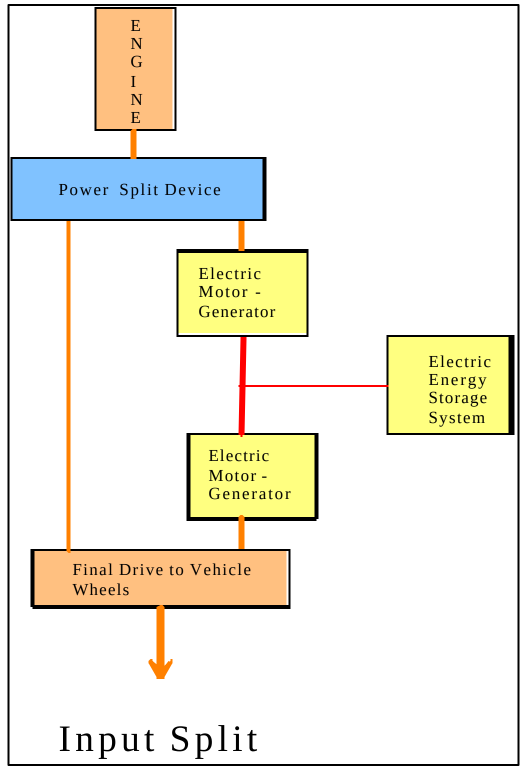


Fig. 10: Schematic diagram of an input split hybrid system[24].

Table 4: An overview of current programs and introduction dates of hybrid passenger cars using split architecture. (Courtesy of J-N-J Miller Design Services)

| Introduct. Date | Company | Hybrid Brand | Vehicle Segment | Engine Power, kWpk | Power Split Type | M/G1 rating, kWpk | M/G2 rating, kWpk | System voltage, V | Electric Fraction, Ef |
|---|---|---|---|---|---|---|---|---|---|
| 2000 | Toyota | Prius-I | car | 53 | I | 10 | 30 | 288 | 0.36 |
| 2004 | Toyota | Prius-II | car | 57 | I | 30 | 50 | 500 | 0.47 |
| 2005 | Toyota | RX400H | Lt-SUV | 100 | I | 35 | 60 | 500 | 0.38 |
| 2005 | Toyota | Highlander | F-SUV | 100 | I | 35 | 60 | 650 | 0.38 |
| 2004 | Ford | Escape | Lt-SUV | 98 | I | 45 | 70 | 300 | 0.42 |
| 2006 | Mercury | Mariner | Lt-SUV | 98 | I | 45 | 70 | 300 | 0.42 |
| 2007 | Mazda | Tribute | Lt-SUV | 98 | I | 45 | 70 | 300 | 0.42 |
| 2008 | Ford | Fusion | Lt-SUV | 98 | I | 45 | 70 | 300 | 0.42 |
| 2007 | GM-DCX | Tahoe | F-SUV | 164 | C | 60 | 60 | 300 | 0.27 |
| 2007 | GM-DCX | Yukon | F-SUV | 164 | C | 60 | 60 | 300 | 0.27 |
| 2008 | GM-DCX | Durango | F-SUV | 164 | C | 60 | 60 | 300 | 0.27 |
| 2008 | GM-DCX | Mercedes | F-SUV | 164 | C | 60 | 60 | 300 | 0.27 |
| 2006 | Nissan | Altima | Car | 57 | I | 30 | 50 | 500 | 0.47 |
| ? | FAW | THS-II | car | 57 | I | 30 | 50 | 500 | 0.47 |
| 2007 | Porsche | Cayenne | Lt-SUV | | | | | | |

Highlighted data: vehicle is in the market and ratings are published.
Non-highlighted data: vehicle introductions are published, but ratings are not.
FAW=First Auto Works, China GM-DCX=GM-Daimler Chrysler joint venture
Legend:
I Input split system. This is the Toyota power split of the single planetary gear type.
C Compound split system. This is the GM (Allison) power split of the double planetary gear type.
Ef Electric fraction = Peak M/G power/(Peak M/G power + Peak ICE power)

