VSDs for Electric Motor Systems

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ACKNOWLEDGEMENTS

The Project Officer in the European Commission, Directorate-General for Transport and Energy, SAVE II Programme 2000, in charge of this contract was Paolo Bertoldi, whose interaction with the project team is much appreciated. In particular we want to thank the collaboration of Dr. Herbert Auinger, Siemens, and Steve Schofield, British Pump Manufacturers Association. The successful implementation of the project was achieved not only by the commitment of the 6 partners, but also due to the valuable collaboration of many institutions and experts

ISR-University of Coimbra wants to acknowledge the several industrial/commercial companies including ABB, BELCHIOR, CLV, DANFOSS, EFACEC-Universal Motors, FIMEL, OMRON, SEW-Eurodrive and SIEMENS who have collaborated in the market characterization and in the analysis of the impacts tasks.

ETSU would like to thank the many people who have contributed to this work, in particular Roger Critchley, Alstom, Steve Parker, Siemens, and Professor Steven Williamson, UMIST, Manchester.

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EXECUTIVE SUMMARY

Electric motor systems are by far the most important type of load in industry, in the EU, using about 70% of the consumed electricity. In the tertiary sector although not so relevant, electric motor systems use one third of the consumed electricity. It is their wide use that makes motors particularly attractive for the application of efficiency improvements. In the previous SAVE II project, "Improving the Penetration of Energy Efficiency Motors and Drives", the application of Variable Speed Drives (VSDs) was identified as the motor systems technology having the most significant energy savings potential.

The loads in which the use of speed controls in electric drives can bring the largest energy savings are the fluid handling applications (pumps, compressors and fans) with variable flow requirements. Other applications which can benefit from the application of VSDs include conveyors, machine tools, lifts, centrifugal machines, etc.. The diffusion of speed controls for fluid circulation applications has been very slow. This is in striking contrast to process control applications for which speed/torque variation is necessary for industrial reasons, (for instance in paper production lines, or in steel mills), where the newest generation of electronic variable speed drives have become the standard technology. The dominant speed control technology - electronic VSDs coupled with alternated current (AC) 3-phase motors (induction or synchronous) - have practically replaced other technological solutions: mechanical, hydraulic as well as direct current (DC) motors.

In this report the main results of the "VSDs for Electric Motor Systems" project are presented. The project was carried out for the European Commission, and was sponsored by the Directorate-General for Transport and Energy, under the SAVE II Programme.

The main objectives of this project were:

- Characterisation of current market of the VSDs, in order to estimate per power range the average prices, the installation costs and, VSDs end-use, and the total sales in each country;
- Estimate the potential energy savings through the use of VSDs;
- Evaluation of the cost-benefit analysis of VSDs use/improvements;
- Analysis of the impacts on electric utilities, manufacturers (VSDs, motors and end-use devices), OEMs and end-user of VSDs;
- Identification of actions to promote VSDs;
- Dissemination of the results;

Market Characterisation

The current market for *VSDs* in the EU was characterised. Namely the number of units sold in each country, the average retail prices of *VSDs* per kW, the average installation costs, as well as the market segmentation by end-use and by type of VSD technology, was sought per power range. The information was collected, through several sources (questionnaires, trade associations, large manufacturers, etc.) in each country of the study (Denmark, United Kingdom and Ireland, France, Germany and Austria, Netherlands, Portugal and Spain). These European Union (EU) countries represent around 70% of the total EU VSD market, and the estimated average values were then extrapolated to the EU, based on previous SAVE studies and EU statistics. The base year for the market characterization was 1998.

Figure E.S.1 shows the number of VSDs sold in the EU per power range. This figure shows that the VSDs market, in 1998, was dominated by low power drives in the range of 0.75 to 4 kW, representing about 76% of the total units sold in the considered countries. Figure E.S.2 shows the disaggregation of the VSDs market by country in the EU. The number of VSD units sold in the EU in 1998 was 1 268 400, representing a total value of 930 400 000 Euros.

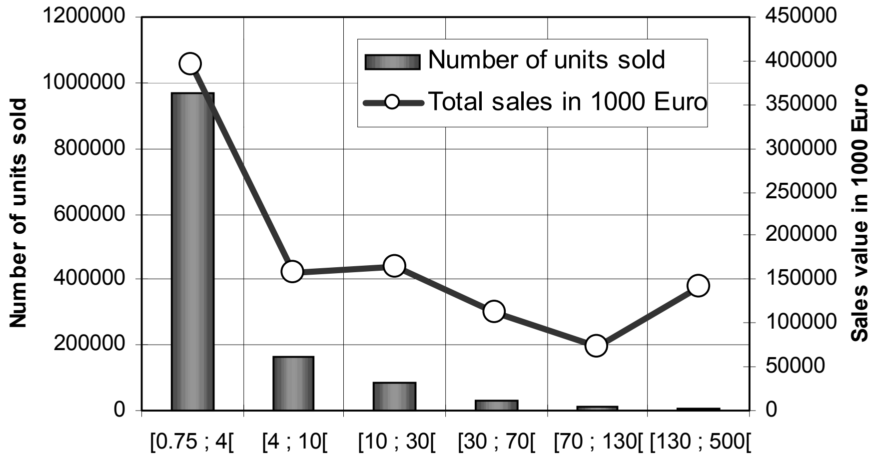


Figure E.S.1 - *Number of units sold in the EU and sales value per power range, in 1998.*

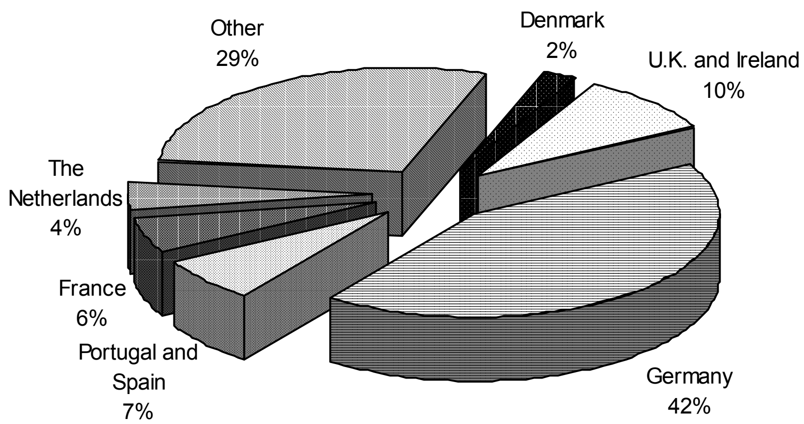


Figure E.S.2 - *Distribution of the VSD market in terms of the total number of units sold per each country.*

Induction motors are by far the dominant type of motor used with VSDs, but other more advanced motor designs are entering the market, particularly in the low power range.

Savings Potential

The estimated motor electricity consumption in the EU by 2015 is 721 TWh in Industry and 224 TWh in the tertiary sector. For the assessment of electricity savings potential with the application of VSDs, three different scenarios have been considered: the technical savings potential, economic savings potential assuming constant VSD prices, and the economic savings potential assuming a VSD price decrease of 5% per year. In general, VSDs are not cost-effective in the lower power ranges. Table E.S.1 summarises the technical and economic savings potential in the industrial and in the tertiary sector with the application of VSDs.

Table E.S.1 *- Estimated total electricity savings potential in TWh pa, by 2015.*

Potential Savings (TWh pa)		VSDs	
		Constant prices	5%/year price decrease
Economic Potential	Total Industry	39	43
	Total Tertiary	8	11
	Total	47	54
Technical Potential	Total Industry	62	
	Total Tertiary	22	
	Total	84	

The identified electricity savings potential with the application of VSDs, by 2015, would translate into 19 Mton CO_2 savings (Economic savings potential with VSD constant prices), contributing to the goal of reducing the greenhouse gas emissions in the E.U.. Table E.S.2 shows the technical and economic potential CO_2 and Euro savings in industry and in the tertiary sector, with the application of VSDs, by 2015.

Table E.S.2 *- Estimated total CO_2 and Euro savings potential in pa, by 2015.*

Total savings	Technical potential	Economical potential	
		Constant prices	5%/year price decrease
[1]Savings (Mton CO_2)	33	19	22
[2]Savings (Euro*10^6)	5600	2050	3500

[1] Considering average CO_2 emission of 0.4Kg CO_2/kWh generated.
[2] Considering average electricity prices of 0.05 and 0.1 Euro/kWh in industry and in the tertiary sector, respectively.

Cost/Benefit Analysis

Anticipated future developments in semiconductor technology are likely to lead to lower power loss devices and hence smaller and cheaper VSDs, which will further reduce costs. It is unlikely that the now standard Pulse Width Modulation (PWM) inverter will lose its dominant market share in the Low Voltage market. However, there are though other types of VSDs, particularly in low power range (< 7.5 kW), that look set to enjoy greater market share in niche applications, such as Switched Reluctance and Permanent Magnet drives. The availability of lower cost VSD "modules" is also hoped to offer a very low cost way to incorporate VSDs in low power OEM equipment, (similarly < 7.5 kW). Many manufacturers have introduced integrated motor/VSD units, and it is anticipated that sales of these will rise fast to become a significant part of the VSD market. While OEMs generally find it hard to pass on the extra costs of fitting their equipment with speed control as standard, there are cost and performance advantages from fundamentally re-designing some products to take advantage of variable speed operation. For instance, re-designing a centrifugal pump or an air compressor to work at variable speed can reduce both the cost premium of variable speed, and give an increase in efficiency to the basic machine.

While the falling price of VSDs has made them more cost effective, this has further reduced manufacturers profit margins, and the large number of suppliers makes the "lowest cost" market unattractive. An immediate effect of this situation is the much lower level of free application support available to purchasers of lower cost equipment. Successful manufacturers are differentiating themselves by for instance giving high levels of technical support, fast delivery of new units/spares, or dedicating themselves to particular industry sectors or applications.

Analysis of impacts

The influence of VSDs on the number of motors and quantity of materials used is disputed controversially. Some experts think that there is no significant difference in the number of motors sold caused by the application of VSDs. On the other hand there are examples of hundreds of pumps being saved by installing controlled larger pumps with VSDs. But there is also the impression, that the availability of VSDs and specialised motors leads to additional use of motors. Manufacturing of motors is also influenced by VSDs because of their higher requirements in the insulation. Insulation, therefore, has to be strengthened in motors which are used in connection with VSDs and may lead to slightly higher prices for the motors.

An increasing number of manufacturers are providing VSDs integrated to form a single unit with the motor, reducing costs by about 15% to 20%. However, integrated systems may have some deterrents: being part of the motor, the electronics may be contaminated by oil or other aggressive materials, they may suffer from the vibrations of the motor, and there are also the heating effects, specially for larger motors. The integration rate is estimated to be 6-15% and is expected to increase 20 to 30% in five years time and 30 to 50% in ten years time. If there is a significant increase in the penetration rate of VSDs it is expected that this will generate more business opportunities for VSD manufacturers and they lead to further price reduction. OEMs are still reluctant to integrated VSDs in their machinery. They only offer VSDs in their products if the benefits for outweigh the costs. In applications such as HVAC systems, small pumps and compressed air systems, OEMs already apply VSDs and offer integrated systems. Some OEMs are also applying VSDs integrated in their machinery for motors up to 75 kW, since these integrated systems lead to lower installation costs and higher reliability.

It is not expected that an increased number of VSDs shall have an impact on the shape of the load curve. In the long-term evaluation, the load curve will decrease throughout all 24 hours of the day, rather than “shrink” in the daytime period. This is based on the fact that the main energy-savings potential lies in larger motors, which are mostly applied by major industries and large-scale consumers rather than in private homes, agricultural machines and so forth. These large consumers often have a 24-hour production period.

Actions to promote VSDs

Although there is a large electricity savings potential associated with the use of VSDs, they still are not perceived sufficiently as good value for money in many motor system applications. Market parties will only buy or integrate VSDs if they perceive a favourable balance between alleged benefits and expected efforts (including money, time and risks).

Table E.S.3 summarises the various identified actions to promote VSDs and gives a brief indication on their cost efficiency. Most actions are system related and not specifically aimed at VSDs as such. The present market requires a system approach. Most energy benefits with VSDs also result from their integration in motor systems. The study team identified several basic approaches. None of these will likely do the job alone; however they can be considered as extremes in which, depending on preferences of the policy makers, a balance should be found.

- **The ‘awareness’ approach** - An essential approach in innovation is making information and know-how available. This aims to increase awareness with relevant parties. This approach deals with overcoming the lack of information and of know how.
- **The ‘demand stimulation’ approach** - This approach focuses on increasing market demand. The core would obviously be negotiated agreements with end-users on utilities. This step is planned in the Green Motor programme.
- **The ‘improved services’ approach** - The focus in this approach is stimulating and facilitating system suppliers and installers to develop product or service packages that better suit present market demand. The suppliers have to shift from product sellers towards providers of total solutions integrating VSDs.

- **The 'prescriptive' approach** - Activities could also aim at developing standards and minimum efficiency levels. The OEM sector would likely be more defensive in defining standards, labels, etc. This would be a very costly approach, only feasible for selected specific systems. Control measures and sanctions in case of non-compliance, are cumbersome and would add extra cost and efforts.

***Table E.S.3 -** Indicative summary of cost-efficiency of various actions in disseminating VSD.*

Overview of actions				
The actions	*Cost*	*Likely cost-efficiency*	*Time to effect*	*VSD applications that (may) benefit*
Negotiated agreements				
- on energy efficiency	medium	Limited	medium	all
- on utilities	medium	Good	medium	all
Procurement/contests/awards	high	Medium		only possible for some priority subsegments
Labelling/testing/standards:				
- for VSDs	high	Low	medium	not relevant
- for systems with VSD	high	Low	long	not considered feasible
Joint action of OEM sectors	medium	Good	medium	priority segments
Information/training				
- decision support tools and databases	medium	Good	medium	per application type
- guidelines, formats, cases	limited	Good	short	all
- training material	limited	Medium/good	short	all
- articles, PR, internet	limited	Good	short	all, mainly as support to other actions!
Technical demonstration projects	medium	Limited	medium	in present market little added value
Subsidies/fiscal incentives	medium	Limited	medium	to be considered if specific financial barriers occur with other actions
Negotiated agreements with:				
- VSD suppliers	medium	Low	medium	all
- OEM sectors	medium	Medium	medium	priority segments
-				
Outsourcing:				
- guidelines	limited	Good	short	
- case material	limited	Good	medium	

Improving the awareness of relevant parties combined with demand stimulation and the promotion of improved energy services is recommended. The Green Motor Programme offers a good basis for integration of actions for dissemination of VSDs.

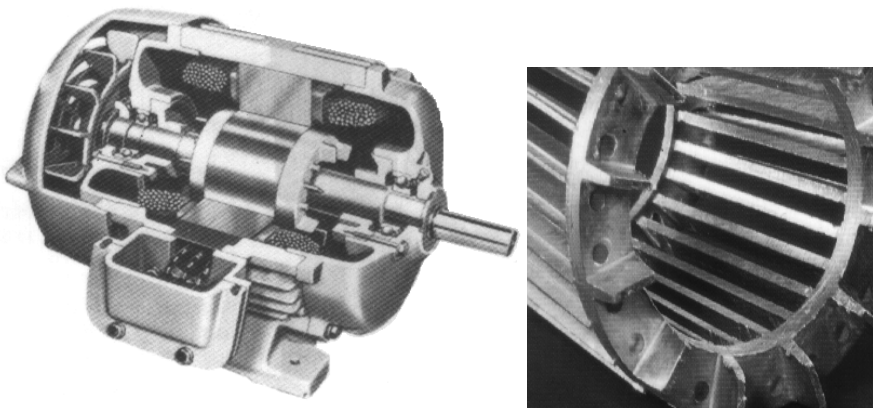
The proposed actions require a high degree of commitment of the parties involved and a close collaboration with market parties. It is essential that the actions be developed and implemented in close co-operation with the relevant market parties. To this end the European Commission could consider an advisory committee with relevant trade associations of the involved market parties for further development of pilot actions.

1. VARIABLE SPEED DRIVES - TECHNOLOGY ASSESSMENT

1.1 Main Types of motors

1.1.1 Induction Motor

The induction motor is by far the most widely used choice for development application in industry and in the tertiary sector. Being both rugged and reliable, it is also the preferred choice for the variable-speed drive applications. Low cost, high reliability, fairly high efficiency, coupled with its ease of manufacture, makes it readily available in most parts of the world. Figure 1.1 shows the typical constitution of a *Squirrel-Cage Induction Motor*, which is composed by three sets of stator windings arranged around the stator core. There are no electrical connections to the rotor, which means that there are no brushes, commutator or slip rings to maintain and replace. Large induction motor can also have a wound rotor - *Wound-Rotor Induction Motor*. As the name suggests, these motors feature insulated copper windings in the rotor similar to those in the stator. The rotor windings are fed with power using slip rings and brushes, and therefore this rotor is substantially more costly, presenting more maintenance problems than squirrel-cage rotors. This type of induction motor was used in industrial applications in which the starting current, torque, and speed need to be precisely controlled. In new applications squirrel cage motors are by far the most widely used solution.



(a) (b)

Figure 1.1 *- Squirrel-Cage Induction Motor:*

(a) General structure; (b) Rotor Squirrel Cage (bars and end rings).

In the induction motor, a rotating magnetic field is created in the stator by AC currents carried in stator windings. A three-phase voltage supply applied to the stator windings results in the creation of a magnetic field that moves around the stator - a rotating magnetic field. The moving magnetic field induces currents in the rotor conductors, in turn creating the rotor magnetic field. Magnetic forces in the rotor tend to follow the stator magnetic field, creating a motor torque. The speed of an induction motor is determined by the frequency of the power supply, the motor number of poles, and to a smaller extent by the motor load. The speed decreases a few percent (typically 1-3%) when the motor goes from no-load to full load operation. Driven directly from the mains supply, induction motors have essentially a constant speed. Therefore, to control the motor speed, without the use of external mechanical devices, it is necessary to control the power supply frequency.

Many motor applications would benefit in terms of energy consumption and process improvement, if the motor speed was modulated as a function of the process requirements.

1.1.2 Permanent Magnet Motor

Permanent Magnet (PM) Motors have a stator winding configuration similar to the three phase induction motors, but they use permanent magnets in the rotor instead a squirrel cage rotor or a wound rotor. The permanent magnet rotor tracks with synchronism the stator rotating field, and therefore, the rotor speed is equal to the rotating magnetic field speed. A wide variety of configurations is possible, and the 2-pole version can be seen in Figure 1.2. Motors of this sort have output ranging from about 100 W up to 100 kW. The key advantage of the permanent-magnet motor is that no excitation power is required for the rotor and therefore its efficiency is higher than the induction motor. Early permanent-magnet motors besides being very expensive, suffered from the tendency for the magnets to be demagnetised by the high stator currents during starting, and from a low maximum allowable temperature. Much improved versions using high coercivity rare-earth magnet were developed since the 1970s to overcome these problems. Rare-earth alloys namely, Ne-Fe-Bo, developed in the mid-eighties have allowed increase in performance with a decrease in costs. For starting from a fixed-frequency supply a rotor cage is required. They are usually referred to as "line-start" motors, to indicate that they are designed for direct-on-line starting. Because there are no electric and magnetic losses in the rotor, cooling is much better than in a conventional motor, so higher specific outputs can be achieved. The rotor inertia can also be less than that of an induction motor rotor, which means that the torque/inertia ratio is better, giving a higher acceleration. The torque to weight ratio, the steady-state efficiency and the power factor at full load of PM motors are in most cases better than the equivalent induction motor, and they can pull in to synchronism with inertia loads of many times rotor inertia.

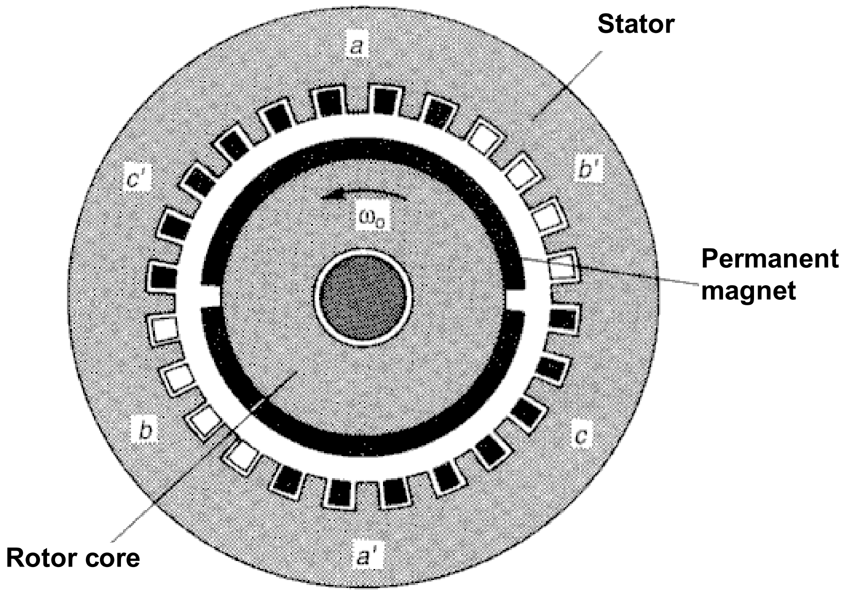


Figure 1.2 *- Permanent Magnet Motor: 2 pole version.*

Although better efficiency and low speed performance can be obtained with permanent magnet synchronous motors there would need to happen a significant reduction in the cost of rare-earth permanent magnet material for these motors to the replace induction motors in most applications. Permanent magnet motors are in most cases used with electronic speed controls, being normally called brushless DC motor (BLDCs). In the brushless D.C. motor, the stator windings currents are electronically commutated by digital signals from simple rotor position sensors. The stator winding also creates a rotating field which creates a rotating torque by pulling the permanent magnet rotor. This combination permits the motor to develop a smooth torque, regardless of speed. Very large number of brushless D.C. motors is now used, particularly in sizes below 10 kW. The small versions (less than 0.75 kW) are increasingly made with all the control and power electronic circuits integrated at one end of the motor. The typical stator winding arrangement, and the control scheme are shown in the Figure 1.3.

Many brushless motors are used in demanding servo-type applications (e.g. robotics and high performance mechatronic systems), where they need to be integrated with digitally controlled systems. For this sort of application, complete digital control systems which provide torque, speed and position control are available. New applications such as energy-efficient lifts, with direct-drive (gearless) permanent magnet motors are also entering into the market.

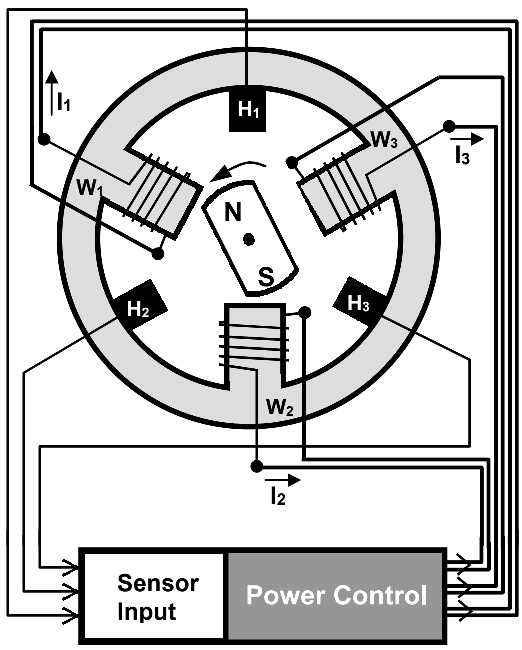


Figure 1.3 *- Control system scheme of a Brushless DC Motor*
(H_1, H_2 and H_3 are magnetic Hall position sensors).

