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Motor Drive Technologies for the Power-By-Wire (PBW) Program: Options, Trends and Tradeoffs

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MOTOR DRIVE TECHNOLOGIES FOR THE POWER-BY-WIRE (PBW) PROGRAM: OPTIONS, TRENDS AND TRADEOFFS

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Abstract

Power-By-Wire (PBW) is a program involving the replacement of hydraulic and pneumatic systems currently used in aircraft with an all-electric secondary power system. One of the largest loads of the all-electric secondary power system will be the motor loads which include pumps, compressors and Electrical Actuators (EAs). Issues of improved reliability, reduced maintenance and efficiency, among other advantages, are the motivation for replacing the existing aircraft actuators with electrical actuators.

An EA system contains four major components. These are the motor, the power electronic converters, the actuator and the control system, including the sensors. This paper is a comparative literature review in motor drive technologies, with a focus on the trends and tradeoffs involved in the selection of a particular motor drive technology. The reported research comprises three motor drive technologies. These are the induction motor (IM), the brushless dc motor (BLDCM) and the switched reluctance motor (SRM).

Each of the three drives has the potential for application in the PBW program. Many issues remain to be investigated and compared between the three motor drives, using actual mechanical loads expected in the PBW program.†

1.0 Overview of the Power-By -Wire Program

Power-By-Wire (PBW)/ Fly-By-Light (FBL) is a program, managed by NASA Lewis Research Center, to adopt many of the new technological advancements in power and communication for application in commercial aircraft. The PBW program deals with aerospace Electrical Actuators (EAs). These actuators have many potential advantages over the hydraulic and pneumatic actuators currently used in aircraft. Issues of improved reliability, reduced maintenance and efficiency, among other advantages, make the EAs better candidates for aircraft power supplies and actuation. Major aerospace companies such as McDonnell Douglas, Boeing, AlliedSignal, Martin Marietta (previously General Dynamics Aerospace Branch), General Electric and Sundstrand have been working on contracts involving EAs for aircraft engine and thrust vector controls [1]-[6], [51].

2.0 Electrical Actuator (EA) System

Figure 1 shows a block diagram of an EA system. The dashed part contains the system's four major components. These are the motor, the power electronic converters the control system including the sensor requirements, and the actuator. The four components have been the focus of many researchers in the area of motor drives and motion controls. Although the EAs are considered a mature technology by many researchers, they still remain as a high to medium risk technology in the aircraft industry. The aforementioned companies together with other aircraft industries are continuing to study the technology to assess requirements such as reliability, redundancy, safety, environmental factors, and others needed to assure a successful PBW program [1] -[2],[5].

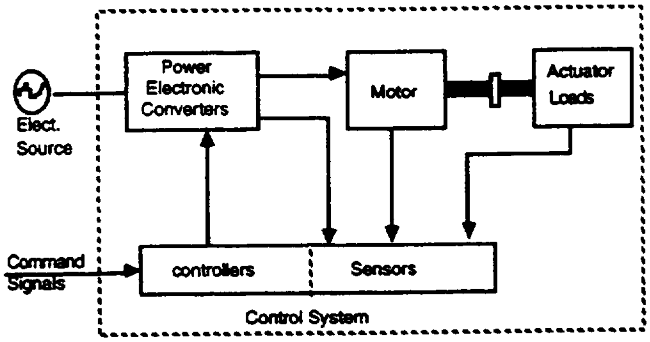

Figure 1 Block diagram of an EA system

Two major aircraft companies, Boeing and McDonnell Douglas, have independently prepared an integrated requirement analysis and preliminary design studies for the PBW program. The Boeing study is based on their 757-200 aircraft. A flight demonstration is planned to take place in 1999. The flight demonstration will consist of subsystems which are part of a larger architectural blueprint defined by their analysis and preliminary design of the PBW architecture given in [1]. McDonnell Douglas has prepared a similar study based on a conceptual 600 passenger aircraft which is expected to present a greater challenge for the design of the PBW system, and should result in a more comprehensive system definition, applicable and scalable to

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a broad scope of aircraft configurations [2]. The estimated cost of the test program proposed by each company is about $28 Million dollars over the next four years [1].

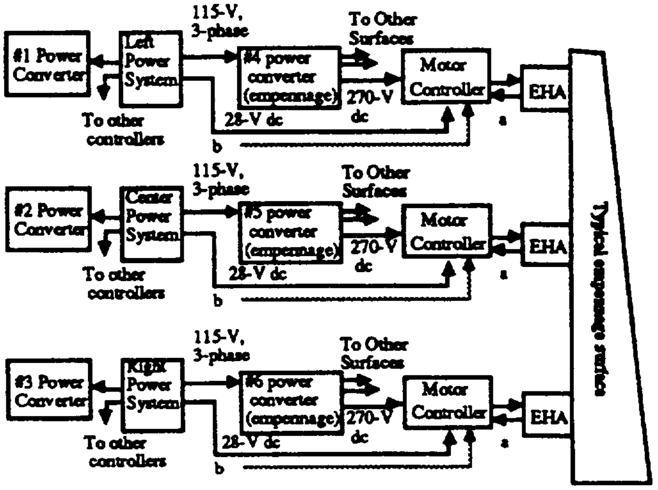
Whereas the reports of the aircraft industries have more detailed analysis and design architecture for the PBW/FBL program, they lack an in-depth study of the alternatives available for EAs. The research done under this NASA summer Faculty Fellowship is intended to be a study of the literature and a comparison of the motor drive technologies available for EAs, with a focus on some comparisons and tradeoffs involved in the selection of one motor drive or another. The research involved three motor drive technologies: the induction motor (IM), the switched reluctance motor (SRM) and the brushless dc motor (BLDCM). Selected literature involving the motors, the power electronic converters, the controllers and sensors in each the three motor drive technologies has been reviewed.

As a result of the tremendous literature available in the motor drives technology, and due to the limited time available for this study, this paper should not be considered as an extensive literature review. However, it is intended to provide guidance and recommendations for a more rigorous and well structured research of the available technologies in motor drive, and their suitability to the different EA systems required in the PBW program.