Table compiled by J-N-J Miller Design Services, from available public data or using engineering approximations

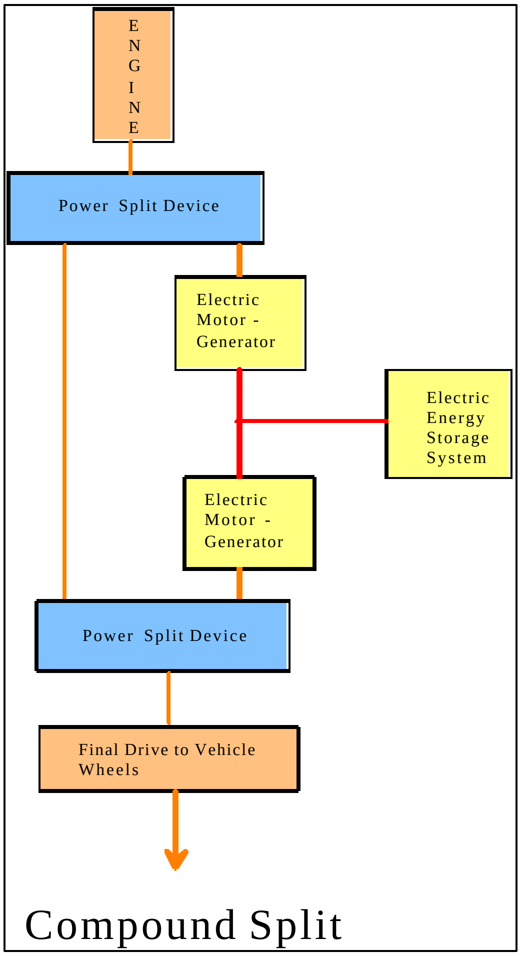


Fig. 11: Schematic diagram of a compound hybrid split system[24].

## 4. Conclusion

The market for AC drives is expanding as the result of improvements in drive reliability, reduction in drive cost, ease of operation and enhanced functionality. While the traditional, industry applications of AC drives are showing a robust growth, the main expansion over the next 5-10 years will come from use of AC drives in consumer products, primarily inverter driven heat pumps and fuel cell/hybrid vehicles. Development of these applications is already influencing, by the sheer volume of the drives used, the development, integration and cost of the components used in the industrial drives. At the same time, the requirement for increased power/volume in automotive drives is helping develop liquid cooled industrial drives and motors.

This paper showed some of the technical trends in both traditional, industrial applications and in hybrid vehicles. While there are still a few of technical problems remaining, the main trust in the future development of AC drives will be reduction in cost and further improvements in reliability, both being driven by the consumer market. On a system level, selection of the best architecture for integration of a drive and internal combustion engine into a hybrid vehicle is an on-going process, where the consensus on the best solution may be reached over the next 5-10 years.

## References


(1) www.yaskawa.co.jp/en/ >AC Servo Shipments

(2) F. Blaabjerg and P. Thoegersen: “Adjustable Speed Drives – Future Challenges and Applications” Proceedings of the 4th International Power Electronics and Motion Control Conference, August 2004, Xi’an, China.

(3) R.J. Kerkman, G.L. Skibinski, D.W. Schlegel. "AC Drives: Year 2000 (Y2K) and Beyond". Proc. of IEEE-APEC '99, Vol. 1, 1999, pp. 28-39.

(4) T.M. Jahns, E.L. Owen. "AC Adjustable-Speed Drives at the Millennium: How did we get here?" IEEE Trans. on Power Electronics, Vol. 16, No. 1, 2001, pp. 17-25.