1.1.3 Switched Reluctance Motor

The switched reluctance (SR) drive is a recent arrival on the drives scene, and can offer advantages in terms of efficiency, power density, robustness and operational flexibility. The drawbacks is that it is relatively unproven, can be noisy, and inherently not well-suited to smooth torque production. Despite being recent, SR technology has been successfully applied to a wide range of applications including general purpose industrial drives, traction, domestic appliances, and office and business equipment.
In the switched reluctance motor both the rotor and the stator have salient poles. This doubly-salient arrangement proves to be very effective as far as electromagnetic energy conversion is concerned. The stator has coils on each pole, the coils on opposite poles being connected in series. The rotor, which is made from machined steel, has no windings or magnets and is therefore cheap to manufacture and extremely robust. The example shown in Figure 2.4 has eight stator poles and six rotor poles, and represents a widely used arrangement, but other pole combinations are used to suit different applications. The motor rotates by energising the phases sequentially in the sequence a-a', b-b', c-c' for anticlockwise rotation or a-a', c-c', b-b' for clockwise rotation, the "nearest" pair of rotor poles being pulled into alignment with the appropriate stator poles by reluctance torque action. In this way, similarly to PM motors, the rotor tracks synchronously the stator rotating magnetic. field.

In a way also similar to the PM motor the SR motor has no electric and magnetic losses in the rotor. Therefore the overall efficiency is generally higher than induction motor efficiency. The SR motor is designed for synchronous operation, and the phases are switched by signals derived from a shaft-mounted rotor position detector. This causes the behaviour of the SR motor to resemble that of a BLDC motor. Because the direction of torque in a reluctance motor is independent of the direction of the current, it means that the power converter can have fewer switching devices than the six required for 3-phase bipolar inverters used in BLDC motor. Some of the early SR motors were deemed to be very noisy, but improved mechanical design has significantly reduced the motor noise.

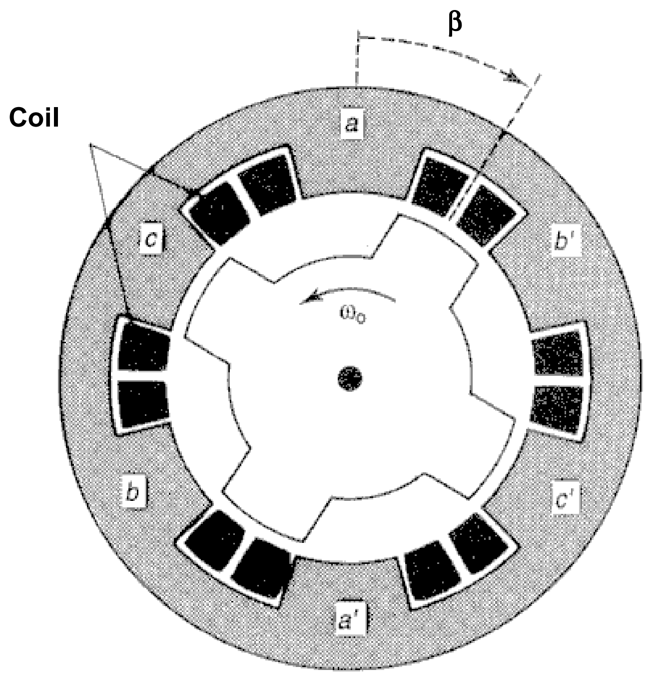


Figure 1.4 *- Switched reluctance motor configuration.*

1.2 Electronic Variable Speed Drives

As previously mentioned, the speed of the rotating field created by the induction motor stator windings is directly linked with the voltage frequency applied to the windings. Electronic Variable Speed Drives can produce variable frequency, variable voltage waveforms. If these waveforms are applied to the stator windings there will be a shift of torque-speed curve, maintaining a constant pull-out torque, and the same slope of the linear operation region of the curve. In this way, the motor speed is going to be proportional to the applied frequency generated by the VSD (Figure 1.5).

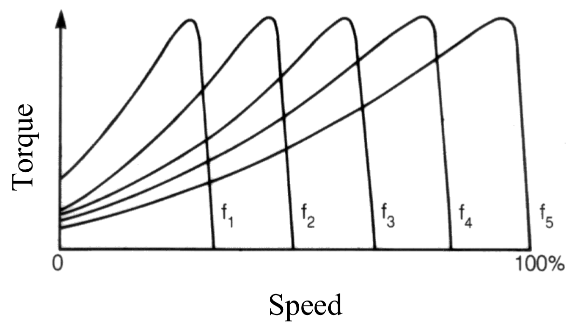


Figure 1.5 *- Speed-Torque Curves for an Induction Motor ($f_1<f_2<f_3<f_4<f_5$ and f_5=50Hz).*

Figure 1.6 shows the general configuration of most VSDs. The three-phase, 50Hz alternated current (AC) supply is initially converted to direct current (DC), then filtered and finally, the DC/AC inverter converts the DC voltage to the variable voltage and variable frequency output applied to the motor.

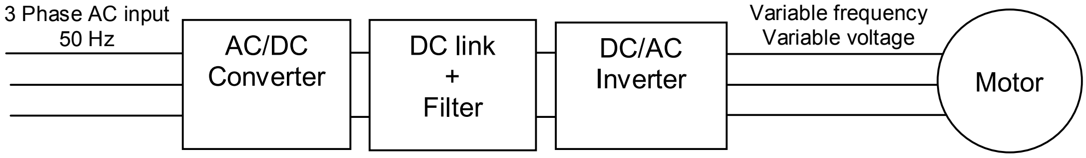


Figure 1.6 *- General Configuration of Inverter Based VSDs.*

The adjustment of the motor speed through the use of VSDs can lead to better process control, less wear in the mechanical equipment, less acoustical noise, and significant energy savings. However, VSDs can have some disadvantages such as electromagnetic interference (EMI) generation, current harmonics introduction into the supply and the possible reduction of efficiency and lifetime of old motors.

Table 1.1 presents an overview of controlled AC-drive technologies, showing five basic forms of power electronic VSDs.

Table 1.1 - Overview of power electronic VSDs [1]

Type of VSD	**Main characteristics**	
	Advantages	***Disadvantages***
Pulse-Width Modulation (PWM) Voltage Source Inverter (VSI)	Good power factor throughout speed range. Low distortion of motor current. Wide speed range (100:1). Multi motor capability.	Limited to VSDs bellow 1 MW. Slightly (about 1%) less efficient than VSI or CSI. Basic circuit has no regeneration capability.
Six-step Voltage-Source Inverter (VSI)	Good efficiency. Simple circuit configuration. Wide speed range (10-200%). Multi-motor capability.	Poor power factor at low speeds (unless a rectifier/chopper AC/DC converter is used). No regeneration capability. Operation below 10% of rated speed can produce cogging.
Force Commutated Current-Source Inverter (CSI)	Simple and robust circuit design. Regenerative capability. Built-in short circuit protection. Wide speed range (10-150%).	Bulky. Poor power factor at low speed/load. Possible cogging below 10% of rated speed.
Load-Commutated Inverter (LCI)	Simple and inexpensive circuit design. Regeneration capability. Built-in short-circuit protection.	Poor power factor at low speed. Can only be used with synchronous motors.
Cyclo-Converters	Can operate down to zero speed. High torque capability with field-oriented control. Can be used with induction and synchronous motors.	Cannot be used above 33% of input frequency. Complex circuit design. Poor power factor at low speed.

1.2.1 Voltage Source Inverters (VSI)

The three-phase voltage source inverter (VSI) is used to control AC-motors in the lower and medium power ranges, from small high dynamic performance servo drives with speed and position control capability (<10kW) to most auxiliary drives in industry, ranging up to several hundred kW. The VSI is suitable for supplying induction, as well as synchronous motors. Figure 1.10 shows a simplified diagram of the basic three-phase voltage source inverter. The input rectifier serves to produce a DC supply, and the relatively large electrolytic capacitor is inserted to filter ("stiffen") the DC voltage which feeds the inverter. Typically, the capacitor of 2 to 20 milifarads, is a mayor cost item in the system. Additionally, it is usual to insert a reactance between the rectifier and the AC supply to limit the fault current and to reduce the harmonic distortion produced by the rectifier. The inverter module converts the DC voltage to a variable frequency, variable voltage output.

Pulse Width Modulated (PWM) Voltage Source-Inverter

Given the basic VSI power circuit, the PWM voltage source inverter is widely accepted as giving the best overall performance below power levels of 1 MW. The PWM inverter maintains a nearly constant DC link voltage, combining both voltage control and frequency control within the inverter itself. The objective of the sinusoidal PWM is to synthesise the motor currents as near to a sinusoid as economically possible. The lower voltage harmonics can be greatly attenuated, and therefore the motor tends to rotate more smoothly at low speed. Higher order harmonic motor currents are limited by the motor inductance. Torque pulsations are virtually eliminated and the extra motor losses caused by the inverter are substantially reduced. To counterbalance these advantages, the inverter control is complex, the switching frequency of the semiconductor power switches is high (typically 500-2500 Hz for GTOs and above 5 kHz for transistors), and the inverter losses are slightly higher than in other modes of operation.

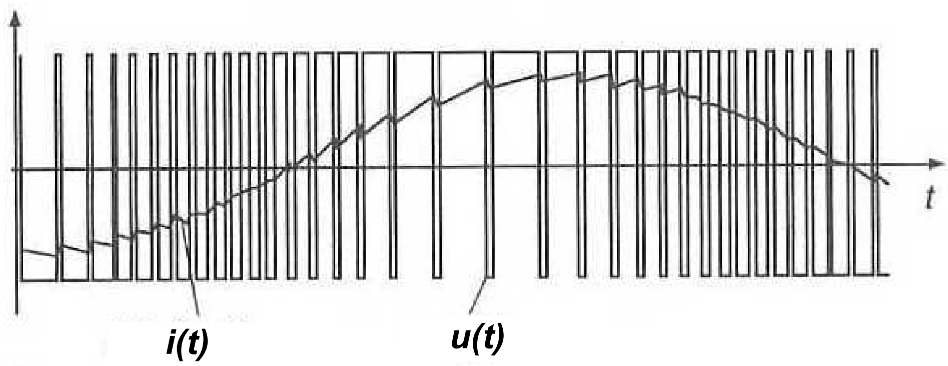


Figure 1.7 - Illustration of a sinusoidal pulse width modulation technique.

More recently, low-to-medium power switches such as IGBTs, or MOSFETs (see Table 1.2), have a switching frequency above 18kHz, i.e., beyond the audible range, so that no objectionable acoustic noise is produced by the VSD magnetic components. The use of transistor PWM VSDs is presently restricted up to few MW. With GTO's the power of the PWM converter extends far into the MW-region.

The advantages of the PWM VSD are the good displacement power factor throughout speed range, low distortion of the motor current, wide speed range, and with proper topology, the regeneration capability.

TECHNICAL NOTE 1

Modern semiconductor technology has provided a wide variety of electronic switches that can be used in the VSDs. In Figure 1.8 the most important semiconductor devices, in symbolic form, can be seen. The typical ratings are shown in the Table 1.2.

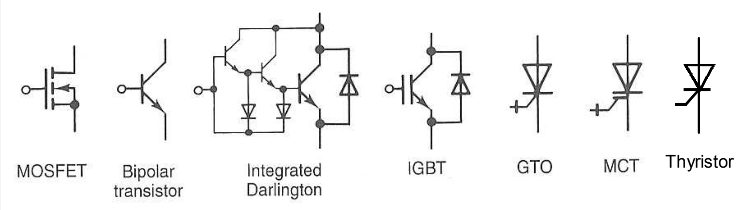


Figure 1.8 *- Power semiconductor switches.*

Table 1.2 - Typical ratings of the most important power semiconductor switches.

	MOSFET	Bipolar Transistor	Integrated Darlington	IGBT	Thyristor	GTO	MCT
Current	50A	500A	3500A	6000A	10000A	6000A	100A
Voltage	500V	1200V	1800V	1800V	7000V	4500V	600V
Frequency	50kHz	2-5kHz	2-10kHz	50kHz	500Hz	3kHz	20kHz

Transistors have nearly completely replaced thyristors in inverter circuits below 1 MW. IGBTs (Insulated Gate Bipolar Transistors) and MOSFETs (Field Effect Transistors) are more recent additions to the transistor family, and IGBTs have effectively replaced BJTs (Bipolar Junction Transistors) in many applications. Overall losses, parts count, and driver cost are markedly reduced with these devices resulting in an increasingly competitive product, even though the devices remain more expensive than a BJT. GTOs (Gate Turn Off Thyristors) are presently available for more than 4500 volts and are becoming widely used in inverters if the motor power exceeds a few hundred horsepower. The availability of BJTs, IGBT, and GTOs first led to the replacement of the conventional thyristors. With the addition of a small capacitor filter in the induction machine input terminals, in conjunction with the machine inductance, there is a great improvement of the waveforms of the voltage and current applied to the machine. Although in principle the voltage-fed inverter is more prone to reliability problems in a harsh environment than the current-fed inverter, protection and control schemes were developed that enabled reliable application for both types of VSDs. Voltage-fed inverters do not need reverse blocking devices, favoring the modern devices such as IGBTs and GTOs. It was the availability of MOSFETs, BJTs and IGBTs that led to the successful penetration of the entire power range (up to a few MWs) by the three-phase diode rectifier-fed, pulse width modulation (PWM) inverter drive for induction machines, allowing quasi-sinusoidal machine waveforms and almost eliminating torque pulsations. The MCT (MOS controlled thyristor) is a promising high switching frequency device that has not yet reached a mature state of development to compete with the existing electronic switches at higher power levels.

Open Loop PWM Inverter - This is still the most widely used PWM control type. The control circuit maintains approximately constant air-gap flux in the machine by constant voltage/frequency control (the current is approximately constant), as it can be seen in Figure 1.9. A constant off-set is added for the stator resistance voltage drop at low frequency/speed (commonly referred as torque boost). When a step-speed change command is applied, the motor accelerates within a current limit, until a steady state condition is reached. The dynamic performance of such systems is poor, relative to the other control strategies, with limited torque control capabilities. Speed regulation is relatively poor as the actual speed feedback is not available as a control variable. However, due to its low-cost this type of VSD is the most widely used in energy saving applications (e.g. control of fans and pumps in which the speed accuracy is not critical). For many mechanical loads, such as pumps or fans, there is no need for high dynamic performance, as long as the speed can be varied with high efficiency over the desired speed range.

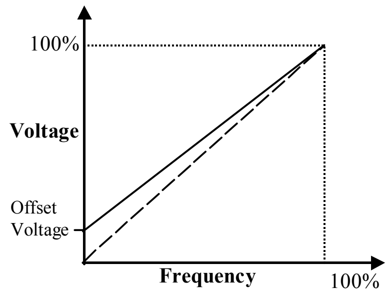


Figure 1.9 *- VSD output Voltage/Frequency relationship showing voltage offset. Other relationship (which deviate somewhat from a fixed V/Hz ratio) are available to suit special applications.*

Closed loop control - By adding a sensor signal for the measured speed, and a reference for the stator speed adjustment in the steady state, *VSDs* can have more accuracy in speed, but this type of control can not be used for high performance applications.

Regenerative Topology versus Dissipative Topology - Typically, the generated (braking) power in the motor operation in the 2nd and 4th quadrants (Figure 1.12), is dissipated in a resistance, as shown in Figure 1.10. As long as the power level is low or when regeneration only occurs occasionally, for instance, during dynamic braking of a conveyor drive, the reverse power is usually dissipated in a ballast resistor, that discharges the link capacitor when the link voltage rises above a preset value.

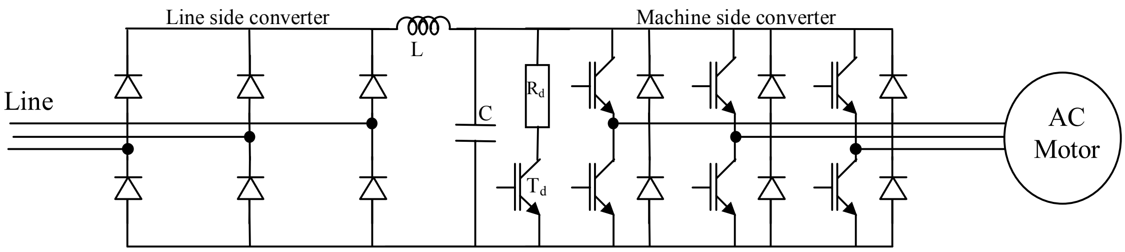


Figure 1.10 *- Topology of an VSI-PWM with dissipation resistance (R_d).*

When the power rating is large and/or the fact that the motor may have to operate for long periods of time in the regenerating region, the line-side converter can be modified to allow regeneration, feeding power back to the line by reversing the direct current in the DC link. New PWM topologies (Figure 1.11) allow that the braking energy be injected back to the source. This feature can be a way of saving a significant amount of energy in applications with high speed/high inertia (ex.: centrifugal separators) and/or long time operations in the braking mode (ex.: Lift).

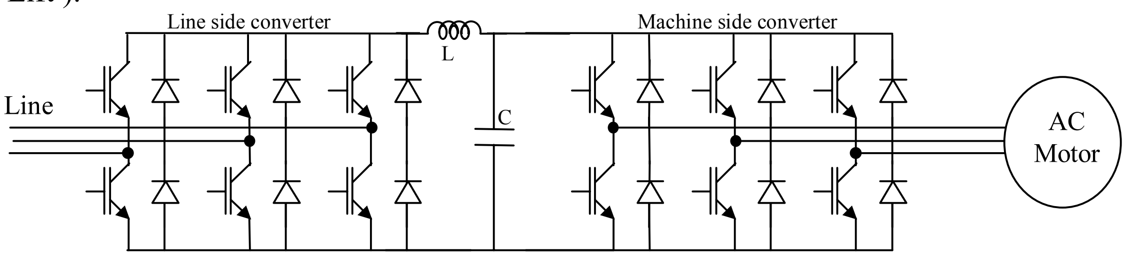


Figure 1.11 *- Topology of an VSI-PWM with regenerative capacity and power factor control.*

Undesirable harmonics can be reduced by choosing a sufficiently high switching frequency (limited by the switching devices), and suitable modulation techniques, both in the motor side and in the line-side part of the converter. Also, the type of AC/DC converter used allows to control the power factor and harmonic distortion in the input stage (supply side). The switching devices used in the AC/DC and DC/AC converters are typically the same (ex.: IGBTs for low-medium power and GTOs for very high power).

TECHNICAL NOTE 2

The supply interaction has remained a problem over the entire power range, in terms of power factor and/or harmonic distortion. . This supply interaction can be solved for regenerative systems (Fig.2.12 shows the 4 operating modes of an electric traction drive) by the four-quadrant converter. The double PWM voltage-fed structure shown in Figure 2.13 represents the ultimate power electronic solution in terms of PWM voltage-fed converter technology regarding a supply-friendly and machine-friendly converter system. Not only regeneration is achieved, but high power factor and low harmonic distortion can be achieved over all the speed range.

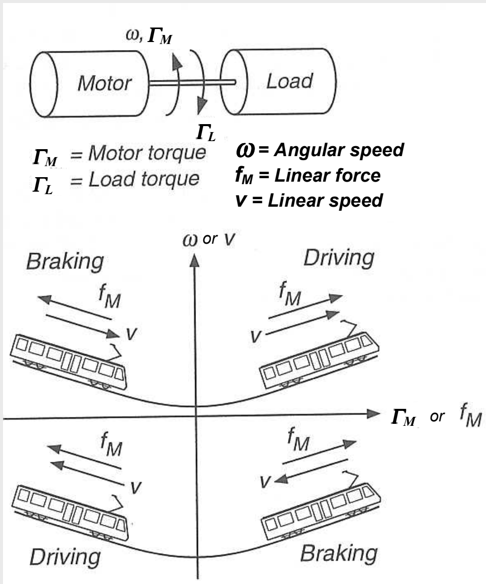


Figure 1.12 *- Operating modes of an electric drive.*

1.2.2 Current Source Inverter (CSI)

In current-source inverter (CSI) drives, the inverter switches are fed from a constant current source. While a true constant current source can never be a reality, it is reasonably approximated by a controlled rectifier (thyristor or GTO) with a current control loop with a large DC link inductor to smooth the current. Figure 1.13 shows a typical circuit of a CSI. Since the current is constant, there will be zero voltage drop across the stator winding self-inductance and a constant voltage drop across the winding resistances. Hence, the motor terminal voltage is not set by the inverter but by the motor. Since the motor is wound with sinusoidally distributed windings, the resulting voltages that appear on the motor terminals are nearly sinusoidal. The motor voltage and current waveforms are shown in Figure 1.15. The CSI produces harmonic currents and harmonic voltages in the motor side, which are limited by the induction motor reactance. The CSI are used for large drives (typically above 500 kW) due to their simplicity, regeneration capabilities, reliability and low speed requirements for the power devices. The power factor is poor at low speeds, as the input stage is a phase-controlled rectifier that uses a small conduction angle at low speed, low voltage operation. The combination of a large inductor in the DC link (L), high voltage thyristors and components to suppress output voltage transients make this converter impractical for small size inverters. In industrial and traction applications these current-source converters are robust in operation and reliable due to the insensitivity to short circuits and noisy environments.

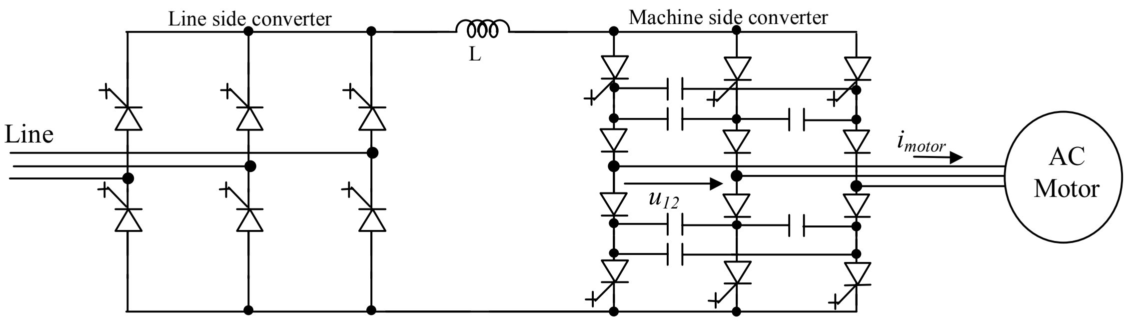


Figure 1.13 *- Diagram of VSD using current-source inverter.*

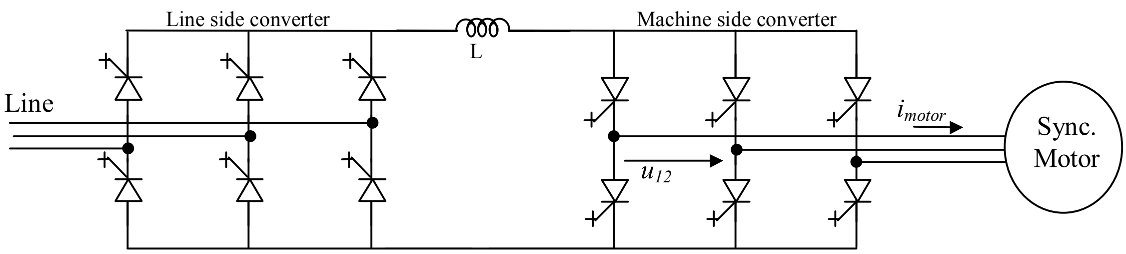


Figure 1.14 *- Typical circuit for synchronous motor VSD system.*

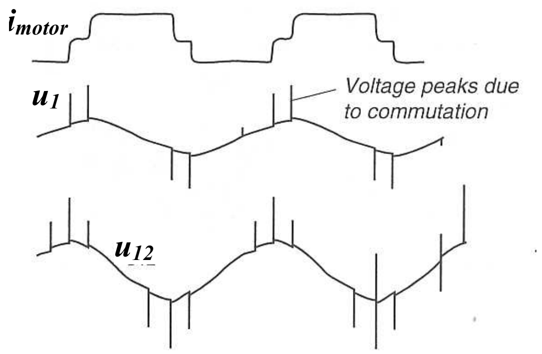


Figure 1.15 *- Six-step current source inverter waveforms showing motor line currents and motor voltages.*

Pulse with modulation can be used to suppress the low frequency 5th and 7th harmonic torque pulsations, which are inherent in the six-step current waveform. A major disadvantage of this scheme is the potential for resonance between the capacitors and the motor inductances. This possibility can be avoided by careful matching of the CSI with the motor. However, since the motor parameters must be known, to implement such an approach, this type of drive is presently not popular for general-purpose applications.