The organization of the paper is based on the four components of the EA system and the options available to suit the PBW program as given in some of the PBW studies [6]. A typical PBW electrical actuation baseline architecture, as proposed in [1], is given in Figure 2. Based on this architecture and other architectures proposed in the aforementioned studies, the PBW EA system options are given in Figure 3 which should serve as a complete layout for the rest of this paper. Each of the EA components, namely, the motor, power electronics, and controller is presented. The available options are mentioned, followed by and briefly described with the related literature. Comparisons and tradeoffs between the options then follow. Conclusions of the study together with proposed directions for future research and development are given at the end of the paper.

The induction motor has received most attention in the PBW program [1]-[14], since extensive research and development are done on its drives. Many induction motor drives have been developed, ranging in power from 5 hp to 70 hp and in frequency from 400 Hz to 2400 Hz [5]. The power converters used are the resonant link type (dc and ac), using the soft switching technique of pulse population density (PPD) or otherwise referred to as pulse density modulation (PDM) [7]-[9]. The Insulated Gate Transistor (IGT) has been the main switching device used in these converters. Some work has been done on the resonant ac link converter using the MOS-Controlled thyristor (MCT) [10]-[11], [34]-[38]. The research and development of the PBW program continues to focus on the induction motor drives.

On the other hand the SRM and the BLDCM have received a lot of attention recently in the motor drives and motion controls research and development. These two motor technologies are emerging as strong competitors to the induction motor in a number of applications including the PBW program [15]-[33]. Minimal work has been done in the PBW program concerning these two motor drive technologies. Although each of the three drives has advantages and disadvantages, many issues of comparison need to be closely investigated between the three technologies in context of the PBW loads and requirements. It is highly recommended that NASA and the Airforce compare the three drive technologies to assess the tradeoffs involved between them using PBW loads.



a = actuator control loop feedback
b= optical data link for actuator commands and health monitoring dat

Fig. 2 A typical PBW electrical actuation baseline architecture

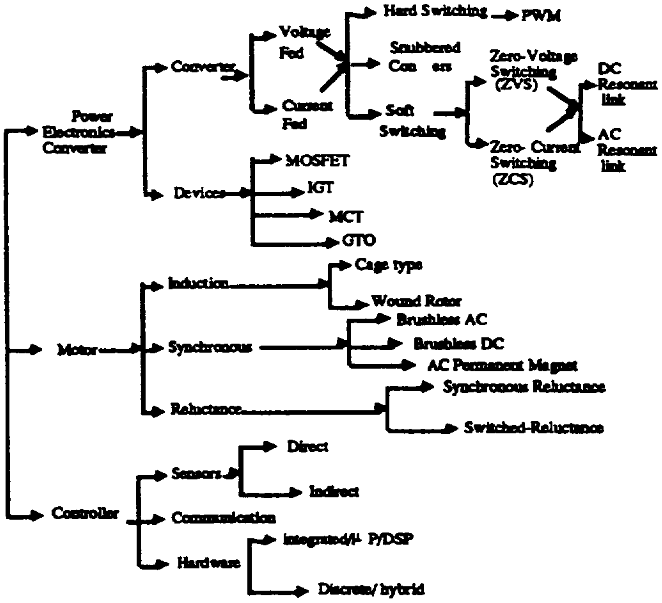


Figure 3 Options for the PBW EA systems

3.0 The Motor Technology Options

The electrical motor is the workhorse in an electric drive system. Understanding its characteristics in details is of crucial importance for a modern high performance drive. Better understanding of a motor characteristics coupled with extensive theoretical studies and availability of new materials have resulted in improvement in motor design. Advancements such as high energy magnets, low loss amorphous metal and high performance superconductors have resulted in a much improved machine design compared to the bulky, primitive, expensive and low performance ac and dc machines. The emergence of new ideas, materials and components have obviously generated many opportunities but also complicated the question of what is the best drive for a particular job. The particular choice of a motor for a specific application depends on such selections as power rating, operating speed range, operating environment, fault tolerance, reliability, performance requirements, thermal capability, cost and other criteria. These criteria determine the characteristics of a complete drive including the requirements of the power electronic circuits, semiconductor devices and controllers.

DC machines have been the primary choice for servo applications because of their excellent drive performance and low initial cost. However the use of commutators and brushes is long considered as a disadvantage for their use in motor drives. The evolution of brushless motors which resulted from the coupling of the three classical motors, namely, dc, ac synchronous and ac induction motors, coupled with electronic controllers, has recently resulted in a variety of machines which can be referred to as ac or "brushless" machines. Recently, due to the enhancement in their control aspects, these machines present many advantages such as torque/inertia ratio, peak torque capability, power density and reliability over the dc brush motor. These machines can be categorized in three types, namely, the induction machines, the switched reluctance machines and the permanent magnet (PM) synchronous machines or brushless dc machines. The following sections present a brief discussion on each machine, pointing out its advantages and disadvantages.

3.1 Induction Motors [6], [13]-[14]

The induction motor, particularly the cage type, has been the traditional workhorse for fixed and variable speed drive applications. The motor has been known to be rugged and relatively inexpensive and almost maintenance-free. However, since the slip and the rotor resistance are essential for torque production in induction motors, it is impossible to achieve zero losses in the rotor. This directly affects the efficiency of the motor. The low efficiency may not be noticeable in very large drives, but the efficiency and power factor of the motor fall off in small sizes because of the scaling, particularly at light loads. In fractional and low integral horsepower range the complexity and cost of the induction motor drive is a drawback, especially when dynamic performance, high efficiency and a wide speed range are among the requirements. These factors favor the use of brushless PM over the induction motor in low power range drives.

3.2 Switched Reluctance Motors [16]-[25]

Switched reluctance motors, a class of variable reluctance motors (VRMs), are beginning to gain acceptance worldwide, particularly because of their use in direct drive applications that eliminate the need for gear units. More recently, the SRM has been investigated for its suitability for actuators in aerospace applications [16]-[17]. The SRM drive technology has gone through a steady and significant development over the last two decades. Tremendous research has been done in the design of the motor and converter topologies. Several topologies exist for driving SRM, each with its unique advantages and disadvantages [15]-[19]. Recent research has focused in the control aspects of these motors [20]-[25].