(5) www.danfoss.com/BusinessAreas/Drives Solutions/>products>frequency converters> VLT®5000 FLUX

(6) Joachim Holtz and Juntao Quan: ”Drift- and parameter-compensated flux estimator for persistent zero-stator-frequency operation of sensorless-controlled induction motors” IEEE Trans.-IA Jul-Aug 2003 pp.1052-1060

(7) www.danfoss.com/BusinessAreas/DrivesSolutions/ >products>frequency converters>low power modules

(8) www.phase.it/eng/index.html> ultract TW

(9) P.D. Ziogas, Y.G. Kang and V.R. Stefanovic: "Rectifier Inverter Frequency Changers with Suppressed DC Link Components," IEEE-IAS Trans. Vol. IA-22, No. 6, Nov./Dec. 1986, pp. 1027-1036.

(10) I. Takahashi and Y. Itoh: “Electrolytic Capacitor-less PWM Inverter”, IPEC 1990, Tokyo, pp. 131 – 138.

(11) Austin H. Bonnet: “Analysis of the impact of pulse-width modulated inverter voltage waveforms on AC induction motors”; IEEE Trans-IA Mar/Apr. 1996 pp.386-392

(12) J. Erdman, R.J. Kerkman, D. Schlegel, G. Skibinski: “Effect of PWM Inverters on AC Motor Bearing Currents and Shaft Voltages”; IEEE Trans-IA Mar/Apr. 1996 pp. 250-259.

(13) D. Busse, J. Erdman, R.J. Kerkman, D. Schlegel, and G. Skibinski: “Bearing Currents and Their Relationship to PWM Drives”; IEEE Trans. on Power Electronics, March 1997, pp. 243 – 252.
(14) R.Kerkman, D.Leggate, G.Skibinski: “Interaction of Drive Modulation & Cable Parameters on AC Motor Transients”; IEEE Trans.-IA May-June 1997, pp. 722-731
(15) D.Rendusara, P.Enjeti: “An Improved Inverter Output Filter Configuration Reduces Common and Differential Modes dv/dt at the Motor Terminals in PWM Drive Systems”; IEEE Trans. on Power Electronics, November 1998, pp. 1135-1143
(16) S. Bhattacharya, L. Resta, D.M.Divan, D.W. Novotny, T.A. Lipo: “ Experimental Comparison of Motor Bearing Currents with PWM Hard and Soft Switched Voltage Source Inverters”; IEEE PESC 1996
(17) Y. Murai, T. Kubota and Y. Kawase: ”Leakage Current Reduction for a High-Frequency Carrier Inverter Feeding an Induction Motor”; IEEE Trans.-IA, July/August 1992, pp. 858 – 863.
(18) E. Zhong and T. Lipo: “Improvements in EMC Performance of Inverter -Fed Motor drives” IEEE Trans.-IA, Nov./Dec. 1995, pp. 1247 – 1256.
(19) S. Ogasawara, H. Akagi: ”Modeling and Damping of High-Frequency Leakage Currents in PWM Inverter-Fed AC Motor Drive Systems”; IEEE Trans.-IA Sept./Oct. 1996, pp. 1105 – 1114.
(20) S. Ogasawara, H. Ayano and H. Akagi: ”Measurement and Reduction of EMI Radiated by a PWM Inverter-Fed AC Motor Drive System”; IEEE Trans.-IA Jul/Aug 1997, pp. 1019 -1026.
(21) A. Trzynadlowski, S. Legowski and R. Kirlin: “Random Pulse Width Modulation Technique for Voltage-Controlled Power Inverters” Conf. Rec. IEEE-IAS 1987, pp. 863-868.
(22) A. Hiruma, H. Kanazawa, T. Uchida and Y. Yamanashi: “Inverter Air-Conditioner in Japan”, Conf. Record, PCIM 2003, P.R. China.
(23) A. Sankaran: “Introducing Power Electronics in Ford Hybrid Escape Vehicle”, Power Electronics Society Newsletter, Vol. 16, No. 3, 2004.
(24) Communication with John Miller, J-N-J Miller Design Services.