The load commutated inverter (LCI), a special type of current-source inverter, is used in very large synchronous motors. LCI uses thyristors as switching devices but avoids forced commutation because it is used only with synchronous motors. By controlling the field current, a synchronous motor can run overexcited, that is with a leading power factor which leads to natural commutation of the thyristors due to the back EMF of the motor. Figure 1.14 shows the generic diagram of an LCI inverter coupled to a synchronous motor. The LCI-synchronous motor combination, although simple and efficient, is generally used only above 500 kW due to the higher cost of synchronous motors.

1.2.3 Cycloconverters

This type of VSD makes a direct conversion from constant frequency, constant voltage to variable frequency, variable voltage in one stage, without resorting to an intermediate DC link with energy storage. By supplying each phase of the motor winding from a reversible converter, a low frequency AC drive system is formed, as shown in Figure 1.16. Although this VSD is complex, cycloconveters use a large number of thyristor switches but they do not require forced commutation circuits and thus can use relatively inexpensive, converter-grade thyristors. The generated structure of cycloconverters presented in Figure 1.16a, shows a large number of power switches and the need for a special three-phase secondary transformer.

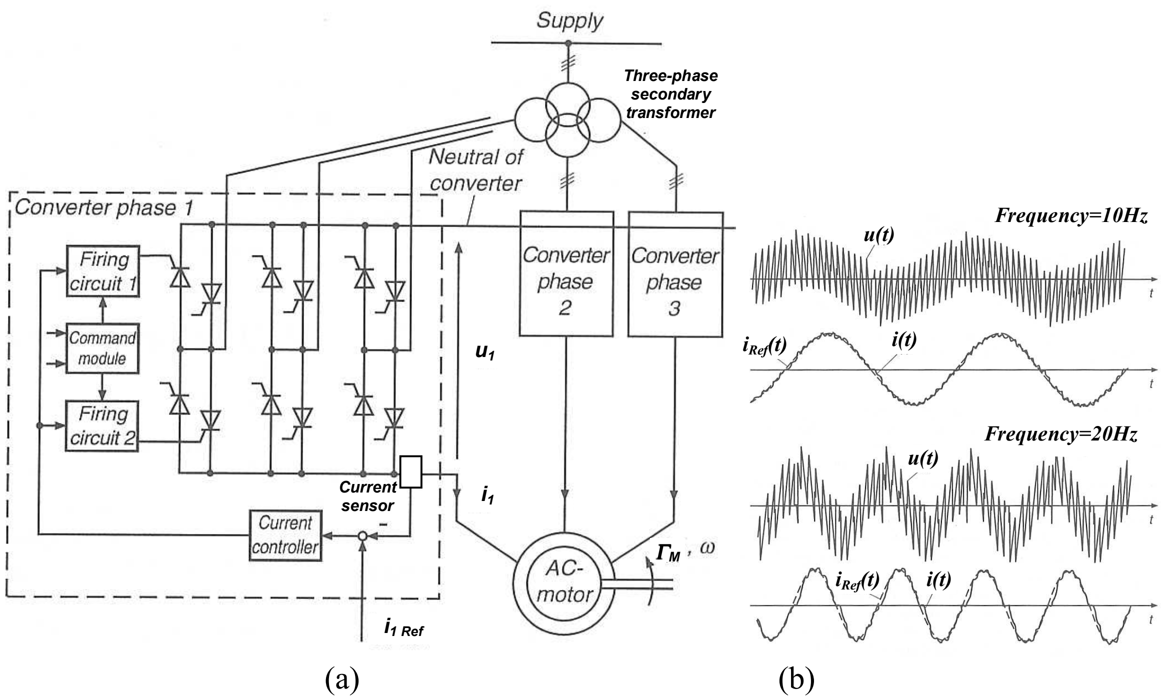


Figure 1.16 *- (a) Diagram of a six-pulse cycloconverter for a three-phase motor load; (b) Cycloconverter output waveforms. Only one of three output phases is shown.*

Cycloconverters are used for high power machines (above 1MW) with low frequency operation (e.g. rolling mills, cement kilns). The output frequency is typically below 25Hz since the quality of the voltage waveforms degrades as the output frequency increases. They can operate down to zero speed and they can be used both with induction and synchronous motors. The main disadvantages are the complex circuit design and the low power factor at low speed.

1.2.4 Vector Control / Field Orientation Control

The rapid growth of electrical variable speed drives and the demand for greater precision and economic solutions has led to a highly competitive market. Traditionally DC motors were used in applications requiring accurate speed and/or torque control. Although DC motor controls are simple and inexpensive, DC motors are more expensive and much less reliable than induction motors. The market has seen an increase in high performance drives. High performance applications can now use induction motor drives with a sophisticated control method designated vector control. Vector control consists of three basic components: the electric motor, the power converter and the associated control system. The objective of Vector Control is to give independent control of torque and flux in a AC machine. In most types of VSDs, by keeping V/f constant, the flux is only held approximately constant and under dynamic conditions this approximation is poor.

In vector control the behaviour of a DC motor is emulated in an induction motor by orienting the stator current with respect to the rotor flux so as to attain independently controlled flux and torque (see Technical Note 3). Vector controllers are also called ***field-oriented controllers*** and require independent control of both magnitude and phase of the AC quantities. This type of controllers allow high accuracy speed and torque control in the most demanding applications (e.g. rolling mills and papers winders).

TECHNICAL NOTE 3

With closed loop flux control it is possible to operate the motor with full torque at low speed or even at standstill, allowing its application as a servo-drive. For this type of control it is necessary to use dynamic model equations of the induction motor, based on the instantaneous currents and voltages, in order to control the interaction between the rotor and the stator, resulting in the flux and torque control.

The field orientation concept implies that the stator current components supplied to the machine should be oriented in phase (the **d**irect flux component) and in **q**uadrature (torque component) in relation to the rotor flux vector. The rotor flux is obtained from the d-axis component of the current space vector. The slip frequency at which the rotor current space vector lags behind the rotor field is obtained from the q-axis component of the current space vector. It is necessary to control independently the stator ***d*** and ***q*** current components. In reality, it is possible to control the physical phase currents i_1, i_2 and i_3, as function of time. Therefore, using a matrix operations, the quantities between the rotating ***d-q*** axis reference frame are transformed in the stationary i_1, i_2, i_3 reference frame, and vice-versa. In short, to control the rotor flux in the machine the ***d*** current component reference is used, and to control the produced torque the ***q*** current component reference is used.

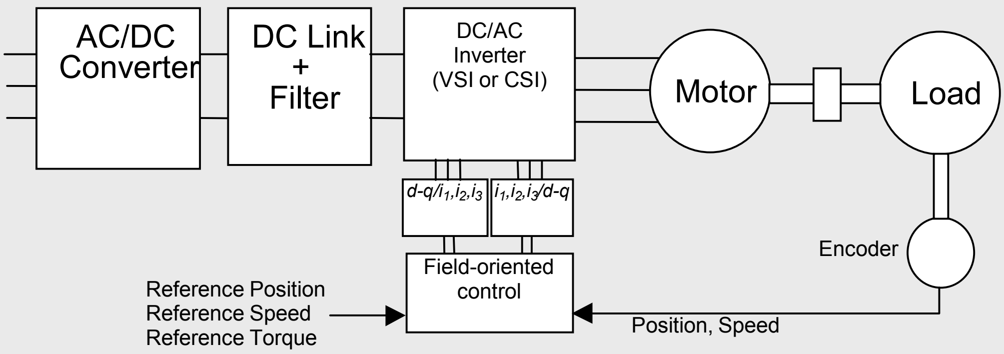


Figure 1.17 *- Block diagram of an induction motor-drive system, with closed loop field oriented control.*

The ***d-q*** components enable the calculation of rotor flux and the slip speed, and therefore the i_1, i_2, i_3 reference currents can be generated. In the Figure 1.17, the currents i_1, i_2, i_3, are measured, and are used to calculate the ***d-q*** currents. The ***d-q*** current references are generated by the speed and the position control loops.

Open Loop Vector Drive - The attention of researchers has turned towards simplification, as well as the refinement of these quite sophisticated control methods. One issue was the desire of avoiding the mechanical speed/position sensor needed with many of these control schemes. Electrical measurements are usually acceptable since the sensors can be placed anywhere, preferably inside the inverter cabinet, but a mechanical sensor is often undesirable because of space restriction or the added cost and complexity. Such arguments have particular weight with smaller motors. Of course, a certain loss of accuracy and dynamic response will be unavoidable when the speed sensor in omitted, making such schemes not immediately applicable to highest performance, as those required by machine tool feed drives. The various proposals for the design of controlled AC drives without a mechanical sensor have in common that only terminal quantities, i.e., stator voltage and currents are measured from which the information on the flux and the speed of the motor must be derived (estimated), given a nominal knowledge of the important motor parameters. The process of estimation reduces the performance of the Open Loop Vector Drive giving a torque bandwidth of typically 300 Hz. Stability at all speeds and load is good.

1.4 Harmonics in the VSD-Motor systems

Harmonics are voltage and current frequencies in the electrical system that are multiples of the fundamental frequency (50 Hz in European power systems). The harmonics are associated with non-linear loads[3] such as magnetic ballasts, saturated transformers and power electronics. The most common sources of power electronics harmonic distortion are found in computers, office equipment, electronic equipment using switch-mode power supplies, VSDs, arc furnaces and high-efficiency electronic light ballasts. Harmonics often come, too, from poor-quality line power - an increasingly important issue for many utilities. Harmonics can affect the equipment performance and are both caused by and can interfere with the function of VSDs. Harmonics increase equipment losses and have also raised concerns about excessive currents and heating in transformers and neutral conductors. Harmonic waveforms are characterised by their amplitude and harmonic number. Figure 1.18 shows how the 50 Hz fundamental changes when harmonics are added.

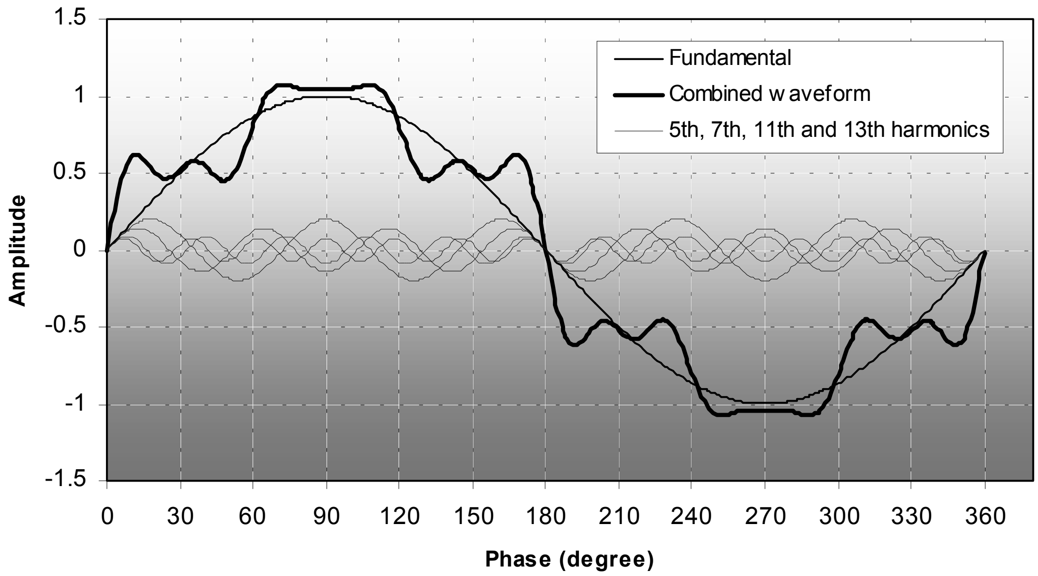


Figure 1.18 *- Waveform with VSD harmonics: Combined waveform reflects combination of fundamental and harmonics.*

The harmonics are usually measured not individually, but collectively as total harmonic distortion (THD) which is the RMS value (square root of the sum of the squares) of all the harmonic frequencies, divided by the RMS value of current or voltage.

Other important concept is the harmonic associated sequence, which is necessary to understand the impact of harmonics in the motor torque. The Table 1.3 presents the frequency and sequence of the harmonics. A positive sequence generates a rotating field in the same direction

[3] Non-linear load is a load in which the current is not proportional to the voltage.

as the one generated by the fundamental component (e.g. non-distorted 3-phase supply). A negative sequence generates a rotating field in the opposite direction.

Table 1.3 - Frequency and sequence of the harmonics.

Harmonic	Fundamental	2	3	4	5	6	7	8	9
Frequency (Hz)	50	100	150	200	250	300	350	400	450
Sequence	**+**	**-**	**0**	**+**	**-**	**0**	**+**	**-**	**0**

Typically, PWM-VSDs, with a three phase diode rectifier, have significant levels of 5th, 7th order current harmonics, in the input stage. In the figures 1.19 and 1.20 the typical voltage and current harmonics of a 11kW PWM-VSD feeding a 7.5kW induction motor, can be seen [ISR].

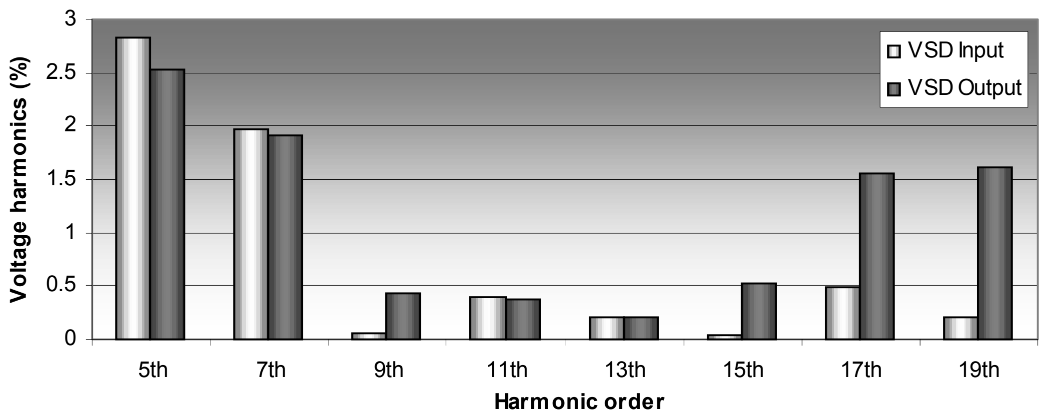


Figure 1.19 *- Percentual values of voltage harmonics, in a VSD input and output (7.5 kW low voltage squirrel cage induction motor fed by a 11 kW PWM-VSD) [ISR] .*

A rectifier behaves like a current and voltage harmonic generator with respect to the supply. These harmonics are propagated in the supply according to the electrical circuit laws.

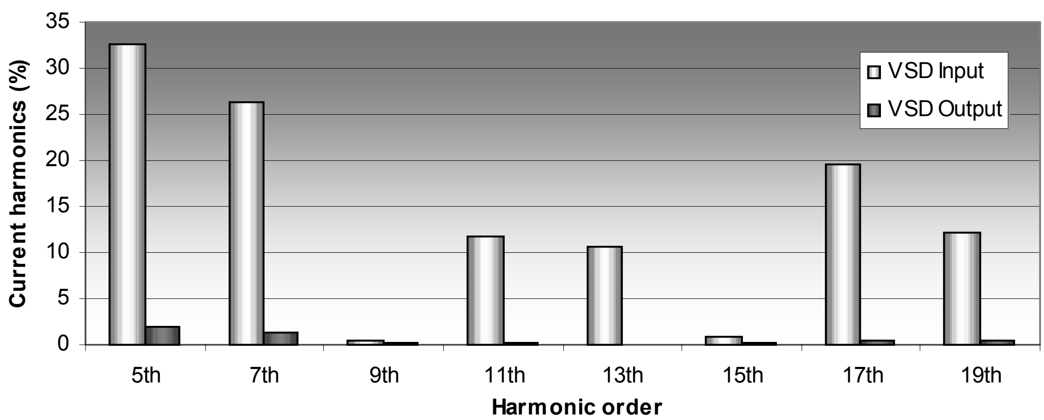


Figure 1.20 *- Percentage values of current harmonics, in a VSD input and output (7.5 kW low voltage squirrel cage induction motor fed by a 11kW PWM-VSD) [ISR].*

Figure 1.21 shows the input current waveform for a PWM drive connected to a low inductance, three-phase supply.

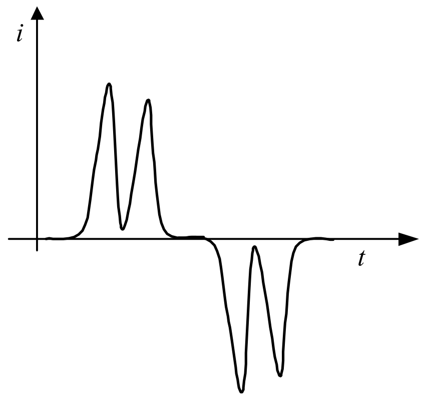


Figure 1.21 *- Typicall PWM-VSD input current waveform: Combined waveform reflects combination of fundamental and harmonics.*

Note that the current harmonics are one order of magnitude larger than the voltage harmonics.

In the tested VSD, the voltage output is optimised to reduce the low order harmonics, and the result is a quasi sinusoidal line-to-line voltage wave. Although the 5th, 11th and 17th harmonics present low values, they will create a rotating field, in opposite direction to the fundamental field. These harmonics will reduce the starting and nominal torque of the motor, beside increasing the motor losses.

The high PWM frequencies will generate radiated noise, and additionally they may cause significant damage to the motor by producing bearing currents and insulation voltage stress. These stress can be particularly serious if the length of cable between the VSD and motor exceeds 50 to 100 feet. Because harmonics increase heating in induction motors with a commensurate impact on expected motor life, older motors with long cable runs may have a shortened lifetime when used with PWM-VSDs.

Current harmonics in the VSD input stage can also feed back into the power bus grid, and can disrupt other types of equipment. Harmonics can also cause supplementary losses and temperature-rise of all the elements in the supply system (machines, transformers, cables, capacitor banks). In certain instances, harmonics can also excite resonances (usually parallel), especially when distributed power factor correction capacitors are present. These high frequencies can produce electromagnetic interference (EMI) both as high frequency airborne radiated interference mostly in the inverter to motor cable, as well as the conducted noise in the supply cables. The EMI sources are shown in Figure 1.22.

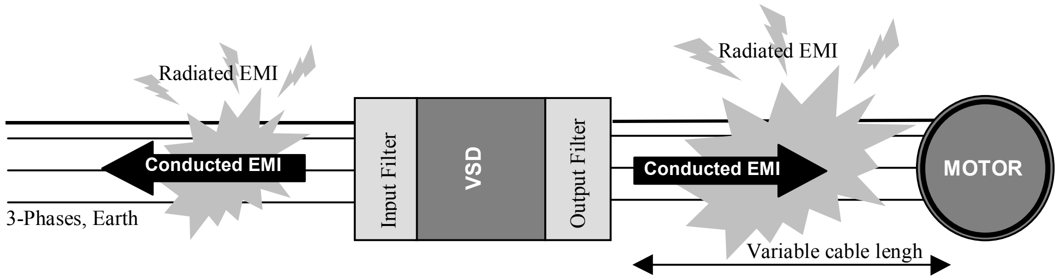


Figure 1.22 *- VSD-Motor system EMI sources. Input and output filters may be use to attenuate EMI to acceptable levels.*

If proper precautions are not taken, the harmonics can disturb nearly sensitive electronic devices. The fast transitions in current level include high frequencies that, while necessary to the operation of the drive, can have detrimental effects on other pieces of equipment (e.g. leading to measurement or counting errors, and unexpected operation of relays). Possible problems can be avoided in virtually all cases by the following precautions:

- Keeping the link motor-VSD as short as possible;
- Proper grounding;
- Proper shielding;
- Passive or active harmonic filters;
- Isolation transformers.

Sophisticated control techniques have been developed in modern PWM-VSDs, to minimize harmonics, particularly on the motor side.

1.5 Applications

VSDs have a wide variety of possible applications in electric drives. In the industrial sector it is possible to identify a few typical functions covering the majority of these motor applications, namely, robotics, machine-tools, materials handling, small and medium power process machines, compressors, centrifugal pumps and fans, etc.. In Table 1.4 the typical in power ranges of common applications can be seen.

Electrical VSDs, are normally incorporated into more or less complex systems. Depending on the driven machine, it is possible to:

- control speed (angular or linear), torque, position, acceleration or braking;
- optimise energy and/or material consumption, provided that a suitable sensor can be found and that the control algorithm can be defined;
- combine several machines and control their speeds in a coordinated manner;
- communicate with different systems or different hierarchy levels in the same system, the drive and the machine being considered as a single unit within a structure grouping together the complete process.

Table 1.4 - Positioning in power of the typical industrial applications.

Application	P<10 kW	10<P<50 kW	50<P<500 kW	P>500 kW
Robotics				
Machine Tools				
Material Handling				
Small and medium process machines				
Large machines (e.g. mills, compressors)				
Centrifugal machines (excluding large machines)				
Replacement of thermal engines				

The possibilities offered by VSDs are enhanced by the integration with computerised manufacturing systems.

The criteria for VSD selection involve knowing of a certain amount of basic data which namely includes: power required, supply voltage, torque/speed requirements, speed range and speed accuracy. A VSD must be capable of:

- Starting the controlled load;
- Driving this load in accordance with the operating requirements;
- Stopping this load in accordance with the criteria linked to the operating mode;

To meet these three functions, common to all applications, it may be necessary to add the positioning or the synchronisation with other devices in the system.

To ***start*** a load the electromagnetic torque of the motor must be larger than the total resistive torque. The difference gives the acceleration torque, which is a function of the total inertia of the system and of the required accelerating time. Table 1.5 shows a few examples of starting requirements linked to typical applications and gives possible solutions.

Productivity normally increases with speed. The quality increases with steady-state accuracy if the load varies little during the production cycle. Dynamic accuracy is relevant if the load cycle significantly varies and if there are many variations in the torque reference. Often, the transmission quality of the shaft line (backlash, elasticity, flexion, torsion,...) limits the improvement in performance due to the use of VSDs. One of the characteristics of VSDs is that the drive can be located as close as possible to its utilisation. It is therefore possible to reduce to a minimum the problems linked to couplings and transmissions (backlash, elasticity, critical speeds).