The switched reluctance motor is compatible with a voltage square wave output of a switching inverter [40]. It requires unipolar excitation currents leading to a simple converter topology that requires half as many switches. The torque in these motors is developed by controlling the magnetomotive force in accordance with the periodic reluctance variation. The torque-speed characteristics are similar to those of a series connected dc motor. This indicates that the SRM may represent an alternative in applications of the dc series motor.

The advantages of the SRM are the compact simple construction, lower overall cost, high torque-to-inertia ratio, high torque output at low to moderate speeds and faster system response in servo applications. The most attractive feature of SRM drive is the series connection of the converter phase-leg switches with the motor phase winding, which eliminates the possibility of any shoot-through fault caused by the converter switches.

Two main disadvantages of the motor are the high torque ripple and the need to have an absolute position sensor to help the controller establish the phase current pulses. Other undesirable characteristics and tradeoffs present in the design of direct drive SRM are: (i) The small rotor inertia which exhibits a tradeoff in applications where changes in the load inertia are frequent. (ii) Compared to the gear driven linkages, direct drive types demand an advanced and more complicated controller architecture. This occurs because, in direct drive, nonlinear load disturbances are directly seen by the motor shaft instead of being diminished by the gear reduction mechanism. Moreover, gear servos have natural damping, whereas direct drive servos must employ velocity feedback with high bandwidth and high gains to introduce artificial damping and attain faster acceleration rates. (iii) Direct drive motors are usually difficult to model because of the inherent nonlinear dynamics.

3.3 Brushless DC Motors [26]-[33]

In a brushless dc motor the stator structure is similar to that of a polyphase ac motor. The field is produced by a permanent magnet in the rotor and is not affected considerably by the armature current. The obvious advantage of the brushless dc configuration over the commutator-type dc and ac motors is the removal of the brushes. Therefore, brush maintenance is no longer required, and many problems associated with brushes, such as electromagnetic interference (EMI) and its associated sparking are eliminated. The absence of commutator reduces the motor length so the lateral stiffness of the rotor is greater, permitting higher speed, especially in servo applications. The motor conduction of heat through the frame is improved, and therefore an increase in electric loading is possible, and may provide a higher specific torque (torque/amp), and higher efficiency. The major disadvantage of brushless dc motors is the need for shaft position sensing . With improved performance and reduced cost, the brushless dc motor has been used in many variable speed drives and servo-applications previously reserved for dc brush and ac induction motor systems, especially in fractional and low-integral hp variable speed applications.

3.4 Motor Comparisons and Tradeoffs

A qualitative comparison of induction, switched reluctance and permanent magnet motors is given in Table 1 [52]. Although these comparisons may generally be true, they need to be closely investigated under similar loading conditions. Issues such as robustness and closed-loop simplicity may be difficult to quantify.

Table 1 : Comparison of induction, switched reluctance and BLDC motors [52]

	IM	BLDCM		SRM
		SPM	IPM	
Robustness	+			+
Motor Cost	+			+
Efficiency		+	+	+
Open-Loop Control	+		+	
Closed-Loop Simplicity		+		+
Torque Smoothness	+		+	-
Wide Speed Range	+		+	+
No Need for Rotor Position Feedback	+	-	-	-
Acoustic Noise				-

+ : advantage - : Disadvantage
SPM= Surface PM IPM := Interior PM

4.0 Power Converter Options

The performance, complexity and cost of the power electronic requirements must be considered in addition to the selection factors of the motor while designing a motor drive system. The converters are generally classified according to the supply source into voltage- and current-fed types. Each of these converters is further classified into three types according to the switching of the device. These are the hard switching converters, the snubbered converters and the soft switching converters.

4.1 Hard-Switching Converters [39]-[41],[50]

In hard switching converters, the device is stressed heavily during turn-on and turn-off. At turn-on the device voltage drops after the current reaches the load current, and at turn-off, the device voltage rises before the current equals zero. Furthermore, stray effects such as capacitance, inductance and diode reverse recovery further increase the switching losses. Example of a hard switching converter is the pulse width modulation (PWM) inverter which has replaced the square wave inverter. The PWM inverter has been implemented in many of the commercially available induction motor and BLDC drives [40]. In this technique the ac source voltage is converted to an uncontrolled dc voltage which is then converted to a variable voltage and frequency ac, using sinusoidally varying pulse width. This technique usually shifts the harmonics to a much higher frequency, and results in low filtering requirements in the load current which can be considered nearly sinusoidal. Figure 4 shows a typical switch voltage and current waveforms in a PWM dc to 3-phase inverter usually used in induction motor drives. The device voltage and current limits of the safe operating area (SOA) may be exceeded [50].

The major consequences of hard switching are low switching frequencies, high device stress and, hence, low reliability, reduced efficiency and limited power range for the converter (i.e. not applicable in high power)

4.2 Snubbered Switching Converters [45]-[50]

Snubbered switching is a modification of a PWM switch by adding a combined turn-on (a series inductor) to limit the inrush current and a turn-off capacitor snubber to limit the voltage rise. The purpose of the snubber is to reduce the stress on the device and operate the device within the SOA. The snubber provides an easy method to diverting the energy that would be dissipated in the device during the switching transition. In this switching, the parasitic elements destroy the effectiveness of the snubber and the diode reverse recovery causes severe EMI. Fig. 5 shows a typical dc/ac switch waveforms and SOA [50].