In applications that require a wide range of speeds and/or accurate speed control, the most appropriate technique is to use electronic variable speed drives (VSDs). VSDs can match the motor speed to the load requirements. Motor-driven loads can be classified into three main groups according to whether the torque required increases, remains constant, or decreases as the speed increases (Figure 1.23). The mechanical power is equal to the product of torque times angular speed. In centrifugal pumps and fans (quadratic torque loads) the power required varies approximately with the cube of the motor speed. This means that in a fan system, only about half of the full power is required to move 80% of the rated flow.

Table 1.5 - Examples of starting requirements linked to certain typical applications and possible solutions.

STARTING		
Requirements	***Typical applications***	***Possible solutions***
Limiting mechanical shocks	Belt conveyor, escalator, conveyor for fragile products	Speed ramp
Eliminating backlash	Gearings, transmission handling line	Parabolic or S-shaped ramp
High inertia machine	Centrifuge	Motor with high starting torque
Machine with high resistive torque	Crusher, Grinder	
Load with driving torque	Lift	System operating in 2 or 4 quadrants
Frequent starting in a given time	Handling machine	Appropriate thermal rating
Within a time limit	Centrifuge smoke extractor	Speed ramp
Within a time and space limit	Ski lift	Special acceleration control

In terms of response, the pumps and fans controlled by VSDs can respond to changing conditions faster and more reliably than valves or dampers can. This is particularly true at the extremes of the flow range where valves become highly nonlinear, even when equipped with linearizing trims.

In the case of cube-law loads (ex.: centrifugal fans and pumps), significant reductions in the consumption can be obtained, compared to the throttling flow control. VSDs can also make induction motors run faster then their normal full speed ranges. Provided that the rotors can withstand higher operating speeds. Therefore VSDs have also the potential to extend the useful operating range of compressors, pumps, and fans. For the many applications (such as forced draft fans) that are limited by fan or pump capability, a properly selected VSD and motor can extend both the high and the low end capability.

VSDs also isolate motors from the line, which can reduce motor stress and inefficiency caused by varying line voltage, phase unbalance, and poor input voltage waveforms. In some applications VSDs can drive multiple motors simultaneously, as in many web process. For example, a single 100 kW PWM-VSD could be used to drive two 50 kW induction motors at exactly the same frequency. This approach can provide significant cost savings.

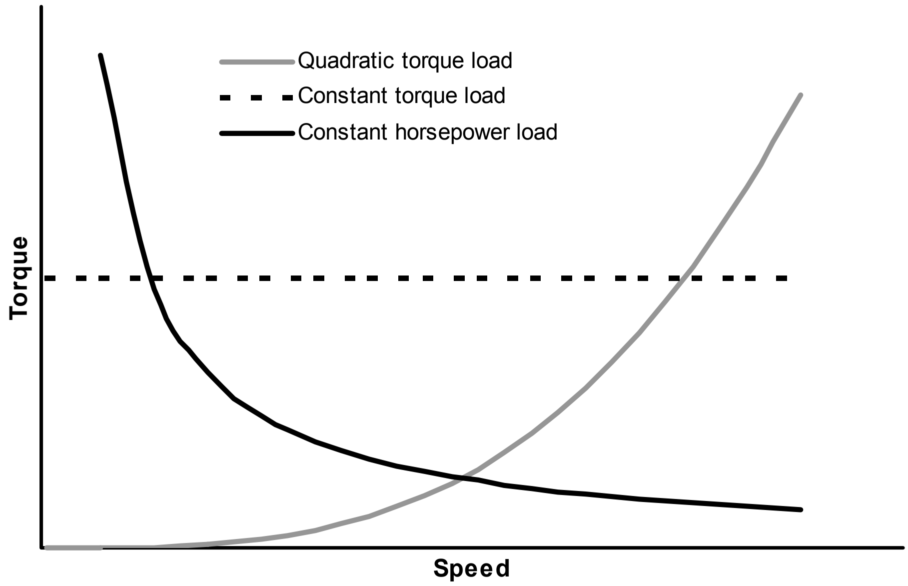


Figure 1.23 - Types of torque-speed curves: Quadratic torque load (e.g. centrifugal fans and pumps); Constant torque load (e.g. conveyors, positive displacement pumps); Constant horsepower load (e.g. traction, winders, rolling mils).

Stopping a system can be carried out in different ways depending on the performance required by the application. Table 1.6 summarises the main aspects related to the stopping operation. The problem of stopping is linked to that of positioning.

Table 1.6 - Main aspects related to the VSD stopping operation.

STOPPING		
Requirement	***Typical applications***	***Possible solutions***
Simple stopping	Fans	Freewheel or mechanical brake
Limit mechanical shocks	Belt conveyor drives	Deceleration ramp, torque limitation
Backlash elimination	System incorporating gears	Parabolic deceleration ramp
Short time	Emergency stop centrifuges	Speed ramp, DC injection
Load with driving torque	Lifts, hoists	Reversing drive
Electrical braking without motor heating, with or without regeneration	Rolling mills, electric traction	Rheostatic or regenerative braking

1.5.1 Pumps

Single pump - The centrifugal pumps without lift (e.g. closed loop circuit), respect the cube power law, i.e., the consumed power is proportional to the cube of the speed, as shown in Figure 1.24(a) If the user wants to reduce the flow in the process, valve control can be used, or alternatively speed control can be applied, using a VSD. Although both techniques fulfil the desired objective, the consumed energy is significantly higher when valve throttle control is used. If there is a system head associated with providing a lift to the fluid in the pumping system the pumps must overcome the corresponding static pressure, as shown in Figure 1.24(b).

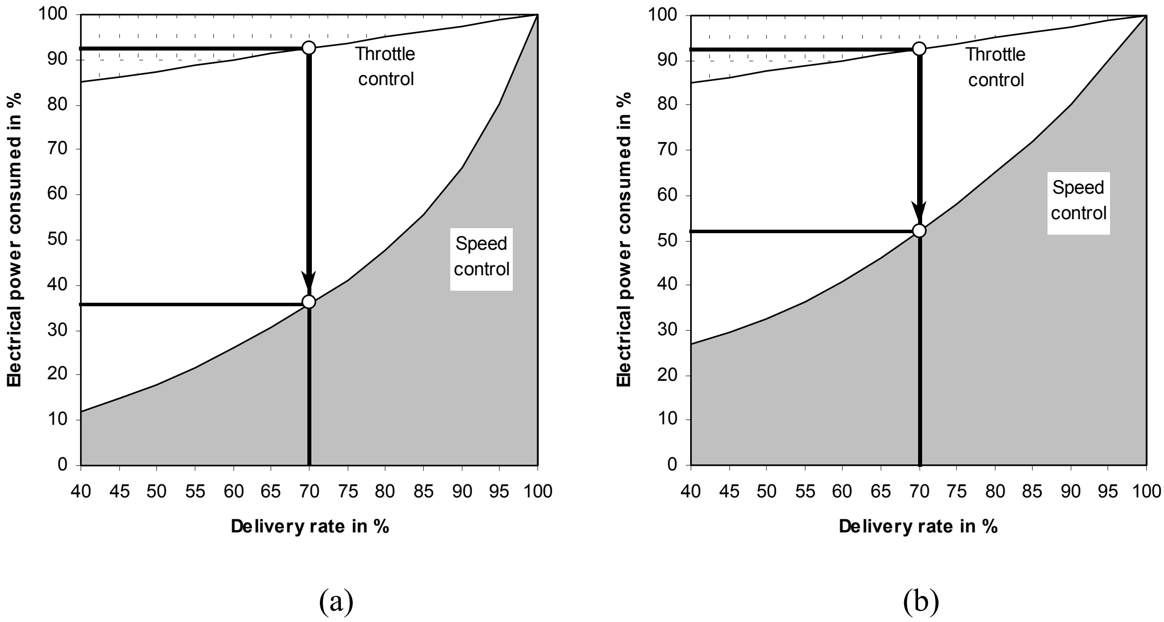


Figure 1.24 *- Electrical power input of a pump with throttle control vs. one with speed control: (a) without static pressurre head (e.g. recirculation systems); (b) with static pressure head.*

In these pumping systems the mechanical energy is used to overcome the friction in the pipes, plus the mechanical work associated with lifting the fluid against the gravity as shown in Figure 1.25.

If the percentage of the power associated with overcoming the pipe friction is relevant, energy savings can still be achieved although typically less than in systems without static pressure head.

The overall efficiency of the pumping system depends on the efficiency of the different components of the system. Figure 1.26 shows an example of the power absorbed by a pump system with different components. For the same end-use power, the inefficient system absorbs more than twice the power absorbed by the optimized system.

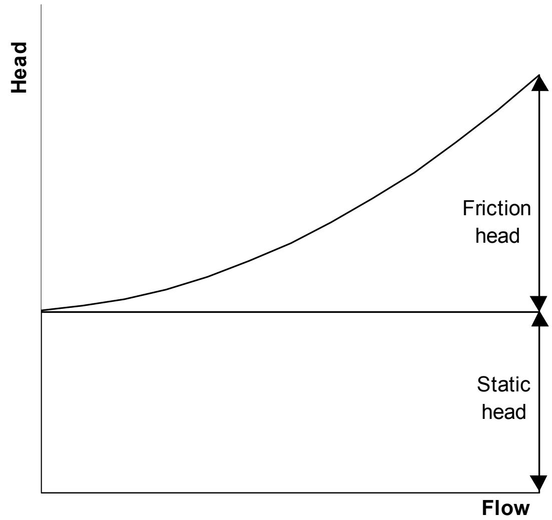


Figure 1.25 *- Total system resistance from frictional losses plus static head losses.*

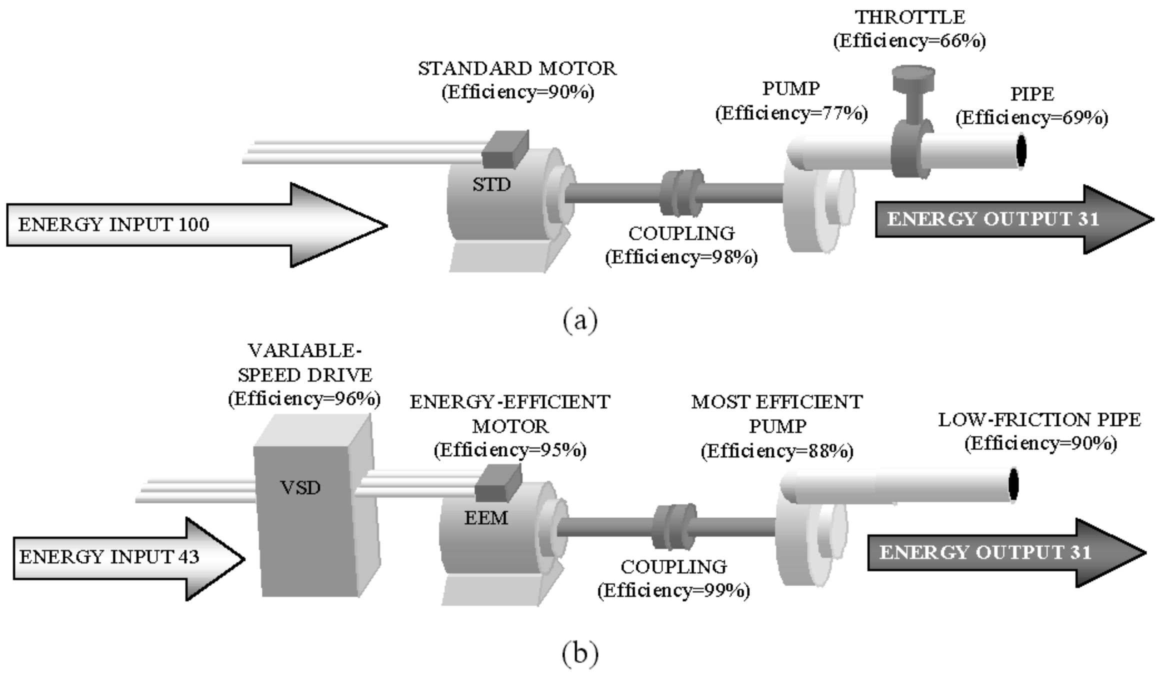


Figure 1.26 *- Two pumping systems with same output: (a) Conventional system (Total Efficiency = 31%); (b) Energy-efficient pumping system combining efficient technologies (Total Efficiency = 72%).*

Staged pumping plant - In many pumping applications several pumps are used in parallel to produce the required flow. Operating all pumps at reduced speed rather than cycling the pumps on/off according to the demand, significant energy savings can be reached. For example, in a low static head two pump system, with independent piping circuits, operating both pumps at 50% of the rated flow requires approximately 25% of the power required for a single pump operating at 100%. Other advantages are that pumps stay warm (no condensation in the windings), seals stay wet and alive, also eliminating high-shock starts on system. Figure 1.27

illustrates this situation. Also it is possible to control the "water-hammer" effect which degrades the pipes by controlled acceleration/deceleration using VSDs.

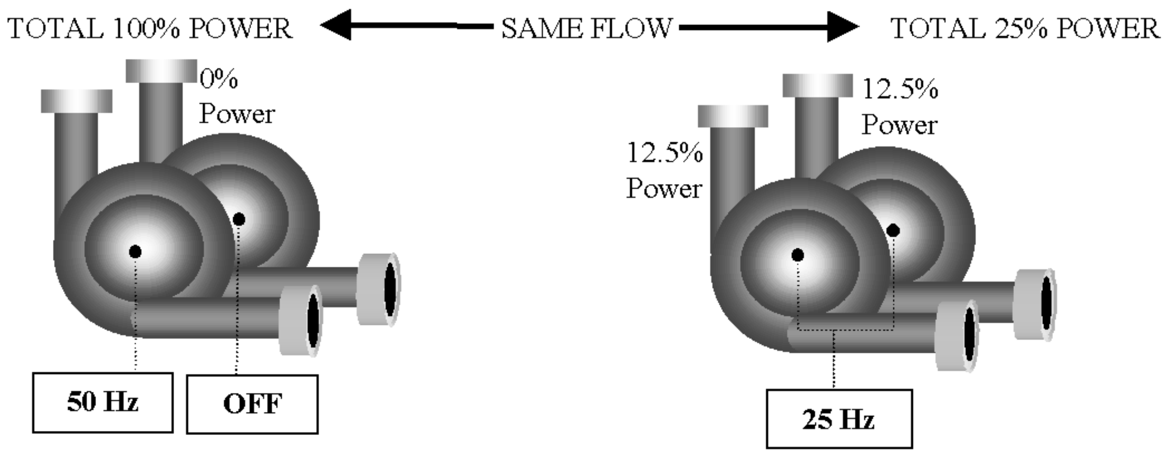


Figure 1.27 *- Pumping plant: Useful relationship to consider with closed loop circulating independent systems where "head" is not a major factor.*

1.5.2 Fans

Savings from adding variable speed control to fans can be significant even with fairly heavily loaded motors. Figure 1.28 illustrates the savings potential with an VSD versus common throttling methods.

High amounts of energy are wasted by throttling the air flow versus using adjustable speed. The worst method is outlet dampers, followed by inlet vane control. For 50 % flow, a VSD can save 80% and 68% of the consumed power when compared with dampers and inlet vanes, respectively. For example, a 100 kW motor driving a load continuously throttled to 50 percent of output will save almost 18000 Euro per year (assuming 0.06 Euro/kWh, 6000 hours per year). The energy consumption in these loads is so sensitive to speed that the user can achieve significant savings with even modest speed adjustments.

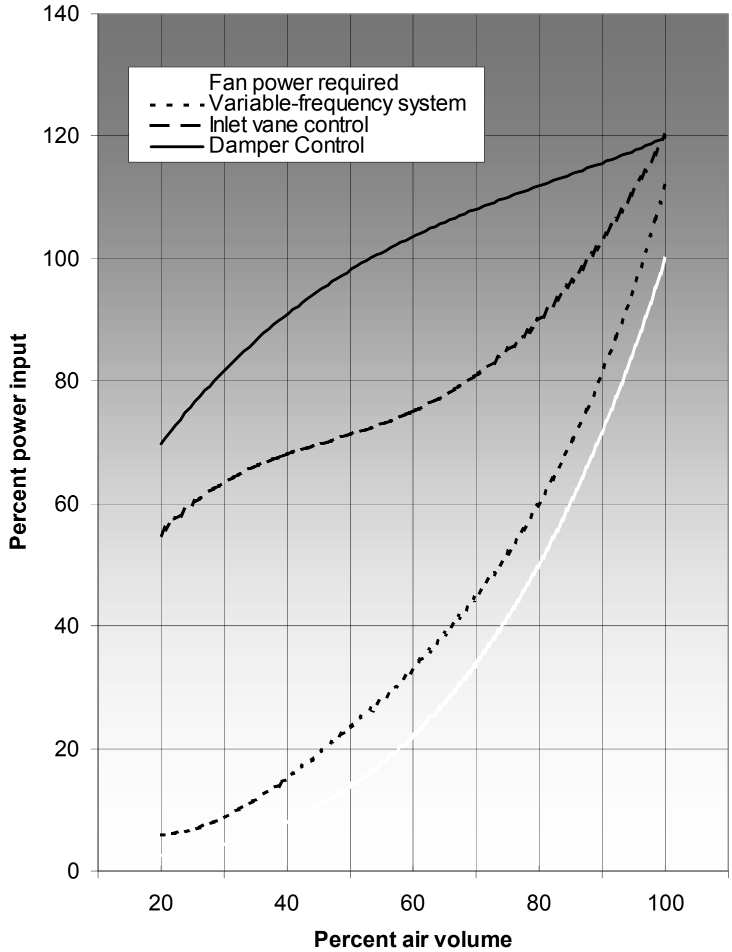


Figure 1.28 *- Relative power consumption of different air flow control methods.*

Example: In a roof top chiller system (Figure 1.29), VSDs can be applied to modulate the pump speed, based on zone temperature control, and/or to control the fan speed, based on the coolant return temperature. The result, compared with a on/off cycling control, is a constant temperature in the controlled space for more efficient operation.

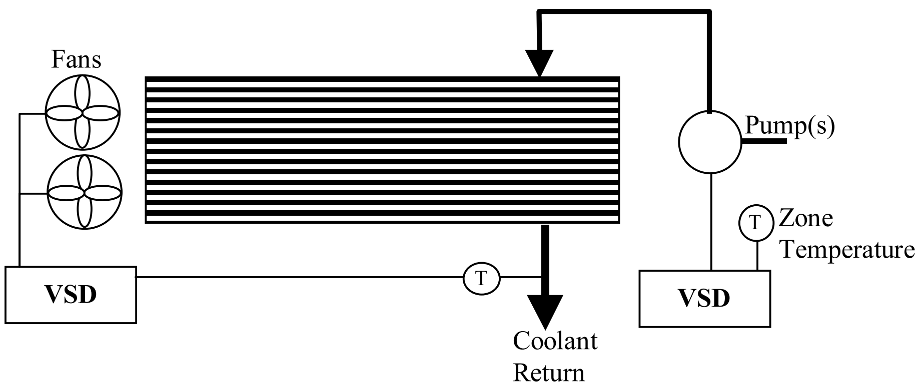


Figure 1.29 *- Roof Top Chiller.*

1.5.3 Compressors

Rotary screw and piston air compressors are essentially constant torque loads and can also benefit from the application of variable speed control. The savings related to the use of variable speed control are dependent on the control system that is being replaced. In Figure 1.30 the energy savings achieved by fitting a VSD to a rotary screw compressed air unit, compared to other methods of flow control at partial load, can be seen. In a compressor, with modulating control, if the demand is 50% of rated capacity, the energy savings associated with the VSD integration is about 38%.

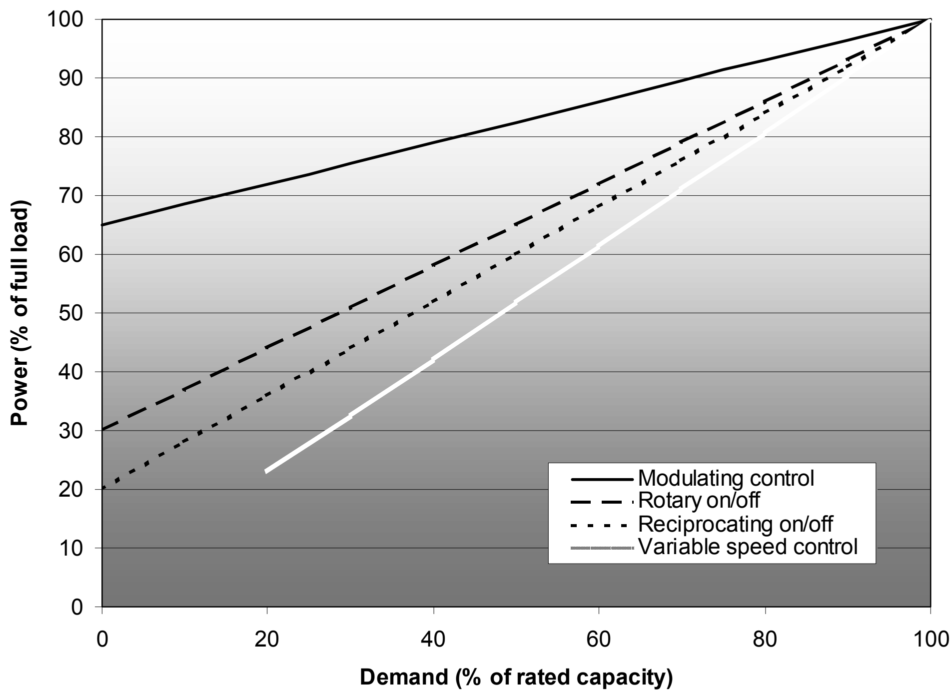


Figure 1.30 *- Energy saved by using a VSD on a rotary srew air compressor.*

Energy savings with constant torque loads is typically considerably less than with centrifugal pumps or fans which obey the power cube law, and so to retrofit a VSD to a compressor it is less likely to be economic on the grounds of energy savings alone. Additionally, care needs to be taken to ensure adequate lubrication at reduced speeds. However, the introduction of screw compressors with integral speed control has enabled the additional price of variable speed control to be significantly reduced. These machines therefore deserve to be considered for all new applications with long running hours, when there is a widely varying demand. Further energy savings will also be achieved through improved pressure control, by reducing the mean generation pressure.

Another example of VSD application in compressors is for refrigeration purposes (Figure 1.31). The use of VSD for temperature control (floating head operation) in the refrigeration pumps/compressors (ex.: Walk-in Freezer) can eliminate the on/off cycling, with large energy savings. The temperature control can also be improved, in terms of differential between internal and external temperatures.

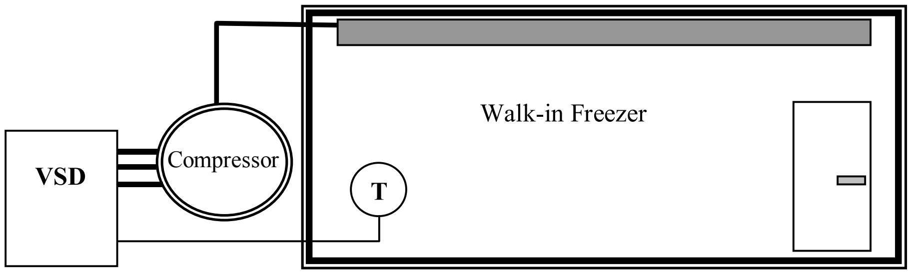


***Figure 1.31** - Variable speed refrigeration compressor.*

1.5.4 Lifts

New VSD topologies allow the braking energy to be injected back to the source/grid. This feature can be a way of saving a significant amount of energy in applications with frequent braking operations, namely, lifts. This is only possible if the motor mechanical transmission allows this mode of operation. When the lift is going down, and the load weight (people inside) is larger than the counterweight, then the motor torque is in opposite direction to the speed, i.e., the motor is braking. In the same way, when the lift is going up unloaded, energy savings can be reached if the motor is controlled with a regenerative VSD.