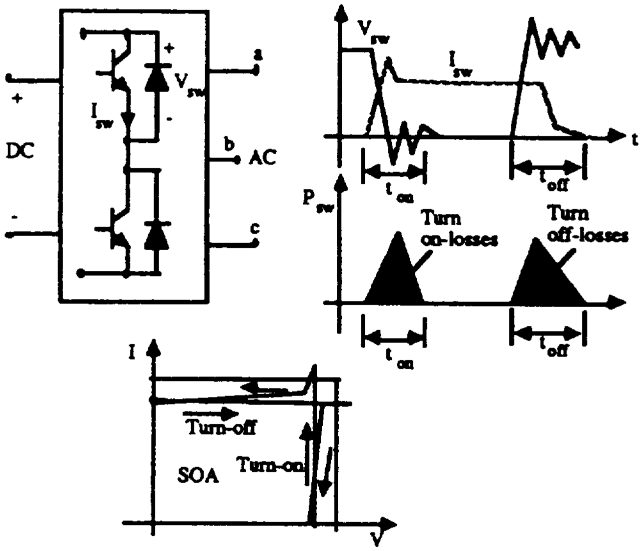


Figure 4 Switching device waveforms and SOA under hard switching

The consequences of snubber switching are high switching losses dissipated in the snubber, low switching frequency and requirement of special diodes, large inductors and low inductive power resistors.

4.3 Soft Switching Converters [7]-[12], [34]-[37]

In Snubber switching, normally, the stored energy has to be dissipated in an external resistor during a subsequent part of the switching cycle. However, a class of circuits has been shown to provide an automatic lossless resetting of the snubber network through inherent circuit operation. This allows for an oversizing of snubber network without incurring the normal penalty of trapped energy which needs to be dissipated. Such circuits are referred to as "soft switching converters".

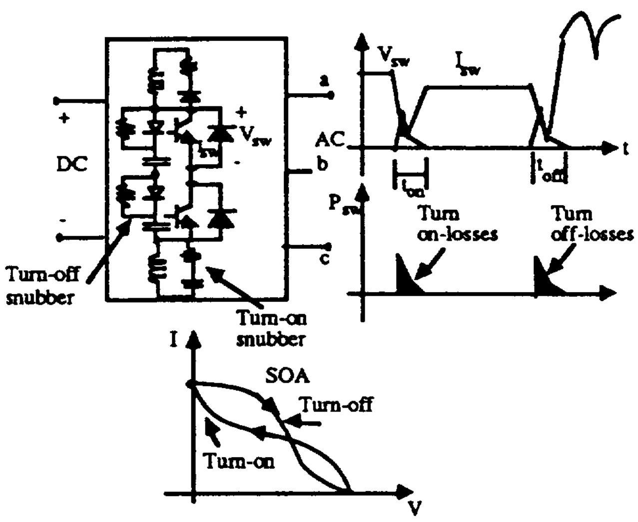


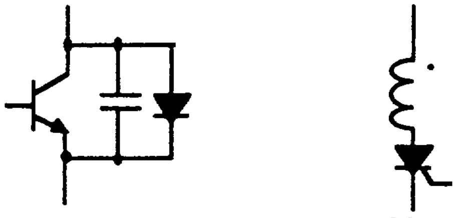
Figure 5 Switching device waveforms and SOA under snubbered switching

Soft switching converters are of two types. Zero current switching (ZCS) which uses purely inductive snubbers so that the device turn-on and turn-off occur with virtually no current in the device. Zero voltage switching (ZVS) use purely capacitive snubbers that require the device to turn-on with an anti-parallel diode conducting. Fig 6 shows the soft switch for ZVS and ZCS [12]. Fig. 7 shows the switch waveforms and SOA under ZVS [50]. At turn-on, the device voltage equals zero prior to initial current flow. At turn-off the device voltage is substantially reduced while the current is turned off. In this case, the parasitic elements are partially used in the circuit operation, and the diode reverse recovery is eliminated.

The consequences of the soft switching are reduced device losses that allows high switching frequencies, higher converter efficiency, and higher reliability.

With the use of PWM voltage source inverters, the adjustable speed ac drives became economically viable and competed with the prevalent dc drive technology. The PWM allowed the use of a single power stage for effecting fundamental voltage and frequency control simultaneously.

A typical 3-phase PWM voltage source inverter is shown in Fig. 8. This circuit is by far the most popular inverter used by the industry today. The topology has been implemented with a wide range of power devices, including MOSFETs, BJTs, IGTs and GTOs for a wide power range from 10 watts to 2 megawatts [12].



(a) ZVS (b) ZCS

Fig. 6 Soft-switching elements

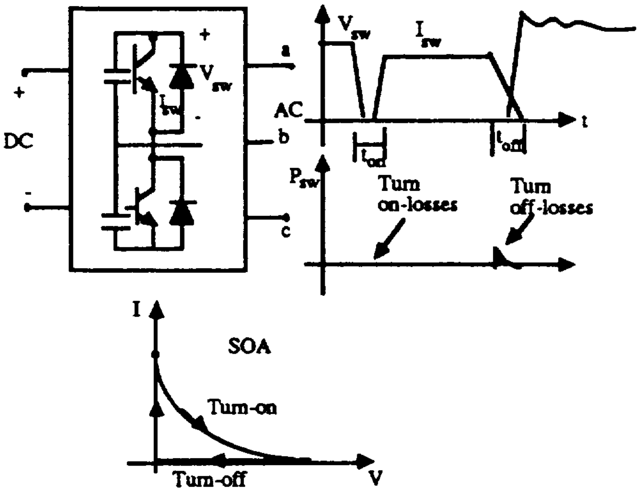


Figure 7 Switching device waveforms and SOA under ZVS

Advantages of the PWM inverter are the simple power structure, minimum Volt-Ampere (VA) rating of the device, easy control and low cost. The disadvantages are peak stresses in the devices as a result of inductive switching (typical in motor drives) and diode reverse recovery, the need for snubbers, and low switching frequency operation which causes acoustic noise and poor control. Other disadvantages include larger reactive and filter elements, low power density, high dv/dt that results in high electromagnetic interference/radio frequency interference (EMI/RFI) and acoustic noise, and possible destructive failures [7]-[12].

Two alternative soft switching topologies have been proposed, and are expected to overcome many of the limitations of the PWM inverters.. These are the resonant dc link converter and the resonant ac link converters, as discussed below.

4.3.1 The Resonant DC-Link Converter [7]- [9],[12]

Typically, the resonant dc link converter is used with a dc source, and drives a single machine. It converts a fixed dc input to a pulsating dc form [7]. The purpose of this conversion is to allow the devices to switch either at zero voltage (ZVS) or zero current (ZCS). Fig. 9 shows the actively-clamped resonant dc link inverter, one of the modifications of the conventional voltage-fed resonant dc link [12]. The clamp is proposed to limit the peak voltage stress on the devices to a reasonable value.

Compared with the PWM dc link converter, the resonant dc link offers many advantages such as low switching losses, higher efficiency, lower heat dissipation and less cooling requirements, higher operating frequency and low acoustic noise, improved device reliability, and low EMI problems due to reduced dv/dt and di/dt. Also, the resonant dc link does not require snubbers.

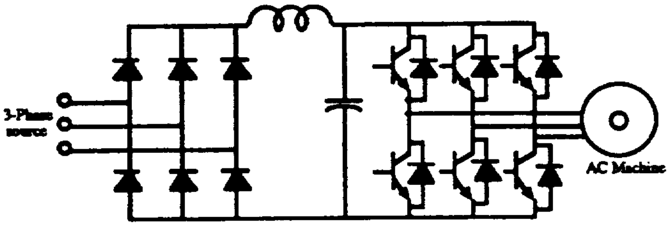
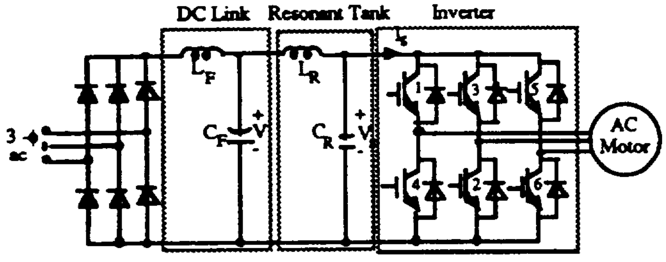
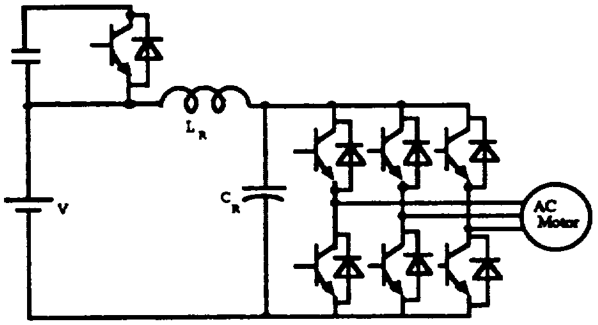


Fig. 8 Hard-switched PWM 3-phase voltage source inverter



(a) The conventional resonant dc link inverter



(b) The actively-clamped resonant dc link inverter

Fig. 9 Resonant dc link inverter topologies

4.3.2 The Resonant AC Link Converter [10]-[11]

The AC resonant link is intended to operate from a single phase high frequency link feeding many loads. It converts either a dc or a 3-phase low frequency voltage to a single-phase high frequency voltage which is then cycloconverted to a three-phase variable voltage and frequency for ac drives. The ac link voltage amplitude is maintained constant by a parallel resonant circuit as shown in Fig 10. This scheme, in addition to the advantages of the dc link, has bi-directional power flow (four quadrant operation), and its displacement power factor can be programmed to unity. Furthermore, the input power factor can be programmed to be unity, leading or lagging. Since the link voltage is ac, the devices should have symmetric voltage blocking capability and must carry bilateral current, as shown in Fig. 10. Both the input and output converters switch at zero voltage to synthesize the low frequency voltage waves by integral half cycle PWM method known as Pulse Density Modulation (PDM). The line currents are nearly sinusoidal, and the power can be controlled to flow in either direction. The need for high frequency switches is the principal drawback of the scheme. Also, since the tank capacity is small, any small mismatch between the input and output instantaneous power will tend to modulate the link voltage. Besides, the link frequency will drift because of the loading effect. This will cause harmonic deterioration of the input and output currents, and possible system instability during fast transients [40].

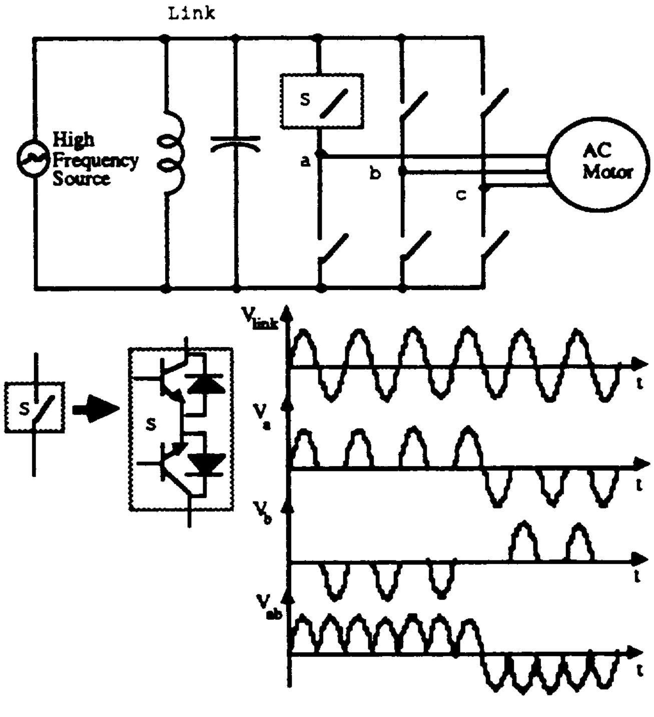


Fig. 10 The Resonant ac link converter system and configuration of ac switches

4.4 Converter Comparisons and Tradeoffs

In case of the power converter, the comparison should include the type of power devices, the converter rating, the direction of power flow, the harmonic content in the supply and motor, the line power factor, the levels of electromagnetic interference (EMI) and of acoustic noise, the efficiency, the cost and the control complexity. A comparison of the voltage-fed PWM , dc resonant link and ac resonant link converters is given in [40], and is summarized in Table 2. Although some of these comparisons may generally be true, it is believed that the continuing research in these converters and the advances in devices and their control may change some of the comparisons and tradeoffs. For example the control complexity could be a rapidly diminishing problem.