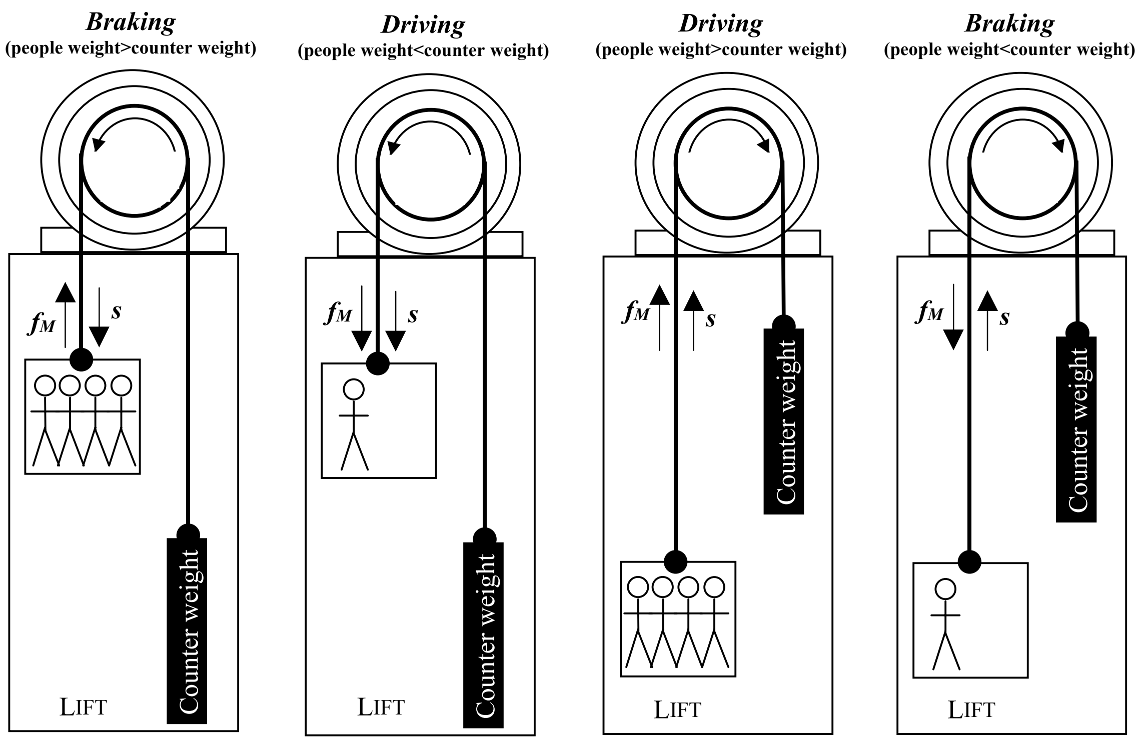


***Figure 1.32** - Lift motor operating modes (f_M - Motor force ; v - Speed).*

In Figure 1.33, possible energy savings in lifts, using different technologies, can be seen. The use of regenerative VSD system, and special gear, the consumed energy can be reduced to 19%, when compared to a conventional system, using a pole changing drive. Permanent magnet motors with direct drive (without gears) coupling and regenerative braking are also being introduced in new high efficiency lifts.

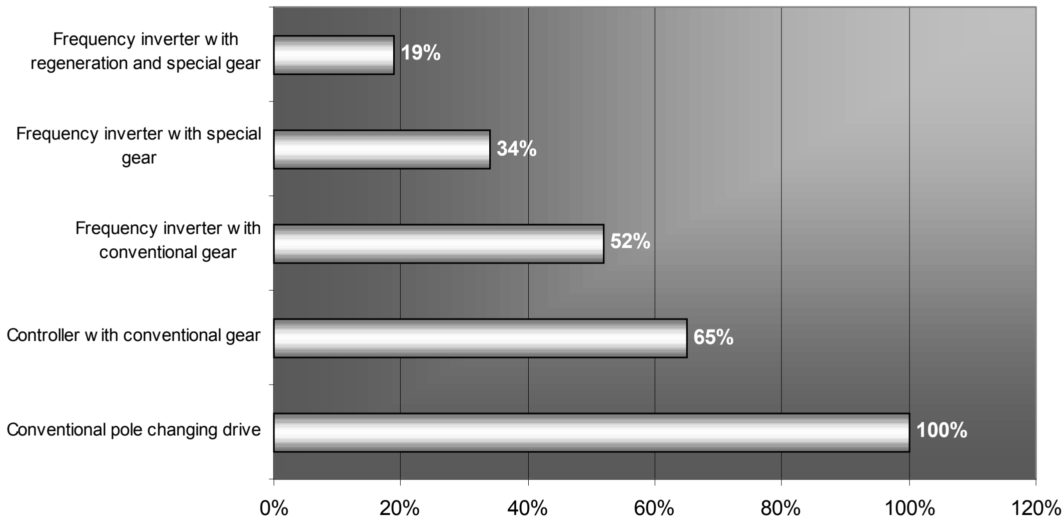


Figure 1.33 *- Energy balance of lifts, Average energy consumption, percentage, Source: Flender-ATB-Loher, Systemtechnik.*

1.5.5 Centrifugal Machines and Machine-Tools

In high inertia loads (e.g. machine-tools) or/and high speed loads (e.g. centrifugal machines), with frequent accelerating/braking operation, it is possible to save significant amounts of energy. When running, this type of loads has a large amount of kinetic energy, that, in a braking process, can be regenerated back to the grid, if a regenerating VSD is used (same regenerative process as used in lifts). Examples of this type of loads are high speed lathes with an automatic feeder or high inertia saws (Figure 1.34).

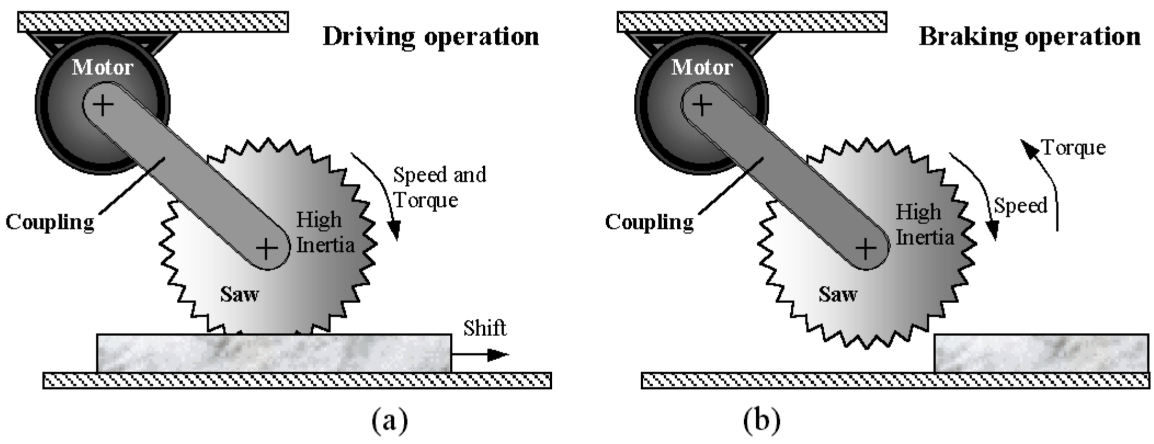


Figure 1.34 *- Operation modes of a high inertia saw: (a)Driving operation; (b)Braking Operation.*

In fact, when a high inertia saw or high speed lathe are running the speed and torque are in the same direction, but when the operation ends, typically it is necessary a fast stop. So, the braking energy can be re-injected to the grid, instead of been dissipated in a resistance. Another important aspect is the acceleration process. As it can be seen in Figure 1.35, if the motor is simply turned on (situation (a)), without any speed control, the rotor losses will be higher than if is used a pole changeable motor (situation (b)). A more efficient acceleration technique uses a VSD (situation (c)), that will significantly reduce the energy consumption, comparatively to the other mentioned techniques.

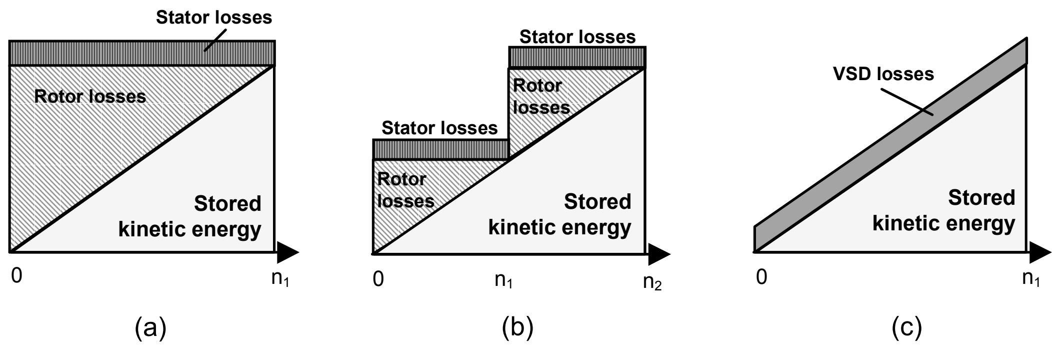


Figure 1.35 *- Energy-Consumption for an Acceleration Period: (a) Standard Motor; (b) Pole Changeable Motor; (c) Variable Speed Drive (VSD) [source: Siemens].*

1.5.6 Conveyors

In the constant torque devices (ex.: horizontal conveyors), the torque is approximately independent of the transported load (is only friction dependent). Typically, the materials handling output of a conveyor is controlled through the regulation of input quantity, and the torque and speed are roughly constant. But, if the materials input to the conveyor can be changed, it is possible to reduce the speed (the torque is the same), and, as it can be seen in Figure 1.37, significant energy savings will reached, proportional to the speed reduction.

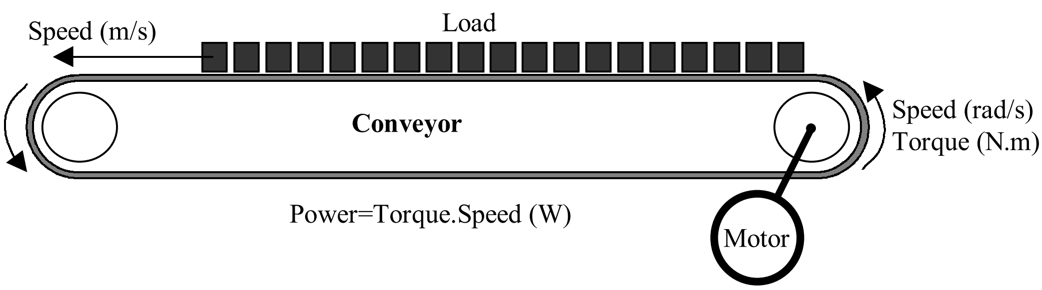


Figure 1.36 *- Power required by a conveyor.*

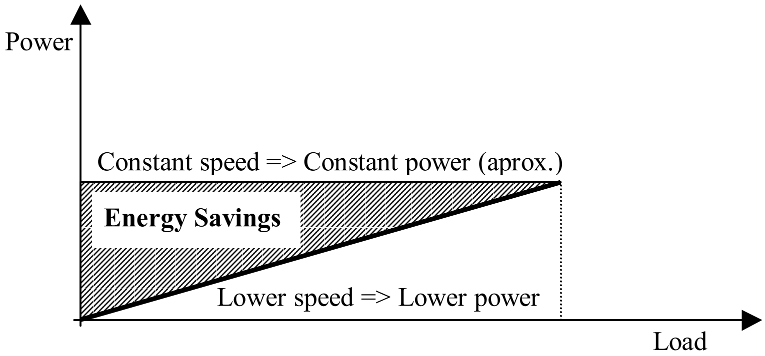


Figure 1.37 *- Energy savings in a conveyor using speed control, in relation to the typical constant speed.*

2. Characterisation of the Current Market for VSDs

A more detailed VSD market knowledge was obtained based on the characterisation of the current market for VSDs in the most relevant EU countries, integrating the market surveys by different types of data. Namely the following data was sought per power range ([0.75 4[, [4 10[, [10 30[, [30 70[, [70 130[and [130 500[kW):

- Number of units sold per country;
- Country sales (Euro value);
- Average Retail Prices of VSDs per kW of rated output;
- Average Installation Costs;
- Market segmentation by end-use and by type of design;

The information was collected, through several sources (questionnaires, associations, etc.) in the following countries:

Institution	*Country*
ADEME	France
ETSU	United Kingdom (U.K.), Ireland
FhG-ISI	Germany, Austria
ISR-UC	Portugal and Spain
NESA	Denmark
NOVEM	The Netherlands

The individual results from each partner are presented, as well as final figures, which represent the final estimated averages and total extrapolated values for the EU.

It is estimated that the VSD market of the countries included in this study represents about 71% of the total EU VSD market. This value is based on the electricity demand of each country, in 1998 [3], shown in Figure 2.1.

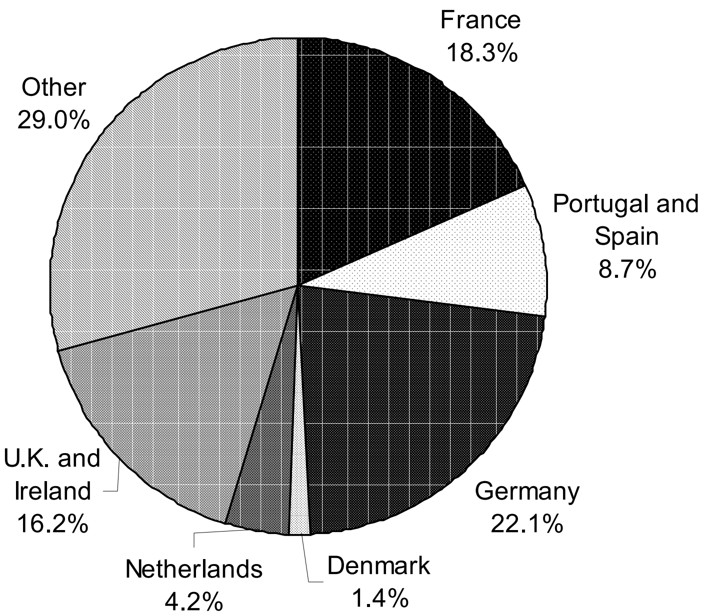


***Figure 2.1** - Electricity demand of the considered countries, by 1998 [3].*

In Table 2.1, the number of VSD units (discrete drives) sold in each country, per power range, can be seen.

Table 2.1 - Sum of Number of VSDs (AC induction motor discrete drives) units sold in each country in 1998.

Number of units	***Power range (kW)***						
EU Country	**[0.75 4[**	**[4 10[**	**[10 30[**	**[30 70[**	**[70 130[**	**[130 500[**	**Total**
Denmark	14 900	8 600	1 800	900	400	0	26 600
U.K. and Ireland	90 000	18 000	8 500	3 500	900	600	121 500
France	55 400	11 500	3 000	1 300	300	200	71 700
Germany	423 000	59 000	38 000	14 000	6 000	4 000	544 000
Portugal and Spain	65 000	11 000	6 000	2 500	1 000	700	86 200
The Netherlands	40 000	7 000	3 000	500	100	0	50 600
Total (71% of EU)	688 300	115 100	60 300	22 700	8 700	5 500	900 600
Total EU	969 400	162 100	84 900	32 000	12 200	7 800	1 268 400

Figure 2.2 shows the number of units sold in the EU per power range. This figure shows that the VSDs market, in 1998, was dominated by low power drives, in the range of 0.75 to 4 kW, representing about 76% of the total units sold in the considered countries.

Figure 2.3 shows the unit sales in the different countries. Germany has the higher percentage of the unit sales with 42% of the total EU market.

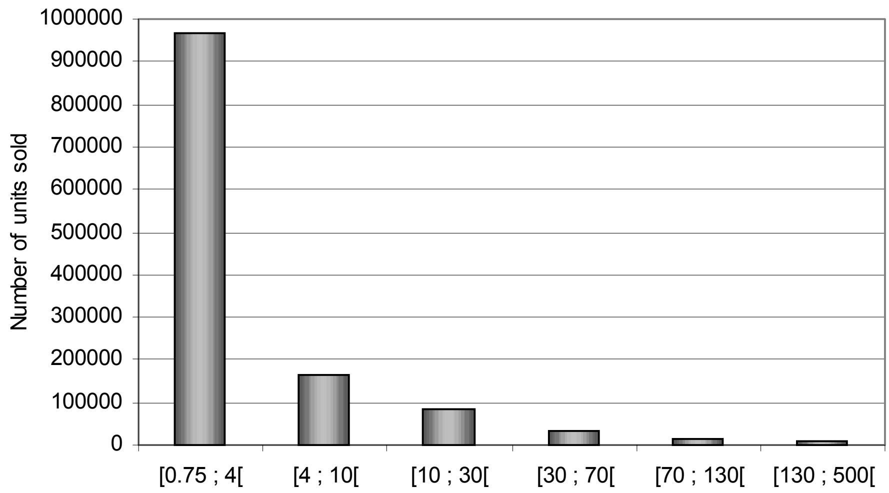


Figure 2.2 *- Number of units sold in the EU per power range.*

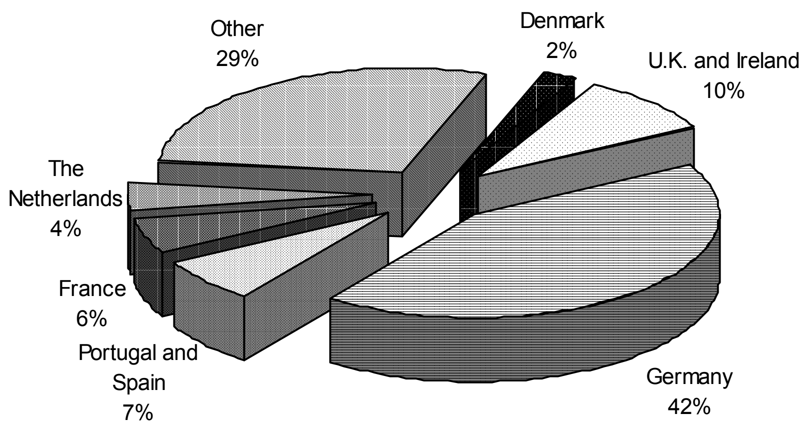


Figure 2.3 *- Distribution of the VSD market in terms of the total number of units sold per each country.*

The Figure 2.4 shows the number of VSD units sold in EU in 1998 as a percentage of the number of AC induction motors sold in Industry[4] and Tertiary Sector in EU. An important conclusion is the necessity of a higher promotion of the VSDs in the lower/medium power ranges (up to 70 kW), although the application of VSDs be low in all power ranges.

[4] These values were extracted from the SAVE II project "Study on Technical/Economic and Cost/Benefit Analysis of Energy Efficiency Improvements in Industrial Three-Phase Induction Motors", EC-DGXVII, Energy, 1999.

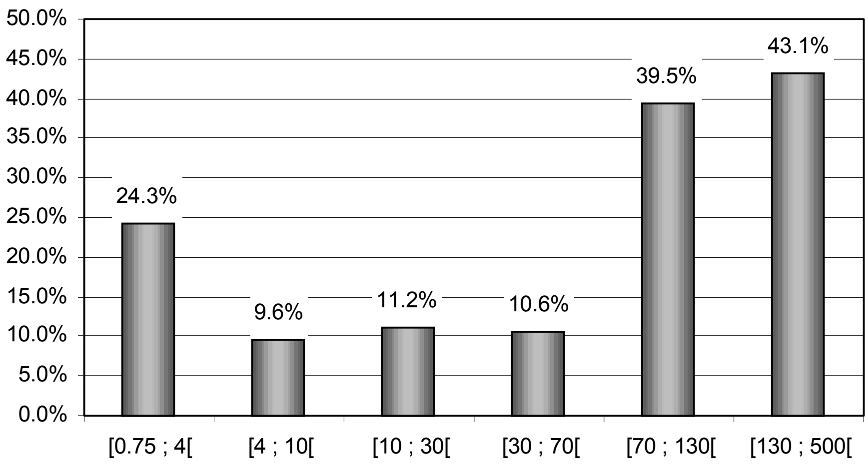


Figure 2.4 *- Number of VSD units sold in EU in 1998 as a percentage of the number of AC induction motors sold.*

The total sales value of VSDs are shown in Table 2.2.

Table 2.2 - Sum of total sales of VSDs (AC induction motor discrete drives) in each country in 1998.

Total sales in 1000 Euro	***Power range (kW)***						
EU Country	**[0.75 4[**	**[4 10[**	**[10 30[**	**[30 70[**	**[70 130[**	**[130 500[**	**Total**
Denmark	7 300	9 000	6 000	2 600	4 100	0	29 000
U.K. and Ireland	31 000	20 000	20 000	16 000	7 500	10 500	105 000
France	28 500	12 200	7 900	6 700	2 900	5 100	63 300
Germany	158 600	51 600	61 800	42 000	30 000	72 000	416 000
Portugal and Spain	37 000	13 000	14 000	11 000	7 000	13 000	95 000
The Netherlands	18 300	6 800	6 900	1 800	800	0	34 600
Total (71% of EU)	280 700	112 600	116 500	80 100	52 300	100 600	742 900
Total EU	395 300	158 600	164 100	112 800	73 700	141 700	1 046 300

The Figure 2.5 shows the total *VSDs* sales per power range. As it can be seen in this figure, the sales in the 0.75 to 4 kW range represent 43% of the total sales value in the surveyed countries.

In Figure 2.6 the distribution of the VSD market in terms of the total sales per each country can be seen. Germany has a leading role in the VSD market (40%).

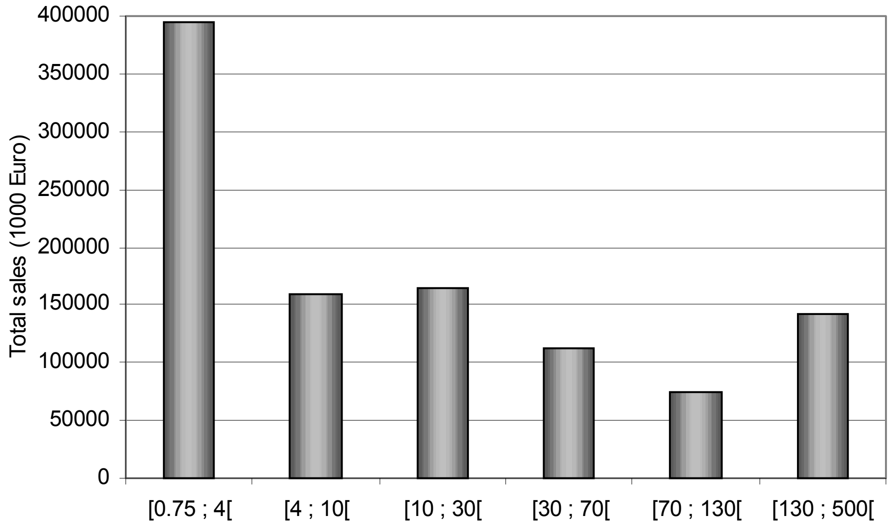


Figure 2.5 *- Total VSD sales in the EU per power range.*

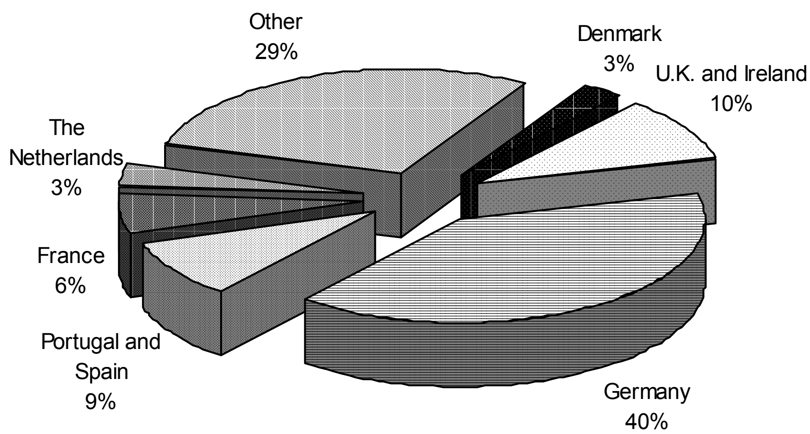


Figure 2.6 *- Distribution of the VSD market in terms of the total sales per each country.*

Table 2.3 shows the average prices per unit in each power range. Some significant differences in the prices, in the surveyed countries, can be observed.