Table 2 : Comparison of voltage-fed hard- and soft-switching converters [40]

	PWM	Resonant DC Link	Resonant AC Link
Power devices	Asymmetric high frequency, fast recovery diodes	High frequency asymmetric ac switches	High frequency symmetric ac switch
Converter Rating	Hundreds of KWs to MWs	Tens of KWs	Tens of KWs
Power Flow	Only to output	Only to output*	Bidirectional power flow
Load & Line Harmonics	Low load and high line harmonics	Medium low Load & high line harmonics	Medium low load and line harmonics
Line power factor	Low due to high distortion current	Somewhat low	Near Unity. Leading or lagging possible
Acoustic noise	High	Very low	Very low
Losses & Efficiency	High switching loss & Medium Efficiency	No switching losses High efficiency	No switching losses and possibly high efficiency
Cost	Low to medium	Medium	High
Control Complexity	Somewhat complex	Complex	Very Complex
Comments	popular Technology in most ac drives	High future potential	Topology under development

* Bidirectional power flow may be possible [40]

5.0 Semiconductor Device Options [34]-[41]

The power semiconductor devices constitute the heart of modern power electronic converters. The trends in the devices are an important factor in assessing the technology of power converters. In a power circuit , although the cost of a device may not exceed 20 -30% of a converter total cost, the device heavily influences cost, size, weight and performance of the total power electronic apparatus. An important trend in power electronics is that the operating frequency of high power devices is continually increasing, and converter topology is undergoing modifications constantly to handle high frequency with high power, in order to shrink equipment size and improve its performance [40].

There are four options of the power devices that show potential for application in the power converters mentioned earlier. These are the Gate Turn-off thyristor (GTO), the power MOSFET, the Insulated Gate Transistor (IGT) and the MOS-Controlled thyristor (MCT). Although all the four devices are fully controlled, their characteristics, and application in terms of power and frequency ranges differ over a wide range. Fig. 11 gives a comparison of the four devices in terms of operating frequency and power handling capability, and the projections for 1990 through the first decade of the twenty first century [40]-[43]. The projections given in the figure are subject to the developments in each device. Such developments may change the frequency and power ranges. The next section discusses each of the four devices and their suitability for each of the aforementioned converters. This is followed by a comparison of the four devices.

5.1 Gate Turn-off Thyristors (GTO) [39]-[47]

The GTO is basically a thyristor-type device that can be turned on by a positive gate current pulse, and has the capability of being turned off by a negative gate current pulse. GTO's with improved characteristics are made possible due to the work of many Japanese corporations. It is available as a device with asymmetric or symmetric voltage blocking capability. It has poor turn-off current gain. A voltage spike in the anode voltage is introduced during turn-off, and due to the high current concentration, the device may create hot spots causing second breakdown. Therefore, a well designed snubber with large capacitor is necessary. The large switching losses of the GTO limit the device to a PWM frequency of 1.0-2.0 kHz. Typical uses of the GTO are in voltage source PWM inverter (600-1500 Vdc, 0.75 - 1.5 kVA and 500-600 Hz) or in soft switching ZVS (1.5-6.5 kVdc, 2 -12 MVA, and 700 - 1,200 Hz) [50]. The state of the art device ratings are about 4500 V, 3000 A [39].

5.2 Power MOSFETs

The power MOSFET is a unipolar, majority carrier, voltage controlled device. The power rating characteristics of power MOSFETs have been improved dramatically with a sharp fall in prices, and that makes them a key competitor to all other devices. The MOSFET offers a number of advantages compared to other power devices. It is an extremely fast device, with low switching losses and, therefore, minimal snubbing is required. It has a positive temperature coefficient of resistance which makes it easy to parallel a number of devices. This, also, causes the device to have negligible second breakdown. Two drawbacks of the device are the drain resistance which increases with the voltage rating (a $V^{2.5}$), and the slow reverse body diode in parallel with the device. Typically, MOSFETs are used in high frequency applications (hundreds of kHz) of a few watts to few kilowatts. Typical application can be in PWM voltage source inverters and a ZVS converter with ratings of 0-400 Vdc, 0.1-2 kVA, and 0.5-2 MHz. The device is popular in switch-mode power supplies and rarely used in ac drives [50]. However, if used in ac drives, the device will reduce the cooling requirements and increase reliability of the converter. The state of the art ratings of MOSFETs are 500 v with 140 A [39].

5.3 Insulated Gate Transistors (IGT) [39]-[43]

The IGT is basically a hybrid MOS-gated turn on/off bipolar junction transistor (BJT) that combines the attributes of a MOSFET and a BJT. The device was commercially introduced in 1983, and since then its ratings and characteristics have been improved significantly. The device offers significant advantages over the BJT in medium power (a few kilowatts to a few hundred kilowatts), medium frequency (upto 50 kHz) power converter applications. Typical applications of the device would be in PWM voltage source inverter (0 -750 Vdc, 0 -300 kVA, 1.5 - 5 kHz) drives and ZVS voltage source converter (750 Vdc, 20 -150 KVA, 40 kHz) drives [50]. In these drive applications, the device offers many advantages such as reduced cooling requirement and increased reliability, improved utilization and reduced voltage spikes at turn-off, lower module inductance, and improve thermal life. The state of the art modules available are upto 600V, 400 A, or 1200V, 300A ratings. It is expected that these ratings will be extended to 1200V, 500A [39].

5.4 MOS-Controlled Thyristors [34]-[43]

The MCT is a MOS-gated thyristor. It is more of a GTO-like switching device except that the turn-off current gain is very high. An MCT is a high power, high frequency, low conduction drop switching device. In switching speed, it is comparable to an IGT but has lower conduction drop. At present the device is still under development. The first commercially available MCT was out in 1993 (600 V, 75A). Developmental devices were released by Harris Semiconductor (500V/1000V, 50A/100A). The device is showing tremendous hopes for future applications in drives. especially in snubbered voltage source inverter (0 -400 Vdc, 0 -100 KVA, 2 kHz), ZVS converter (0- 400 Vdc, 20-150 KVA, 25 kHz), and ZCS converter (750 Vdc, 150 kVA, 40 KHz) drives [50]. The MCT will be a competitor with the GTO in the future.