Table 2.3 - VSDs prices per unit in each country.

Price in 1000 Euro per unit	*Power range (kW)*					
EU Country	**[0.75 4[**	**[4 10[**	**[10 30[**	**[30 70[**	**[70 130[**	**[130 500[**
Denmark	0.49	1.04	3.33	2.85	10.58	----
U.K. and Ireland	0.34	1.11	2.35	4.57	8.33	17.50
France	0.52	1.06	2.63	5.17	9.76	24.45
Germany	0.38	0.88	1.63	3.00	5.00	18.00
Portugal and Spain	0.57	1.18	2.33	4.40	7.00	18.57
The Netherlands	0.46	0.97	2.30	3.68	8.04	----
Average	0.46	1.04	2.43	3.95	8.15	19.62

In Figure 2.7, the estimated prices per unit in each country, by power range can be seen. It can be noted that Germany VSDs unit prices are the lowest in the ranges below 130 kW. This could be explained by the high business volume in the country.

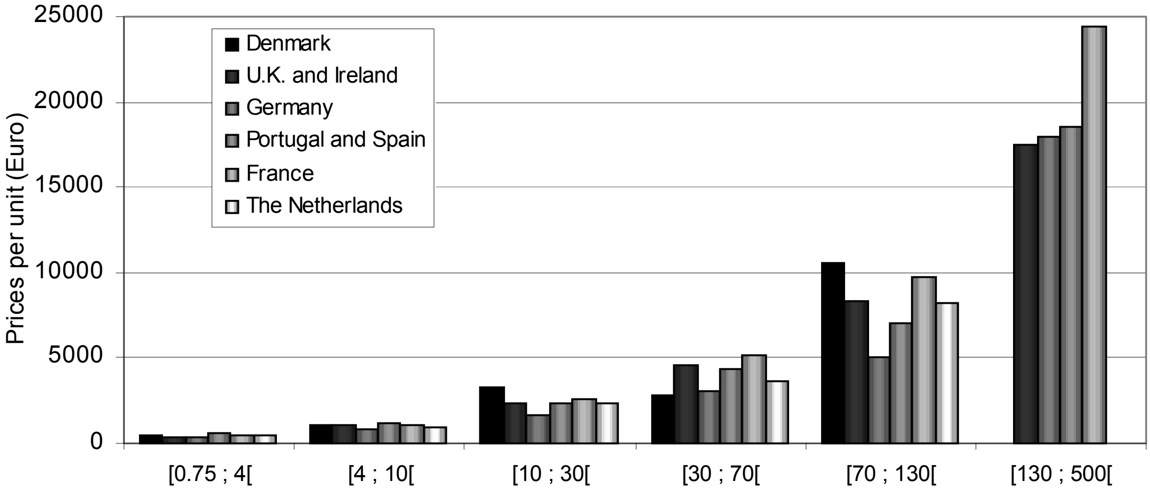


Figure 2.7 *- Average price per unit in each country by power range.*

In order to estimate the average price per kW, it was assumed the same average power values in each power range as in the previous SAVE II Study "Improving the penetration of Energy-Efficient Motors and Drives. The average power and average prices per kW by power range are presented in Table 2.4. The average European Union VSDs prices per kW and final prices per unit in the different power ranges are shown in Table 2.5.

Table 2.4 - Considered average power and estimated EU average VSD prices per kW in each power range.

Power range (kW)	**[0.75 4[**	**[4 10[**	**[10 30[**	**[30 70[**	**[70 130[**	**[130 500[**
Average Power (kW)	1.93	5.37	16.44	38.75	85.49	213.82
Price per kW (1000 Euro)	0.237	0.194	0.148	0.102	0.095	0.092

Table 2.5 - Estimated EU VSD installation costs per kW and total prices per unit and per kW, by power range.

Power range (kW)	**[0.75 4[**	**[4 10[**	**[10 30[**	**[30 70[**	**[70 130[**	**[130 500[**
Installation Costs (% of VSD price)	60%	50%	40%	35%	30%	25%
Total cost per kW (1000 Euro)	0.379	0.291	0.207	0.137	0.124	0.115
Total cost per unit (1000 Euro)	0.732	1.560	3.400	5.326	10.596	24.523

As it can be seen in Figure 2.8, the prices per kW decrease with the increase of the power, but more sharply in the low-medium power ranges. In fact, the prices per kW decrease until the 30 to 70 kW range, then they stabilize in the 70 to 130 kW range, and finally they slightly decrease in the higher power range. The prices per unit have a more regular behaviour, increasing continuously with the VSDs power.

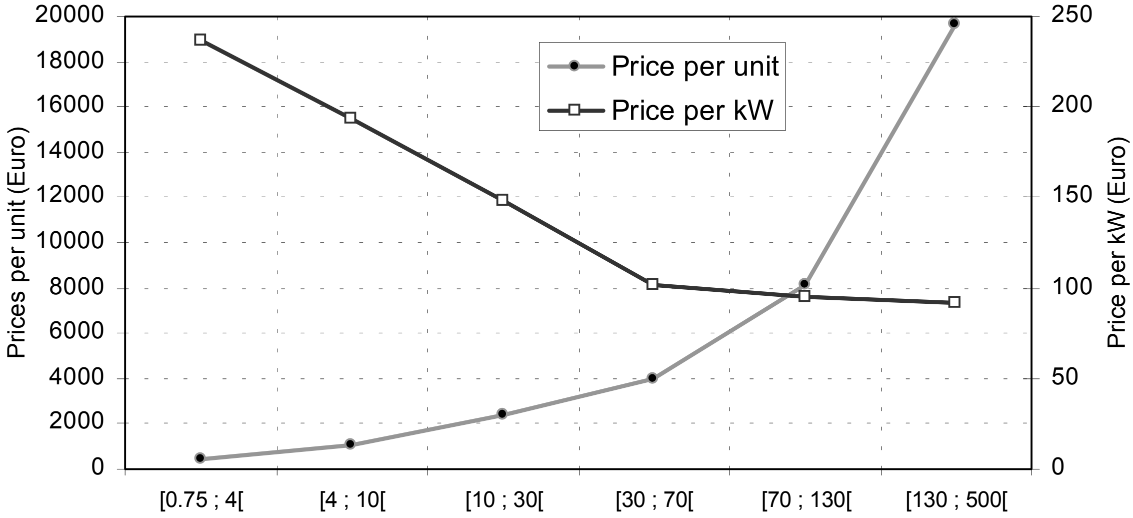


Figure 2.8 *- Average unit and per kW prices per power range, in the EU.*

In Figure 2.9, the final prices per unit per power range can be seen. The higher the power the lower the installation costs, and therefore, the final price difference between power ranges is lower.

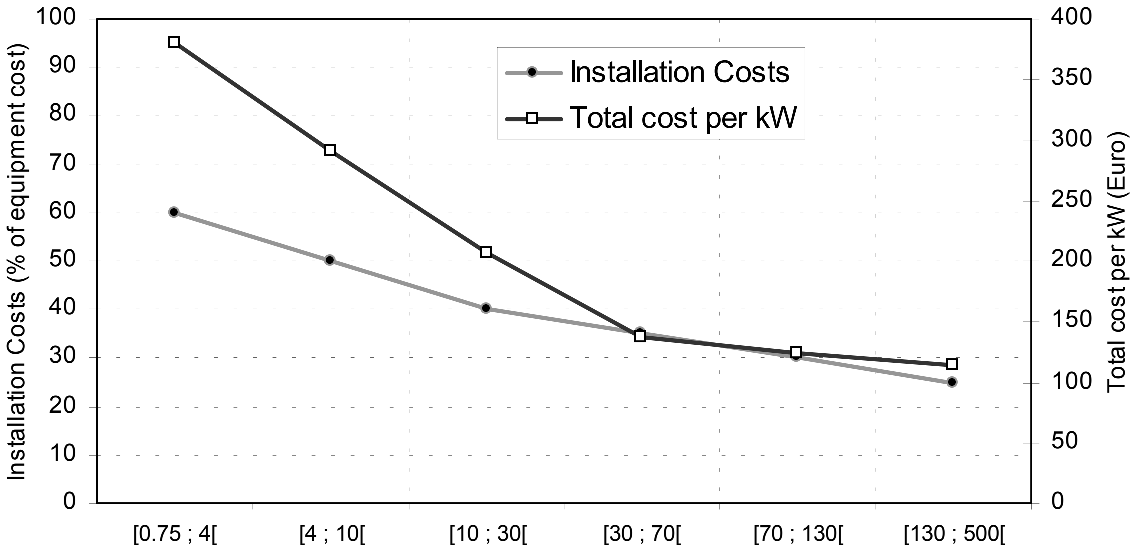


Figure 2.9 *- Total cost per kW, and average installation costs, per power range.*

Table 2.6 shows the total number of units and sales of AC induction motor electronic discrete drives[5], by far, the dominant variable speed technology. This table also presents the disaggregation of the VSDs by application.

[5] VSD sold as separate unit from the motor.

Table 2.6 – Estimated total number of units and sales of AC induction motor discrete drives in 1998 in the EU.

Main information			Application (%)						
Power range (kW)	**Number of units**	**Total sales in 1000 Euro**	*Air compressor*	*Fan*	*Materials handling*	*Materials processing*	*Pump*	*Refrigeration compressor*	*Other applications or no data available*
[0,75 4[	969 400	395 300	2	8	19	35	6	0	30
[4 10[	162 100	158 600	2	11	15	40	14	0	17
[10 30[	84 900	164 100	5	19	11	36	16	2	10
[30 70[	32 000	112 800	2	22	5	40	19	2	10
[70 130[	12 200	73 700	3	13	12	50	12	0	10
[130 500[	7 800	141 700	3	20	20	30	16	0	11

The total number of VSDs sold in the EU in 1998 is estimated to be 1 268 400 units, with a value of 1 046 308 000 Euro. The main end-use application is the "Materials processing" in all the power ranges. The relatively modest penetration in "Fans" and "Pumps" is an indicator that, for many end-users, the technical and process improvement factors are more important than energy savings.

The estimated total number of units of "other" (AC induction integrated drives and Brushless DC) types of drives is presented in the Table 2.7.

Table 2.7 – Estimated total number of units of "other" types of drives per power range in 1998.

	Number of units	
Power range (kW)	**AC induction motor integrated drive**	**Brushless DC Drive**
[0,75 4[	191 200	85 300
[4 10[	29 900	15 500
[10 30[	1 500	7 800
[30 70[	0	3 100
[70 130[	0	1 500
[130 500[	0	300

In Table 2.8 the estimated total number of units by technology, sold in 1998, can be seen.

Table 2.8 - Total number of units and sales value by technology in 1998.

Technology	Number of units
AC Induction Motor Drive - Discrete Drive	1 268 400
AC Induction Motor Drive - Integrated Motor/Drive	222 600
Brushless DC Drive - Discrete Drives	113 500
Total	1 604 500

As it can be seen in Figure 2.10, other more advanced drives had a sales volume of 336 140 units (21% of total number), in 1998. This number, although modest, compared with discrete induction motor VSDs is growing fast, particularly in the low power range.

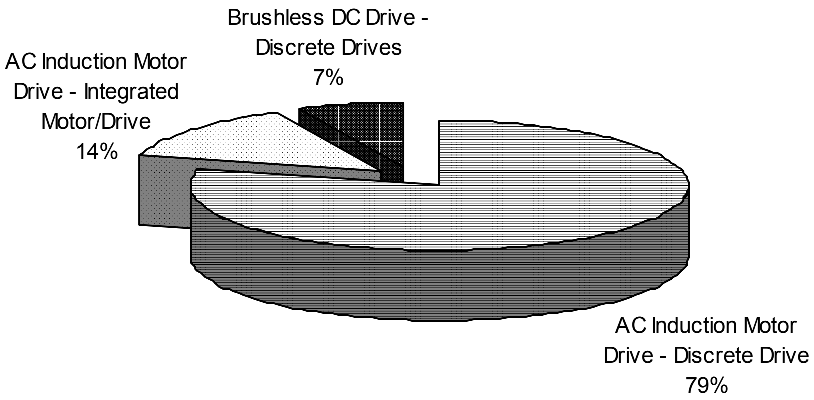


Figure 2.10 *- Disaggregation of EU VSD market in number of units by technology in 1998.*

3. SAVINGS POTENTIAL OF VSDs

Based on the characterisation carried out in the surveyed EU countries (Section 2), the electricity savings potential that can be achieved by the application of present market VSD technologies, by the year 2015, has been calculated considering three different approaches:

- ***Economic Saving Potential, assuming constant VSD prices*** - This potential was estimated considering cost-effectiveness constraints and assuming no significant changes in market conditions in the considered time horizon.
- ***Economic Saving Potential, assuming a 5%/year decrease of VSD prices*** - This potential was estimated considering cost-effectiveness constraints and assuming a 5% decrease per year in the final VSD prices (VSD + installation) in the considered time horizon.
- ***Technical Saving Potential*** **-** This potential was estimated considering that there were no restrictions on cost-effectiveness. Assuming that, all applications which could benefit from speed control would apply VSDs.

The savings potential were determined by industrial and tertiary sectors, power ranges and main end-uses in each sector.

3.1 Methodology

In order to estimate the electricity savings potential, the time horizon of 2015 was used. According to *"European Energy to 2020"*[3], in the "conventional wisdom" scenario, the annual average growth rates of the electricity consumption up to 2015, in the industrial and tertiary sectors are estimated to be 1.2% and 1%, respectively. Table 3.1 shows the estimated motor electricity consumption in the industrial and tertiary sector, by power range in 2015 assuming frozen efficiencies for induction motor systems. In order to estimate the potential savings it was used the same methodology as in the SAVE II project "Improving the penetration of Energy-Efficient Motors and Drives" [2].

Table 3.1 - Estimation of motor electricity consumption by power range, by 2015 based on the average growth rates of 1.2% and 1% growth rates in the industrial and in the tertiary sectors, respectively.

Motor electricity consumption forecast by 2015 (TWh pa)		
Power Ranges (kW)	**Industrial sector**	**Tertiary sector**
[0.75 4]	46.9	66.2
]4 10]	55.8	58.8
]10 30]	95.0	53.6
]30 70]	143.9	12.7
]70 130]	83.6	10.7
]130 500]	166.3	6.3
Total	597.8	222.4

For the assessment of the electricity savings potential with the application of Electronic Variable Speed Drives, two different conditions have been considered: the ***economic savings potential*** and ***technical savings potential***.

3.2 Technical Potential

The technical potential represents the energy savings that can be achieved applying the Variable Speed Drives to all the available opportunities, irrespective of the cost-effectiveness of the measure.

3.3 Economic Potential

The economic savings potential represents the energy savings that can be achieved when the efficient technologies are only applied to cost effective applications.

One of most sensitive factors for the cost effectiveness of VSDs is the number of operating hours. Cost-effectiveness analysis in this study has been based on the cost of saved energy (CSE). The input data for the cost benefit analysis was the field survey realised in the SAVE project "Improving the penetration of Energy-Efficient Motors and Drives". The CSE was determined according to the equation:

$$CSE = \frac{(Implementation\ Cost) * (Interest\ Rate)}{(Saved\ Energy) * (1 - (1 + Interest\ Rate)^{-lifetime})}$$

The cost of implementation includes the cost of the equipment, plus the cost of installation and the interest rate is considered to be 10%.

When the CSE is less than the typical average price of electricity in the industrial and in the tertiary sectors (which was considered 0.055 Euro/kWh and 0.1 Euro/kWh respectively), it is cost-effective to apply the measures under consideration.

There are some situations in which the introduction of variable speed control is not attractive, especially in the lower power ranges.

The considered European average prices of *VSDs* per kW by power range were based on the Section 2 estimated average values shown in Table 3.2. In the first analysis it is considered that the presented prices will be the same in 2015. In the second analysis it is considered that the present prices decrease 5%/year, as it can be seen in Table 3.3.

Table 3.2 - European average total prices per kW, by power range, in 1998.

Power Range (kW)	Average Price (Euro/kW)	Cost of Installation (Euro/kW)	Total Price (Euro/kW)
[0.75 4]	237	142	379
]4 10]	180	90	270
]10 30]	140	56	196
]30 70]	95	33	128
]70 130]	94	28	122
]130 500]	92	23	115

Table 3.3 - European average total prices per kW, by power range, in 2015, assuming a 5%/year price decrease.

Power Range (kW)	Average Price (Euro/kW)	Cost of Installation (Euro/kW)	Total Price (Euro/kW)
[0.75 4]	99	59	158
]4 10]	75	38	113
]10 30]	59	24	83
]30 70]	40	14	54
]70 130]	39	12	51
]130 500]	38	10	48

3.4 Potential Savings with the Application of VSDs

Based on the field survey carried out for the SAVE project "Improving the penetration of Energy-Efficient Motors and Drives", suitability of Variable Speed Drives for motor loads is generally high, but some applications, which could benefit from the speed control, may already have a VSD fitted. Some loads are not suitable for speed control. To determine the potential electricity savings from VSDs it was considered an applicability factor for each type of load, based on the mentioned survey. Table 3.3 and 3.5 show how the existing capacity of VSDs has been taken into account. For the calculation of the potential electricity savings with the application of VSDs, it has also been assumed 35% average savings for pumps and fans, and 15% average savings for compressors (air compressors, air conditioning and refrigeration), conveyors and other motors. These values are average savings based on a variety of case studies. Table 3.3 shows the input data for the estimation of the potential savings in ***industry***, and Table 3.4 shows the economic potential for each industrial sector surveyed.

Table 3.3 - Basic data used to assess the potential savings in the industrial sector.

VSDs	Average Savings (%)	Applicability (%)	Already Applied (%)	Technical Potential* (%)
Pumps	35	60	9	51
Fans	35	60	7	53
Air Compressors	15	30	5	25
Cool. Compressors	15	40	4	36
Conveyors	15	60	8	52
Other Motors	15	60	5	55

* ***Technical Potential = Applicability-Already Applied***

Cost-effectiveness calculations have been carried out in order to define the economic savings potential. With this condition, and because the price of VSDs has been decreasing considerably, it is now cost-effective to apply VSDs in most of the end-use applications. However, since the calculations have been based on the average number of operating hours collected in the field characterisation, it is not realistic to consider that all motors run the average number of operating hours. Therefore, it was conservatively assumed that about 25% of the motors do not work the required number of operating hours to make the application of VSDs cost-effective.

Table 3.4 - Percentage of motors in which the application of VSDs is cost-effective in each surveyed industrial sector.

VSDs	*Non-Metallic Minerals*	*Paper and Cardboard*	*Food, Beverage and Tobacco*	*Basic Chemistry*	*Machinery and Metal*	*Iron and Steel*
Pumps	36	38	26	37	27	32
Fans	39	35	34	40	28	38
Air Comp	19	18	15	19	13	18
Cool Comp	0	27	18	27	0	27
Conveyors	15	33	0	18	0	13
Other Motors	36	41	25	40	0	39

Table 3.5 shows the input data for the estimation of the potential savings in the ***tertiary sector***.

Table 3.5 - Basic data used to assess the potential savings in the tertiary sector.

VSDs	*Average Savings (%)*	*Applicability (%)*	*Already Applied (%)*	*Technical Potential (%)*	*Economic Potential * (%)*
Pumps	35	60	7	53	40
Fans	35	60	5	55	22
Refrigeration	15	30	3	27	20
Air Conditioning	15	40	3	37	11
Conveyors	15	60	7	53	0
Other Motors	15	60	3	57	0

** Percentage of motors in which the application of VSDs is cost-effective*

VSDs are not cost-effective in the lower power range. However this is becoming progressively less true, since the prices of *VSDs* have been decreasing in recent years. In fact, an exception for this situation concerns air conditioning units in the tertiary sector. Although the average number of operating hours of air conditioning loads is low, it is cost effective to introduce electronic variable speed control in the power range [0.75 4] kW, because the extra cost per kW in this power range is very small, typically 50 Euro per kW due to mass production. It is important to mention that this extra cost concerns air conditioning units whose variable speed drives are integrated in the unit.

3.5 Potential Savings in Industry

In order to extrapolate the results for the EU, the savings potential as a fraction of the motor load, in those industries which have not been assessed, is estimated to be 60% of the potential found in the six characterised industrial sectors.

3.5.1 Potential Savings per Power Range

Table 3.6 shows the estimated technical and economic potential savings in EU ***industry*** in 2015, including the potential savings for the other industries, which were not considered in Table 3.4.

Table 3.6 *- Technical and economic potential per power range of VSDs in industry, in 2015*

Total Industry	*Technical Potential (TWh pa)*	*Economic Potential (TWh pa)*	
Power ranges		*Constant prices*	*5%/year price decrease*
[0.75 4]	4.4	2.3	2.9
]4 10]	5.6	3.2	3.7
]10 30]	9.9	5.2	6.2
]30 70]	15.0	9.3	10.4
]70 130]	9.2	6.5	6.9
]130 500]	17.5	12.3	12.9
Total	**61.6**	**38.8**	**43.0**

In Figures 3.1 the technical and economic potential electricity savings by power range for the application of VSDs, in the industrial sector in EU can be seen. The power ranges with the highest potential savings are]30 70] kW and]130 500] kW. This is related with the distribution of motors per power range, which was characterised in the previous SAVE project.

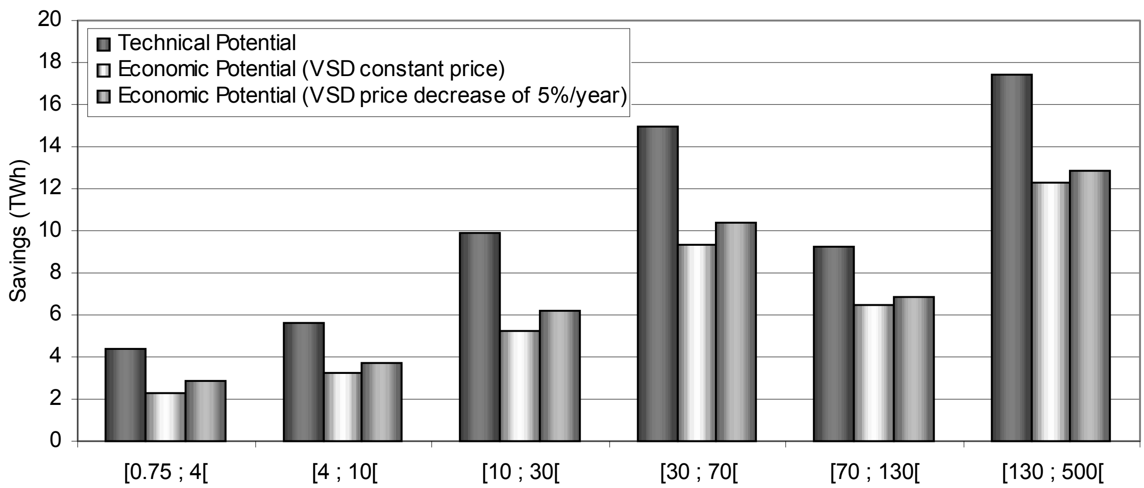


Figure 3.1 *- Technical and Economical Potential for the Industrial sector by power range.*

3.5.2 Potential Savings by Type of Motor Load and by Measure

Based on data from the field characterisation and considering the motor load desegregated by pumps, fans air compressors, cooling compressors, conveyors and other motor loads, the electricity savings potential by end use application for the considered technical options of efficiency improvement and *VSDs* have also been estimated and are presented in Table 3.7.

Table 3.7 - Technical potential savings by type of load in industry.

Type of load	***Savings VSDs (TWh pa)***
Pumps	23.2
Fans	16.6
Air Comp	2.5
Cool Comp	1.7
Conveyors	1.1
Other loads	16.4
Total	**61.6**

Based on cost-benefit analysis the economic savings by type of motor load were also estimated as shown in the Table 3.8.

Table 3.8 - Economic potential savings by type of load in industry.

Type of load	***Savings VSDs (TWh pa)***	
	Constant prices	***5%/year price decrease***
Pumps	16.5	17.4
Fans	11.3	12.4
Air Comp	1.7	1.8
Cool Comp	0.9	1.2
Conveyors	0.4	0.8
Other loads	8.0	9.4
Total	**38.8**	**43.0**

Figure 3.2 presents the Technical and Economic Savings by type of load. It can be seen that the pumps and fans represent the higher savings potential (technical and economic).

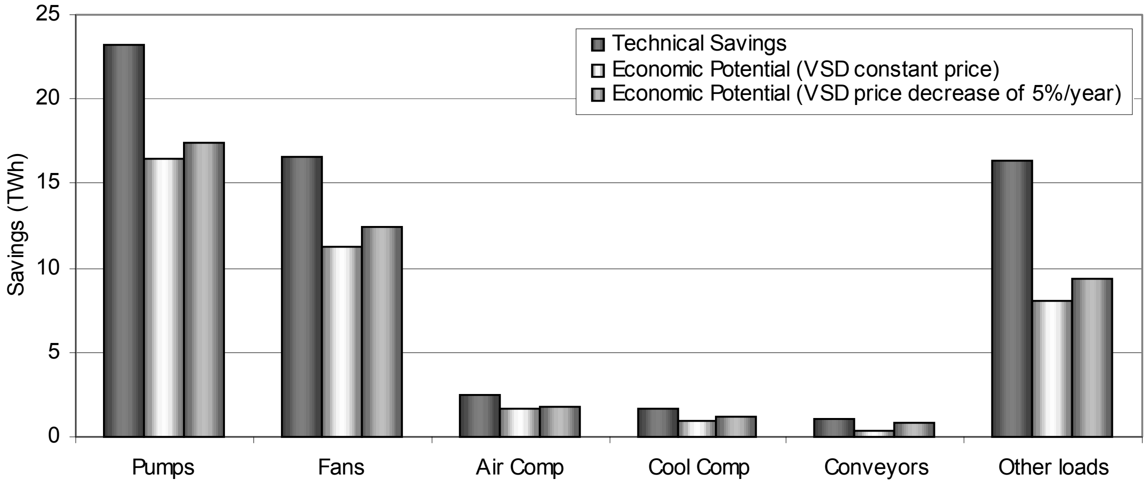


Figure 3.2 *- Technical and Economic Savings Potential in Industry by type of load.*

3.6 Potential Savings in Tertiary Sector

Using the methodology described for the industrial sector, the potential savings for the tertiary sector have been estimated.

3.6.1 Potential Savings per Power Range

Table 3.9 shows the technical and economic potential disagregated per power range in the tertiary sector. The lower power range in the tertiary sector have the higher savings, while in the industry sector, the maximum values are in the larger power range.

Table 3.9 - Technical and economic potential per power range of VSDs in tertiary sector, in 2015.

Power Range	*Technical Potential (TWh pa)*	*Economic Potential (TWh pa)*	
		Constant prices	*5%/year price decrease*
[0.75 4]	8.9	3.4	4.6
]4 10]	5.8	2.2	2.9
]10 30]	4.6	1.6	2.1
]30 70]	1.1	0.4	0.6
]70 130]	1.0	0.4	0.6
]130 500]	0.5	0.2	0.3
Total	**21.9**	**8.2**	**11.1**

Figure 3.3 shows the technical and potential savings by power range in tertiary sector.

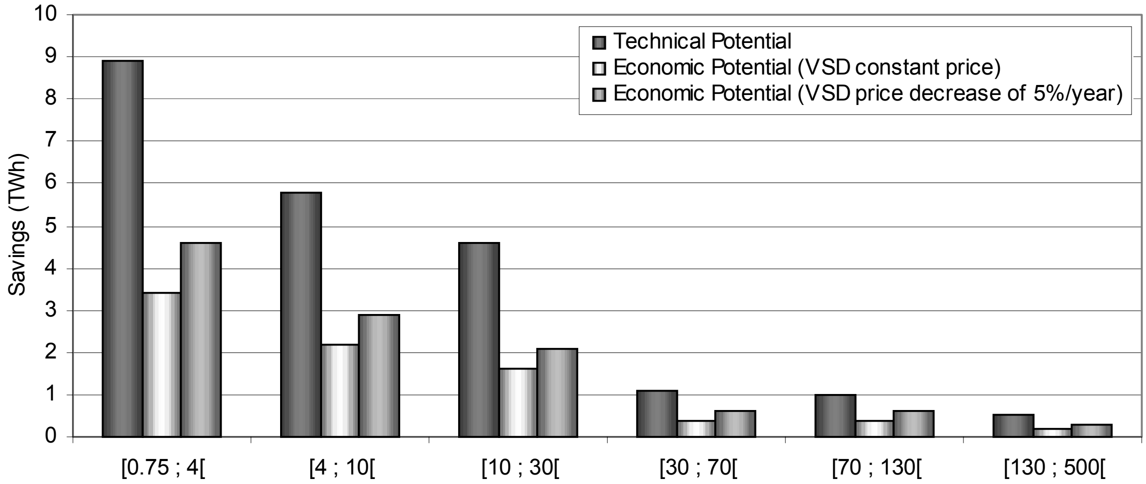


Figure 3.3 *- Technical and Economic Savings Potential in Tertiary Sector by power range.*

3.6.2 Potential Savings by Type of Motor Load and by Measure

Based on data from the field characterisation and considering the motor load disagregated by pumps, fans air compressors, cooling compressors, conveyors and other motor loads, the electricity savings potential by end use application for the considered technical options of efficiency improvement and VSDs have also been estimated and are presented in Table 3.10.

Table 3.10 - Technical potential savings by type of load in Tertiary Sector.

Type of load	*Savings VSDs (TWh pa)*
Pumps	4.4
Fans	10.1
Refrigeration	2.4
Air Conditioning	2.0
Conveyors	1.9
Other loads	1.1
Total	**21.9**

Based on cost-benefit analysis the economic savings by type of motor load were also estimated as shown in the Table 3.11.

Table 3.11 - Economic potential savings by type of load in Tertiary Sector.

Type of load	*Savings VSDs (TWh pa)*	
	Constant prices	*5%/year price decrease*
Pumps	2.8	2.8
Fans	3.3	6.1
Refrigeration	1.5	1.5
Air Conditioning	0.6	0.6
Conveyors	0.0	0.1
Other loads	0.0	0.0
Total	**8.2**	**11.1**

Figure 3.4 presents the Technical and Economic Savings by type of load. It can be seen that the pumps and fans represent the higher savings potential (technical and economic).

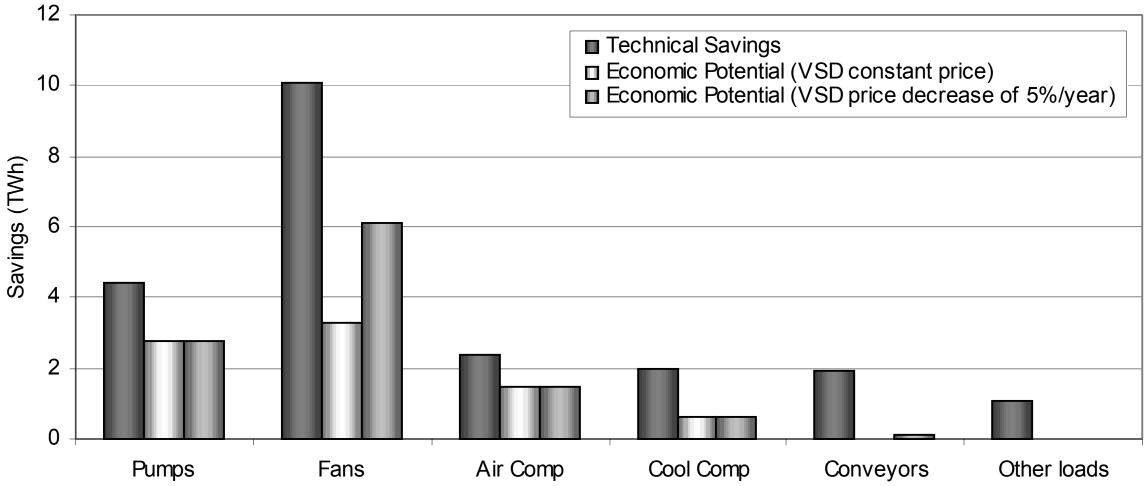


Figure 3.4 *- Technical and Economic Savings Potential in Tertiary Sector by type of load.*

3.7 Technical and Economic Potential Savings in Industry and in the Tertiary Sector

The Table 3.12 shows the technical potential savings estimated in the industrial and tertiary sectors, considering the previous presented prices.

Table 3.12 - Technical potential savings in the industrial and tertiary sectors, by 2015.

Technical Potential	***VSDs (TWh pa)***
Basic Chemistry	12.3
Food Beverage and Tobacco	7.8
Iron and Steel	4.7
Machinery and Metal	6.3
Non-Metallic Mineral	5.4
Paper and Cardboard	14.8
Other Industries	10.3
Total Industry	**61.6**
Total Tertiary	**21.9**
Total	**83.5**

In Table 3.13, the economic potential savings estimated per power range in the industrial and tertiary sectors can be seen.

Table 3.13 - Economic potential savings in the industrial and tertiary sector, by 2015.

Type of Industry	***VSDs (TWh pa)***	
	Constant prices	***5%/year price decrease***
Basic Chemistry	8.9	9.3
Food Beverage and Tobacco	4.2	5.3
Iron and Steel	3.2	3.5
Machinery and Metal	1.5	2.7
Non-Metallic Mineral	3.7	4.0
Paper and Cardboard	10.8	11.0
Other Industries	6.5	7.2
Total Industry	**38.8**	**43.0**
Total Tertiary	**8.2**	**11.1**
Total	**47.0**	**54.0**

From tables 3.12 and 3.13, it can be seen that the industries with higher savings potential are *the Basic Chemistry* and *Paper and Cardboard*.

Table 3.14 presents the total savings in Euro and in CO_2 were estimated, assuming the European average values for electricity prices and CO_2 emissions per kWh generated. Considering that the prices of VSDs will be the same by 2015, the total savings per year will be 2054 Million of Euros, and the CO_2 avoided emissions per year will be approximately 23.5 Million of Tones.

Table 3.14 - Total savings in the industrial and tertiary sector (assuming : 0.4Kg of CO_2 per kWh generated and an electricity price of 0.055 and 0.1 euro/kWh to the industry and tertiary sector, respectively).

Total savings	***Technical potential***	***Economical potential***	
		Constant prices	***5%/year price decrease***
Savings (Mton CO_2 pa)	**33.4**	**18.8**	**21.6**
Savings (Euro*10^6 pa)	**5578**	**2054**	**3475**

4. COST-BENEFIT ANALYSIS OF TECHNICAL CHANGES IN THE DESIGN OF VSDS

4.1 Summary

Advances in the performance and the lower costs of power semi-conductor and microprocessors mean that VSDs have become progressively more cost-effective, reliable and technically superior since they became a "standard offering" in the late 1970's.

Anticipated future developments in technology are likely to lead to lower power loss and hence smaller and cheaper VSDs, which will further reduce costs. It is unlikely that the now standard Pulse Width Modulation (PWM) inverter will lose its dominant market share in the Low Voltage market. However, there are though other types of VSD, particularly in low powers (< 7.5 kW), that look set to enjoy greater market share in niche applications, such as Switched Reluctance and Permanent Magnet drives. The growth of lower cost VSD "modules" is also hoped to offer a very low cost way to incorporate VSDs in such lower power OEM equipment, (similarly < 7.5 kW). Many manufacturers have introduced integrated motor/VSD units, and it is anticipated that sales of these will rise fast to become a significant part of the VSD market.

While OEMs generally find it hard to pass on the extra costs of fitting their equipment with speed control as standard, there are cost and performance advantages from fundamentally re-designing some products to take advantage of variable speed operation. For instance, re-designing a centrifugal pump or air compressor to work at variable speed can reduce both the cost premium of variable speed, and give an increase in efficiency to the basic machine.

While the falling price of VSDs has made them more cost effective, this has further reduced manufacturers profit margins, and the large number of suppliers makes the "lowest cost" market unattractive. An immediate effect of this is the much lower level of free applications support available to purchasers of lower cost equipment. Successful manufacturers are differentiating themselves by for instance giving high levels of technical support, fast delivery of new units/spares, or dedicating themselves to particular industry sectors or applications.

4.2 Technology – The PWM Inverter

The PWM VSD (see Section 1.2) is now virtually the only type offered for low voltage AC squirrel cage induction motors. Their lost cost makes them the VSD of choice for all drive applications unless there are over-riding reasons why they cannot be used.

4.2.1 Technical Advantages of the PWM VSDs

- An important advantage of the PWM VSD is that it can be fitted to existing motors.
- Very reliable, with guarantees of up to 3 years being the norm.

- Easy to retrofit.
- Good supply side displacement power factor at all loads, but because of the un-controlled input bridge there will be undesirable harmonic distortion.
- Now can be very easy to commission.
- Easily available “off the shelf”.
- Can be by-passed in the event of failure.
- Can run in open-loop without any speed sensor.
- Smooth output current waveform
- Good dynamic performance approaching that of DC drives, with suitable control algorithms such as vector control.
- Can run multiple motors from one VSD
- Reduced wear and tear on the machinery due to soft-starting/stopping and lower speed operation.
- Diagnostics and protection helps reduce/identify faults. VSDs can avoid the need to buy and install several types of dedicated motor protection, (e.g overload, loss of phase, under/overvoltage, etc.)

4.2.2 Technical Disadvantages of PWM VSDs

Although it is now a “standard” and widely recognised item, the PWM VSD can cause technical problems. The scale of these problems is very hard to evaluate, as many VSD companies are appearing to amplify some problems when promoting their own products, which of course have eliminated that specific problem!

Premature motor winding failure - The very fast rate of rise of voltage on modern PWM drives, which is exacerbated by higher switching speeds, can cause high voltage transients which damage the motor insulation and hence lead to failure. This problem may be more serious in the case of longer connecting cables between the VSD and the motor, due to the reflection of the voltage waves. With the higher grades of wire insulation now used on modern motors, this is not now regarded as a problem, but users are advised not to fit VSDs on to older motors. Some manufacturers supply dU/dt filters to curb this effect.

Bearing erosion - The high frequency of the output waveform can induce voltages in the shaft, which cause currents to circulate through the housing via the bearing, and hence early bearing failure. Good earthing can usually overcome this, but in addition the use of slightly more expensive insulated bearings will stop the unwanted currents.

Reliability - Early VSDs were often unreliable, but with mass production, and much lower component counts, and better protection, today they are extremely reliable. Guarantees of 1-3 years are offered as standard.

Hard to install/commission - Manufacturers have responded to market demands for easier to fit VSDs by simplifying control panels and offering many VSDs with simple "self commissioning" modes that automatically tune the VSD to the motor. However, inexperienced users will often still need professional support, and it is the norm for larger drives to be installed by specialists.

Harmonic distortion - PWM VSDs cause harmonic distortion to the mains due to the non-sinusoidal shape of current drawn by the (uncontrolled) input bridge rectifier stage. The "noise" can cause problems with more sensitive electrical equipment, and additional heating of the supply-side cables. Harmonics can also increase the losses in other equipment used in the plant. The 5^{th} harmonic is particularly bad in increasing the losses in other induction motors in the plant directly connected to the mains supply.

It is therefore a requirement that all VSDs should be fitted with a passive filter to "smooth" the current and so reduce this distortion to lie within prescribed limits. At the same time the filter also improves the VSD power factor. (Because of the good displacement power factor of a VSD, which is constant over load, Power Factor Correction capacitors are not needed. In fact, to prevent damage to capacitors due to the harmonic distortion, it is usually recommended that any capacitors that were fitted with the motor should be removed). However, site power factor correction is still possible on sites using VSDs.

PWM VSDs generate voltage waveforms on the motor side with lower harmonic content than other types of VSD. Significant progress has been done to reduce lower order harmonics, since higher order harmonics are filtered by the motor inductance. Even so motors supplied with VSDs have higher operating temperatures than if they were directly connected from the mains supply.

Larger drives are often supplied by their own transformer, which then "swallows" the distortion caused by the drive. This also means that the primary-side of the transformer is "unharmed", as are the rest of the electrical installation. This technique require correct dimensioning of the transformer, since there can be an increased heat development due to this.

Radiated emissions - The high frequency of the output voltage acts as an "aerial", which can cause local interference to nearby equipment. The use of shielded cable is therefore imperative to overcome this. In some cases output filters also need to be fitted to the VSD.

All VSD's have thorough installation descriptions regarding which cables to use, how to lay them out and so forth, to ensure EMC-compliance.

Measuring problems - Due to the above-mentioned problems of non-sinusoidal waveforms, high frequency switching etc, it is very difficult to measure correctly electrical parameters on VSDs. Even with modern "True-RMS" instruments, the necessary precautions have to be taken to ensure accurate results. In most cases the user has to rely on shown data on the VSD – even though these are often only within 3-5% accuracy.

De-rating of motors at low speeds - The problem of additional motor heating due to harmonic distortion is exacerbated at lower speeds. This is because most motors are self-cooled with a fan mounted in the non-drive end of the motor, and lower speeds thereby lead to lower air flow. In some (rare) cases separate motors are installed with an external cooling fan, thus eliminating this problem.

Historically VSD manufacturers would have suggested a 10% de-rating of motor power to account the increased heat development, but with modern VSDs, many manufacturers state that no de-rating is required.

Low speed problems - A very big problem when running AC squirrel cage induction motors with VSDs is obtaining continuously steady operation at very low speeds. Although a lot of manufacturers claim differently, the truth is that it's almost impossible without encoder feedback. Especially through longer time periods. Using an encoder increases low-speed performance, but at the penalty of higher cost.

4.3 Likely Future Improvements to PWM VSDS

While the basic topology of the PWM VSD is not expected to change in the near future, there will be changes in the components used. The overall efficiency of a PWM VSD is typically 96-97% at full load, largely independent of size, and so there is little further scope for energy saving. However any reduction in losses reduces the heat that needs dissipating, and hence the size and cost of the VSD. It is this consequent reduced cost of VSDs that makes the improved efficiency of VSDs important for increasing the penetration of VSDs.

Improvements in IGBT packaging - The "on-state" and "switching losses" of IGBTs (Insulated Gate Bipolar Transistors) have slowly improved, allowing operation with lower power loss.

Reducing the operating temperature reduces the actual collector-emitter voltage drop, and hence power loss, and so thermal management of the VSD power transistor (IGBT) assembly is key to a good design. In addition, if there is good thermal transfer of heat from the IGBT module to ambient, then it can pass more current for the size of IGBT, therefore making a more cost-effective design. It is expected that improved packaging of the semiconductors will give improved heat transfer from the semiconductor to its body. In particular, reducing the thermal resistance of the semiconductor to case junctions by replacing the current wires with direct metallic contacts will remove the heat faster.

Figure 4.1 *- Typical dual-switch IGBT module.*

New semiconductor materials - IGBTs are currently built on silicon substrates, but silicon carbide is now being developed to replace this. This will allow higher operating temperature and the ability for higher powers to be switched, and hence much smaller sizes of enclosure. This is still 5-10 years in the future.

Improved switching techniques - To minimise power loss during switching, the resonant technique of "soft switching" reduces the voltage applied during switching.

Liquid cooling of VSDs - Larger VSDs already use liquid cooling to allow greater heat dissipation for a given size of cooling assembly. If the costs become attractive, then applying this technology to lower power VSDs will further reduce losses. The cost of heatsink, enclosure, and usually a fan, can be a considerable part of the overall cost of a VSD, and so these improvements are very valuable.

4.4 Energy Optimising or "Flux Reduction" Techniques

Many VSDs incorporate an "Energy Optimising" feature, which saves energy by reducing the motor magnetising current at low mechanical loads. This energy saving is in addition to that made by reducing the mechanical shaft power drawn by the driven machinery.

The principle is that at low load, the motor does not need to produce such a strong magnetic field to operate. Reducing the voltage will reduce this magnetising current (the magnetising current and hence losses are proportional to the applied voltage squared), and so will reduce the required power. Independent tests were carried out by the University of Nottingham for the UK Energy Efficiency Best Practice Programme on a number of different makes of VSD with this feature. However, the wide variation of algorithms used by manufacturers mean't that no single figure for the effectiveness of this feature could be meaningfully established. But in subsequent discussions with manufacturers it was agreed that the energy savings are only small, and usually much less than from the slowing down of the driven machinery. The generally accepted position is therefore that if you buy a VSD with this feature, then it may save a small additional amount of energy, but it is unlikely to be significant enough to help persuade you to buy a VSD.

4.5 Costs of developing and tooling up for new VSD designs

The technical maturity of the basic PWM VSD means that most designs are very similar, with the key components, the IGBTs and DC link capacitor, available "off the shelf" from major suppliers. It is these component suppliers who carry the costs of developing better components, driven by competitive pressures, with other equipment that uses power components also helping to drive the market. However, for market leaders, the cost of R&D is very high. This is because of the extensive effort spent on developing the VSD software.

Increasingly, a large proportion of the development costs are in designing the control software. The major tooling costs are likely to be for the mechanical assembly, and a smaller amount for the PCB. For comparison, these costs are though very much less than if tooling up for a new motor of similar size. The relatively low development costs of VSDs is shown by the large number of manufacturers, many of whom are very small.

With increased integration of power and control components, and the use of Surface mounted Devices, modern VSDs have far few components than in the past, with automatic assembly being used to varying degrees. Labour costs per unit are therefore low, again shown by the large number of manufacturers still assembling units in Western Europe.

4.6 Alternative Packaging of VSDs

Integrated VSDs - The price premium of VSDs has in the past been a deterrent to OEMs, but this is slowly changing. Manufacturers of some motors, pumps and compressors are now offering VSDs as part of standard items, although sales are still far behind fixed speed machines. However, by re-designing the whole product to take advantage of the VSDs, the price premium for a VSD based machine can fall dramatically. For instance, with a variable speed air compressor, many of the standard controls and the gearbox are no longer needed, bringing the price premium down to 50 Euro/kW. In all types of rotating machinery, the use of a VSD as standard, frees the designer from the traditional constraints of designing machinery for (at 50Hz) 1500 or 3000 rpm rotational speeds, and even allows operation at speeds above 3000 rpm. Particularly for centrifugal equipment such as fans or pumps, this allows machinery to be designed nearer the optimum specific speed for a much wider range of duties.