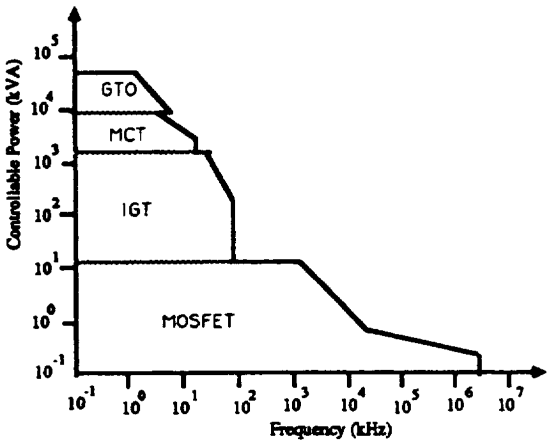


Fig. 11 Territories in power semiconductor devices

5.5 Device Comparisons and Tradeoffs [40]

From the above discussion, it seems that the candidate devices for EAs are the IGT, the GTO and the MCT. A good representative comparison between the three devices is given in [40] and is shown in Table 3.

Table 3: Comparison of the GTO, IGT and MCT [40]

	GTO POWEREX GDM2-30	IGT POWEREX ID226005	MCT Harris MCT60P75
Voltage & current rating	1200 V, 300 A (Peak)	600V, 100A (dc)	600V, 75A (rms)
Power Capability	4500 V, 3000 A	1200V, 400 A	
Voltage blocking	Symmetric or Asymmetric	Asymmetric	Asymmetric
Linear/trigger device	Trigger	Linear	Trigger
Gating	Current	Voltage	Voltage
Temperature (T_j)	- 40°C to 125°C	-20 to 150°C	-55 to 150°C (-196 to 250°C possible)
SOA limit	Second breakdown at turn off	T_j limited	T_j limited
Conduction drop at rated current	4.0 V	3.2 V	1.1 V
Drop sensitivity with °C	Negative	Negative (Positive at high current)	Negative
Switching frequency	up to 2.0 kHz	up to 20 kHz	up to 20 kHz
Turn-off current gain	4 to 5	-------	-------
Reapplied dv/dt	Limit for device loss	Limit for device loss	5,000 V/µs
Turn on di/dt	300 A/µs	Very high	1000 A/µs
Turn-on time	4.0 µs	0.9 µs	1.0 µs
Turn-off time	10 µs	1.4 µs	2.1 µs
Leakage current	30 mA	1.0 mA	1.0 mA
Snubber	Polarized or unpolarized	Polarized or snubberless	Polarized or Snubberless
Protection	Gate inhibit or fast fuse	Gate control	Gate inhibit or fast fuse
Comments	Large surge current capability	Developed and mature device	Device still under development. Expected to challenge IGT & GTO.

6.0 Control and Sensor Options [13]-[33], [40]-[41]

The control and input/output (I/O) signal processing of ac drives are definitely complex than those of dc drives. Two control techniques of ac drives are showing wide application in drives. One is the simple volts/hertz for ordinary application [6], [41], and the other is the vector or field-oriented control (FOC) for high performance applications [13], [41].

Fig. 12 shows the open-loop control volts/hertz of an induction motor where the machine is susceptible to speed and flux drifts. The voltage V_0 compensates the stator resistance drop at low speed. The speed command can only be ramped so that the actual speed tracks it within the maximum slip. The disadvantage of this method is that the dynamic response of the motor is sluggish, because both the torque and flux are functions of the stator voltage and frequency [40].

The vector control orients the flux component of the stator current or the direct-axis current (I_{ds}) to align with the direction of the rotor flux, and the torque component of the stator current or the quadrature-axis current (I_{qs}) to be orthogonal to the rotor flux. With this control, the dynamic performance of the induction motor is made almost identical to that of a separately excited dc motor [40]. Two methods of vector control are used, namely the indirect and direct vector control.. Many schemes of direct and indirect vector controls have been implemented [13].

The indirect vector control method, using current regulation, is shown in Fig. 13. The command flux component of the stator current (I_{ds}^*) is kept constant, whereas the command torque component of the current (I_{qs}^*) is controlled from the output of the speed loop. The slip signal (ω_{ls}^*) which is a function of I_{qs}^* is added to the rotor speed, and the unit vectors cos $\omega_e t$ and sin $\omega_e t$ are generated from the resulting signal.

The direct vector control method, using current regulation, is shown in Fig. 14. Here, the unit vectors are generated from the stator currents and the speed. If the machine speed is not very low, the stator voltages and currents can be processed to generate the unit vectors [13].

Precision implementation of vector-control is difficult, primarily because both the indirect and direct control methods are heavily dependent on the machine parameters. Tremendous work has been done on parameter tuning and adaptation to make vector control insensitive to parameter changes at all speeds [13]-[14].

The vector-control technique is also applicable to synchronous machines [28]-[33]. However, in a synchronous machine, the rotor pole position is absolute and, therefore, an absolute position encoder is mandatory. For conventional surface-type permanent magnet (SPM) synchronous machines, the vector control is similar to that of Fig. 13, except that the slip frequency (ω_{sl}^*) and the direct axis current (I_{ds}^*) are set to zero. The unit vectors cos $\omega_e t$ and sin $\omega_e t$ are generated directly from the absolute position sensor. The control orthogonally aligns the stator current I_{qs}^* to the magnet field flux. Recently, inverters and controllers integrated on one printed circuit board (PCB) have become available. Also, a single-chip power integrated circuit in the low power range, where the BLDCM is very popular, have became available.

In a switched reluctance motor, the machine must have an absolute position sensor that helps the controller to establish the phase current pulses [15]-[25]. Fig. 15 shows a typical switched reluctance motor drive. Recently, several indirect position sensing schemes have been reported in the literature. Some of the schemes are limited in performance, while others attempt to achieve the performance obtained from precision encoders and resolvers [20]-[25].

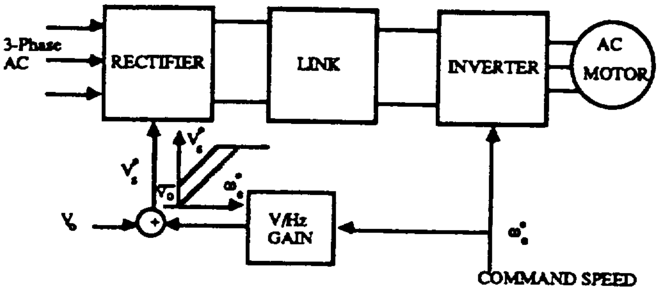


Fig 12 Open-loop volts/Hz control of an induction motor

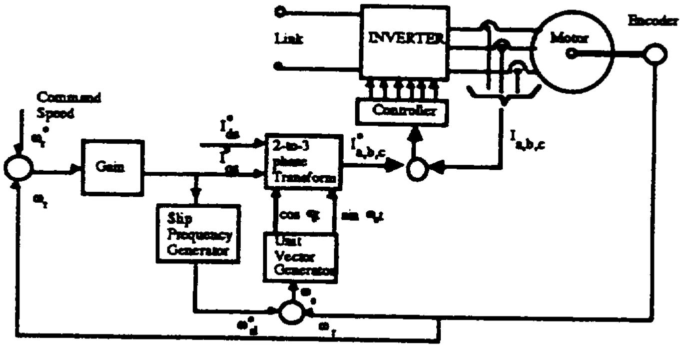


Fig 13 Indirect vector (field-oriented) control of an induction motor

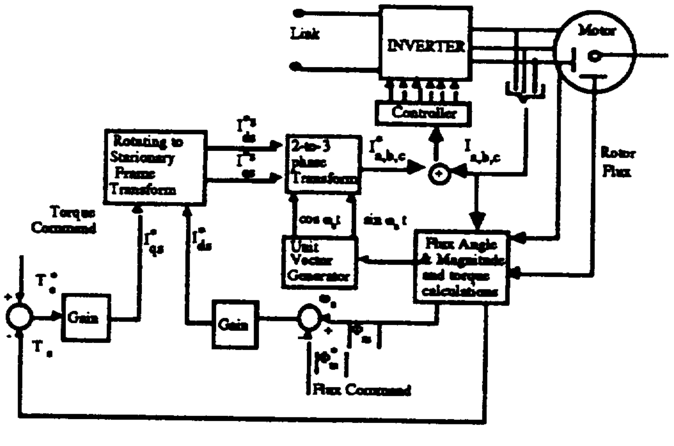


Fig 14 Direct vector (field-oriented) control of an induction motor

There has been, also, a tremendous interest in applying modern optimal and adaptive control theories to ac drives. Such controls increase the system robustness or insensitivity to parameter variation and load disturbance. Sliding mode or variable structure control has been successfully applied to induction and brushless dc motors [41]. Minimal research has focused on applying sliding-mode to switched reluctance machines.

Many of the above control schemes have been implemented using microcomputers and digital signal processors. This has permitted simplification of control hardware (thus, reducing size and cost), improved reliability, and eliminated EMI problems [40]-[41].

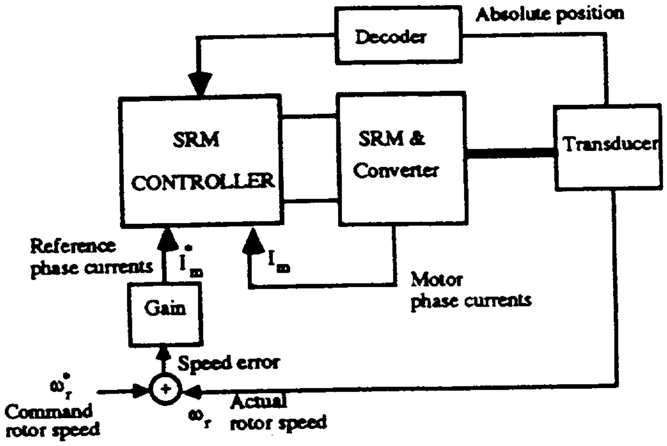


Fig. 15 Typical SRM drive

7.0 Conclusions and Directions for Future Research

The above study has shown that there has been considerable work done on the three ac brushless drive technologies and, as time progresses, there will be a lot of improvement in the design of motors, converters, power devices and controllers. Since there are many actuator loads in the PBW program, it seems that each of the three drives will have some advantages that will make a particular drive superior to the other two drives, when a specific load is considered.

It is recommended that more research be taken in the PBW program to compare the three drive technologies in the context of the PBW loads and their requirements. Issues such as reliability and redundancy of components, continuous power or torque/speed requirements, motoring/braking operation, dynamic or regenerative braking, overload rating and duration, supply voltage and frequency, torque/inertia ratio, torque/ampere, power density, acoustic noise, protection arrangements, control and communication interface, electromagnetic interference (EMI), environmental factors, direct or gearbox drive among many other issues, remain to be closely examined and compared for the three motor drives, using actual PBW loads. At this point, it is very difficult to favor any of the three drives over the other two. Each of the three drives has its potential for application in the PBW program.

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13. ABSTRACT *(Maximum 200 words)*

Power-By-Wire (PBW) is a program involving the replacement of hydraulic and pneumatic systems currently used in aircraft with an all-electric secondary power system. One of the largest loads of the all-electric secondary power system will be the motor loads which include pumps, compressors and Electrical Actuators (EAs). Issues of improved reliability, reduced maintenance and efficiency, among other advantages, are the motivation for replacing the existing aircraft actuators with electrical actuators. An EA system contains four major components. These are the motor, the power electronic converters, the actuator and the control system, including the sensors. This paper is a comparative literature review in motor drive technologies, with a focus on the trends and tradeoffs involved in the selection of a particular motor drive technology. The reported research comprises three motor drive technologies. These are the induction motor (IM), the brushless dc motor (BLDCM) and the switched reluctance motor (SRM). Each of the three drives has the potential for application in the PBW program. Many issues remain to be investigated and compared between the three motor drives, using actual mechanical loads expected in the PBW program.

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