Low cost VSD modules - Particularly in low powers (typically up to 2.2kW), stand-alone VSD modules are available at low cost for integration into products, and as prices fall further it is anticipated that this market could grow fast.

4.7 Development of the AC VSD

Although seen as being a mature product, there are new developments that will further boost their cost-effectiveness and overcome some of the inherent weakness of the AC PWM VSD.

4.7.1 Matrix Converter

A problem with the PWM VSD is that the DC link requires a bulky and costly smoothing capacitor. This also has a long but ultimately limited life which is reduced by high temperature, and so is an undesirable component to have. The matrix converter does though need 18 rather than the usual 12 power devices to directly convert the mains supply to a variable AC voltage, avoiding the need for this intermediate DC link. A disadvantage in some applications is that it is hard to run the motor above its synchronous speed, and braking is harder than with PWM VSDs. As the costs of power semiconductors fall, so the matrix converter will become more economically attractive. As far as is known, it is not yet available commercially.

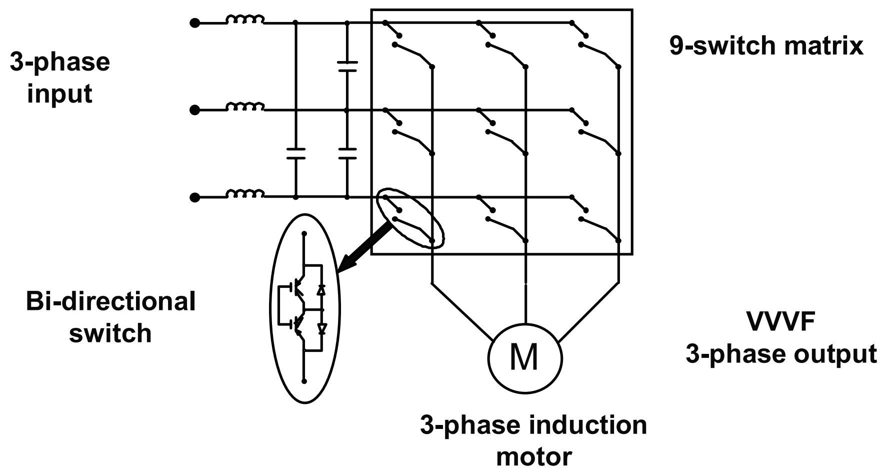


Figure 4.2 *- Schematic diagram of a matrix converter.*

4.7.2 Regenerative PWM VSD

Conventional PWM VSDs rely on a DC "brake" resistor connected to the DC bus to absorb power when slowing the motor down. This is inherently inefficient, particularly in applications with frequent cycling. Regenerative drives (described in Section 1.2) actually reconvert the energy in the rotating load back to a current that is then absorbed by the mains power supply. This is much more efficient, and even reduces the site electricity bill!

To achieve this there needs to be virtually a complete "reverse" inverter circuit, and so regenerative drivers are much more expensive than standard types. One very big advantage is that since there is now a fully controlled mains-side bridge, the current drawn from the mains in normal operation can be controlled to be extremely smooth. This therefore eliminates the need for input side filters. In multiple VSD applications, the DC links may be tied together, thus allowing power from one motor slowing down to be absorbed by others still demanding power.

In most situations the energy savings alone from this technology are not adequate to justify the current price premiums. Lifts and machine-tools are examples of industrial loads in which regenerative braking will make some energy savings. The greater the frequency of stop-starts the larger the energy savings will be.

4.7.3 Variable Speed Motors (VSMs)

Most motor manufacturers are now producing integrated motor/VSD units. These units consist of a motor and VSD produced as a single package, with the VSD unit mounted variously on the top, side, or end of the motor. The market is growing fast (currently at least doubling each year in the UK), with sales of perhaps around 30,000 units pa in the EU. When first launched there was a price premium over a separate motor and VSD, with it being set to about equal the additional installation costs of separate units. However, competition has largely eroded this premium, which is why the market is now growing so fast. There are many features that make these products very attractive, overcoming many of the barriers to the uptake of VSDs:

- Component cost less than that of a separate motor and VSD.
- No wires between VSD and motor, saving installation time and costly screened cable.
- Motor matched to the VSD.
- Reduced overvoltage on the motor due to the short length of the connections, leading to a longer lifetime of the insulation.
- No output cables, and hence radiated radio frequency interference is minimised.
- VSD shares motor cooling system.

As with most VSDs, they are very simple to commission, and available with several types of bus interfaces.

Figure 4.3 *- Combined Motor: VSD units (Brook Crompton).*

They have been slow to gain market acceptance, due to the natural conservatism of users wanting to avoid anything new, particularly concerns over reliability (some early models did have over heating problems, but these now appear to be sorted). The concern is over the following points in particular:

- Placing the inverter on the motor means that it is likely to get hotter, be subject to greater vibration, and may be subject to oily or other aggressive environmental contaminants.
- If it fails, fewer repairers will have the knowledge to repair quickly, and there is the fear that spares might take longer to get than with standard units.

Similarly, there is the fear that if either the motor or VSD fail, then the whole unit is out of action or needs replacing. In practice though, manufacturers do design the units so that the two parts are separable and replaceable.

4.8 Alternatives types of variable speed motors

These "rival" technologies cannot compete with the AC motor and drive, primarily because they all need special motors which don't have the direct on-line running ability, wide distribution, or are as competitive on price. However, they do all have niche applications in which they continue to do well. Some analysts speculate that buyers will become less interested in the technology of a drive, rather just being concerned about performance, which would overcome the natural conservatism against the newer SRD and PM technologies.

4.8.1 Permanent Magnet (PM) Motors

There are many variants of PM motors, but all have the advantage of using a permanent magnet rather that an electrical winding to create all (or part of) the magnetic fields. Since the magnet requires no electrical power, PM motors are inherently more efficient.

The cost of the magnets needed is in general too high to be economic for most industrial applications, but a few are made for mostly specialist fractional horsepower applications. For instance, Schindler and Kone are selling in Europe permanent magnet gearless drives for elevators. Baldor, Meiden and Yaskawa are known to have PM motors available, but EU sales to date appear to be very low. Neodymium-iron-boron magnets currently offer the best price-performance ratio, and are available for operation up to 200°C.

Advantages

- Low power loss, and so often no cooling fan needed.
- Typically 2 or more frame sizes smaller than equivalent power rated induction motor.
- Can be made mechanically inter-changeable with standard induction motors.
- Weight typically 25% less, and volume typically 35% less than equivalent power rated induction motor.

Disadvantages

- Typically they need a shaft encoder and/or sensors. New sensor-less designs are being introduced.
- Currently 3-4 times the cost of same rated induction motors. Motor repair is also more expensive and requires special facilities.
- Strictly limited peak temperature, beyond which permanent magnet failure occurs.

4.8.2 Switched Reluctance Drives (SRD)

SRDs use the principle of reluctance to cause a solid iron motor to rotate in a motor stator consisting of poles that are switched on and off in a sequence determined by a dedicated controller.

Advantages

- Simple, low cost and robust motor construction;
- High torque possible at low speeds;
- Can be designed for high efficiency.

Disadvantages

- Needs a position encoder (although it is hoped that encoder-less SRDs will become available);
- Needs a specialist motor and drive –drives and spares not available from local stockists;
- Can't compete on price with standard AC motors and VSDs in any but very specialist applications;
- Cannot run the motor direct on line.

Although claimed to be "more efficient that AC motors", it should be stressed that if an AC motor was optimised for efficiency at the expense of other parameters, then the efficiency of the AC motor could be higher.

Early attempts to sell standard SRD packages as an alternative to AC motor and drives were not very successful, because the price and features were not sufficiently attractive to justify the change from induction motor solutions. However custom SRDs are now found in a variety of equipment including automatic door-openers, air compressors, and even larger motors for safety critical mine applications.

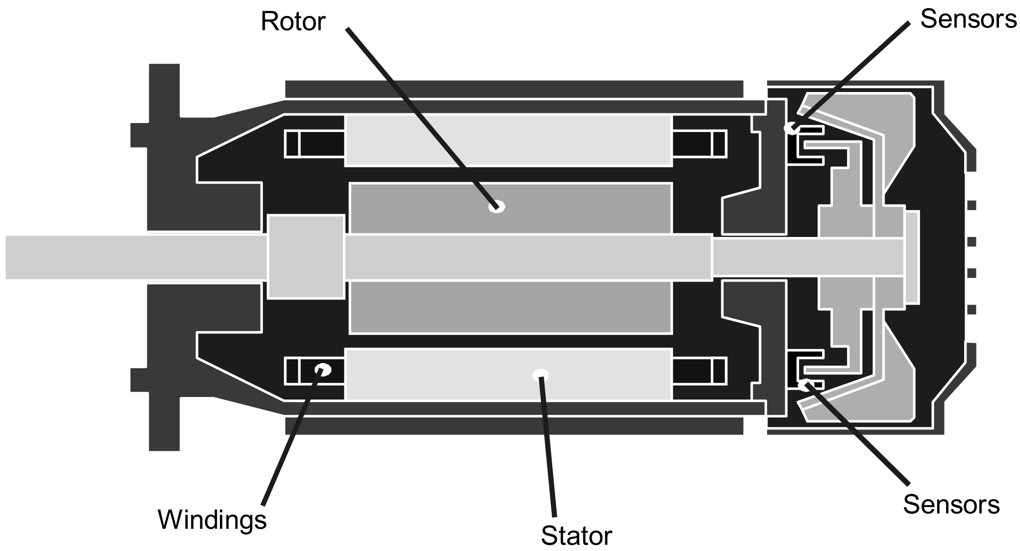


Figure 4.4 *- Cutaway diagram of a Switched Reluctance Drive*

4.8.3 DC Drives

Traditionally the lower cost of DC drives compared to AC Drives was much more significant than the higher cost of DC motors, and so DC drives were the norm for speed control applications.

DC Drives are still used for the following key advantages, but even these are being eroded as AC drive technology improves:

- Very good dynamic response
- Good low speed control

The development of vector control allowed AC drives to be used in high performance applications in which accurate torque/speed control is required. Also the now much reduced cost of AC VSDs means that AC motor/drives are specified as standard. The DC drive market has remained static, but there is now little new commercial development of products.

4.9 Market Trends

The AC PWM VSD is now a standard item, with nothing likely to be a serious competitor in the volume market in the foreseeable future.

The market is still enjoying good growth, but competitive pressures mean that prices keep falling and overall performance improving. The overall result is though that manufacturers now enjoy smaller margins than in the past. There has been less industry consolidation than predicted a few years ago, and surprisingly there are still new EU entrants (e.g. Vacon and Invertek). Against this, there is much badge engineering of VSDs. As the technology has matured, VSDs have converged to essentially very similar designs, using IGBT modules and other standard power components from just a few industry suppliers. The technical differences are now largely in the packaging and user interfaces.

While falling prices are apparently good for the user, the lower profit/kW has meant a re-appraisal of routes to market. It is this that is now the main differentiator between suppliers.

Many Equipment Suppliers are able to increase total sales value by offering software and controls, and this is helping to offset the decline in profit from the VSDs alone.

Local Wholesaler Distribution - This is of growing importance by volume, here offering convenience and reasonable prices, but with little or no technical support. The fact that users and suppliers are happy with this route to market reflects the market acceptance of VSDs as a standard, literally “off the shelf” item.

Direct Sales - Few major suppliers do direct sales to any but their very largest customers. This importantly means that they have little idea as to who most of their final customers actually are.

Local Drives Centres - A growing trend is for local “centres of excellence” to be set up whereby highly skilled distributors can offer complete driver solutions. This gives excellent service, but at a cost to the user.

Mail order/Internal Sales - Generally offering a similar level of service as wholesalers, some manufacturers/suppliers offer sales by post.

Targeted markets - As tackling the high volume mass-market becomes less attractive, many suppliers are focussing on either industry sectors (e.g. water, steel etc) or particular applications (e.g. pumps, injection moulding machinery etc). This ensures that they can offer a high level of expertise into industries where there are often far fewer skilled engineers than in the past.

5. ANALYSIS OF IMPACTS

The aim of this task was to evaluate the impacts of the large-scale application of VSDs on utilities, VSD and motor manufacturers and end-users. This was done by interviews with experts of the involved market groups.

As a first step questionnaires were developed to get an information, which is uniform and easy to evaluate and interpret. Different questionnaires for the main market groups – the motor an VSD manufacturers and the OEMs – were outlined and discussed in the working team. The final versions of the questionnaires are given in the annex.

5.1 Impacts on manufacturers (of VSDs, motors and end-use devices)

The influence of VSDs on the number of motors and quantity of materials used is disputed controversially. Some experts think that there is no significant difference in the number of motors sold caused by the application of VSDs. On the other hand there are examples of hundreds of pumps being saved by installing controlled larger pumps with VSDs. But there is also the impression, that the availability of VSDs and specialised motors leads to additional use of motors. Manufacturing of motors is also influenced by VSDs because of their higher requirements in the insulation. This is caused by the fast voltage changes which are implied by the electronic control. Insulation, therefore, has to be strengthened in motors which are used in connection with VSDs and may lead to slightly higher prices for the motors. Some motor manufacturers now provide VSD grade insulation as a standard feature in their motors. Improved insulation means, that the frequency of rewinding may not change much; older motors (with unsufficient insulation) may have to be rewound more often but newer adapted motors don’t need more rewinding. Because the application of VSDs tends to avoid oversizing, the overall average size of motors slightly decreases in installations with VSDs.

The VSDs themselves are more and more integrated to form a single unit with the motor. Costs are reduced by this by about 15 % to 20 %. The integration rate at present is estimated to be between 6 % and 15 % (of the total number of VSDs installed). There is some concern over problems which may occur in integrated systems. Being part of the motor, the electronics may be contaminated by oil or other aggressive dirt. VSDs also may suffer from the vibrations of the motor.

There is also the heat problem: For larger capacities (say above 5 - 7.5 kW) it is seen as a bottleneck for the integration of motor and VSD. More efficient electronic devices may in the future help to increase the power rating of integrated units.

In any case, the integration rate is assumed to increase in five years to 20 to 30 % and in ten years to 30 to 50 %.

There may be different ways to proceed regarding the further development of integration, as seen by the experts. Development may be based in fast and cheap integrated modules controlled by external software and incorporating special elements for larger OEMs. Alternatively, VSDs may exist in a large variety as plug-in elements easily connected with most motor types.

Concerning the prices of VSDs, most experts estimate that in the medium-long term prices will decrease by 3 to 5 % per year, caused by rising production and more cost-effective power electronic devices. There also is a minority opinion, that the prices are at present already near the lower limit.

5.2 Effect on OEMs and end-user of VSDs

OEMs offer VSDs in their products when these products gain specific and noticeable benefits from it. These benefits may be of technical nature but economic benefits are decisive regarding the decision to incorporate VSDs in the product. OEMs offer integrated VSDs e.g. for pumps and compressors for compressed air systems. If the customer asks for VSDs, OEMs can normally also offer to incorporate them for many other applications. In the case of air compressors, VSDs are always offered, but at present only 10 % - 20 % of the units are finally equipped with VSDs. Investment costs which are typically about 20 % higher prevent VSDs from a broader application despite a payback time of only one to two years due to the high energy savings. Energy cost savings is generally the best argument to sell VSDs in air compressors but energy consciousness and life cycle costing still do not have a high priority for many customers. Lifetime and reliability is not seen to increase substantially by the application of VSDs in OEM equipment. What is gained by reduced wear and tear seems to be lost because of the greater number of components which can fail. OEMs and end users also fear that after a failure repair will become more difficult and time consuming, than in conventional fixed speed operation. In most cases no significant assembly costs arise for OEMs by installing VSDs in their products. Maintenance is only slightly changed by the higher number of spare parts to be held.

As a conclusion, the broader application of VSDs by OEMs is not hindered by any technical or logistical problems. The decisive factor is the customer demand in order to promote further growth of the market penetration.

5.3 Impacts due to electricity savings

5.3.1 Influence on load curves and tariff's

It is not expected that an increased number of VSDs will have an impact on the shape of the load curve. In the long-term evaluation, it would rather decrease the local diagram throughout all 24 hours of the day, rather than "shrink" in the daytime period. This is based on the fact that the main energy-savings potential lies in larger motors, which are mostly applied by major industries and large-scale consumers rather than private homes, agricultural machines and so forth. These large consumers often have a 24-hour production period.

At present time the impact on the load curve due to VSDs is quite small (less than 1% of the peak load). In the Section 2 of the present report, it was estimated an economic savings potential of 47 TWh pa through the large scale installation of VSDs in the industrial and tertiary sectors. These energy savings account for about 6% of the estimated consumption by motors in EU industry and tertiary sector. By now less than 10% of the savings potential has been utilized. It is likely that it will take a long time before we will see a "visible" change in the load curve.

However some consumers with a percentage of loads which can benefit from the application of VSDs (e.g. chemical and paper industries) may experience a significant downward shift of the load curve.

It is not estimated that VSDs should have an effect on tariffs due to the fact that the load shape remains essentially the same. Additionally, large customers individually negotiate tariffs with electric utilities.

5.3.2 Electricity savings and CO_2 emissions

Energy savings by the application of VSDs are estimated to lie between 15 % and 35 % depending on the application. This may amount to a technical potential of 84 TWh per year in the EU and CO_2 reductions of 33 Mton (see Section 3). The economic potential (assuming a 5%/year price decrease) is still assessed to be 54 TWh and 22 Mton respectively.

5.4 Country specific findings

In **Denmark** it's only a small fraction of the potential that has been utilized at his time. There is a huge market for VSDs in the coming years. The market has been growing – and will continue to grow rapidly in the comings years. The impact on the load-curve as these VSDs are implemented will be minimal in the near future. In a longer prospect there is a savings potential worth pursuing.

Regarding the impact on motors (materials, production costs, motor-size etc.) it is not likely to be seen a drop in prices, or saving of materials. Motor-manufacturers will have to make improved insulation on motors to avoid problems regarding VSDs. Cost is likely to increase a bit in regards to the demand for imported insulation, and also the bearings on larger motors have to be insulated to avoid bearing currents. A positive price-development on VSDs is not expected as the prices by now are very "squeezed".

Germany is at present the biggest market for VSDs in Europe. It is said, that the german market comprises 40 % of the European market (and the European market is about 40 % of the world market). But despite of the still increasing market volume in Germany the share of german market is decreasing because in other countries the growth is still higher. Energy savings by the application of VSDs are estimated to lie between 10 % and 30 % depending on the application. The German Association of the Electrical Industry (ZVEI) assesses the possible savings by electric drives to be 19 TWh for Germany. From these 3 TWh belong to EEMs (energy efficient motors), the rest to VSDs.

In the **Netherlands** there is only little manufacture of VSDs, mainly concentrating on niches. Increasingly VSDs are sold as integrated part of motors, pumps and HVAC installations. In the low power range integrated VSDs will become more standard. For larger capacities (above ca. 5 kW) the heat problem is as yet seen as a bottleneck for the integration of motor and VSD. Cost of VSDs has decreased rapidly, though now seem to stabilise more. Expectations are a further (small?) decrease due to larger sales numbers. Some experts see a small increase as an option at the short term as a result of increasing cost of some components and shortages because of high demand.

OEMs see a proper design with integrated VSDs as an option for lower system cost relative to a combination of motor and separate VSDs. For cooling and compressed air systems examples exist of more integrated designs. However, various OEM still see the extra cost of VSD in their machines as a barrier, given the fact that many clients do not ask for this and focus on low investment cost.

In some areas OEMs already apply VSDs and offer actively integrated systems e.g. for

- HVAC sytems
- small pumps
- compressed air systems

If the customer (installer/engineering agency/end-user) asks for it, OEMs of course will provide VSDs in many other applications.

In **Portugal**, in the industrial sector VSDs are usually applied in small and medium power applications mainly for process improvement reasons, rather than for energy savings. In the case of large motors used to drive centrifugal pumps and fans, VSDs are being increasingly applied to save energy. The penetration rate of VSDs is still low, but with the increasing competition in the market, prices tend to decrease, mainly in the lower power ranges, increasing the number of VSDs installed. Integrated motor and drive (VSM - Variable Speed

Motors) are becoming progressively popular among OEMS and motor users, especially for materials handling machinery.

The integration of VSDs in industrial machinery has been perceived by OEMs to lead to lower installation costs (wiring, installation) and more reliability than when VSDs are installed later by the user. This is leading some OEMs to apply VSDs integrated in their machinery for motors up to 75kW.

In the **United Kingdom** the AC PWM VSD is now a standard item, with nothing likely to be a serious competitor in the volume market in the foreseeable future. The market is still enjoying good growth, but competitive pressures mean that prices keep falling and overall performance improving. The overall result is though that manufacturers now enjoy smaller margins than in the past. There has been less industry consolidation than predicted a few years ago, and surprisingly there are still new EU entrants (e.g. Vacon and Invertek). Against this, there is much badge engineering of VSDs. As the technology has matured, VSDs have converged to essentially very similar designs, using IGBT modules and other standard power components from just a few industry suppliers. The technical differences are now largely in the packaging and user interfaces.

6. Actions to Promote VSDs

6.1 Summary

VSDs are not yet perceived sufficiently as 'good quality for money' in many energy-driven applications, such as compressed air, cooling systems, etc. This is not caused by short payback times, but rather by the feeling, that it takes 'too much time and effort' to assess the possibilities and to purchase, install and maintain VSDs. This time is rather spent on core business options. VSDs for energy-driven systems now have to appeal to clients that are less driven by the 'significant advantages' of the systems, but prefer total solutions, that can be acquired and used without extra risks or efforts. They also generally prefer familiar distribution channels, with one single responsible supplier.

Various segments are interesting for targeted actions. For successful dissemination of VSD systems in these segments, all need more standardised systems. There are differences:
- in some segments more or less standard off-the-shelf integrated systems are available such as for small pumps. These can be relatively easy characterised with regard to efficiency.
- other segments systems are more complex and should first be more 'standardised' and made more comparable: compressed air, HVAC and cooling systems.

This study assessed the feasibility and cost-effectiveness of relevant actions. Most of the recommendable actions are not specifically aimed at VSDs as such, but have a system focus. In the present market this is required since clients also are system oriented. It is also the most cost-effective approach since VSDs have most potential when properly integrated in a system.

Actions should be on the one hand directed at increasing interest in VSD systems with end-users. The most appropriate actions in this respect are the already planned pilot agreements with end-users in the Green Motor programme [6]and information and training actions.

Many prospective users though will not be prepared to actively seek VSDs. They rely upon their common suppliers to integrate these in their systems and provide them without extra efforts required for the user. OEMs, installers, engineering consultants and system suppliers have a crucial role in the further successful dissemination of VSDs. Joint actions with these parties are an important part of the action programme. These may serve as step-up towards various other actions that may be reconsidered in a later phase, such as procurement for some type of equipment. Also development of decision support tools and guidelines are of crucial importance. Outsourcing may offer good market transformation perspectives; a few limited actions are recommended to assess effects and develop guidelines to make these services more 'accessible'.

[6] The EU at present is embarking on a project that aims to improve efficiencies of electric drive systems. Preliminarily this programme has been given the name "Green Motor"

The study team recommends a combination of actions with end-users and suppliers. With the Green Motor programme as basis, it is recommended to add a pilot (joint) action package with the supply sectors in a specific segment to offer improved services and/or systems. Various segments have been identified as option for this pilot. In the discussions in the Green Motor programme also the reactions of the sectors may be taken as a basis for further pre-selection of such a pilot and as step-up for negotiations. An advisory committee with relevant trade associations of the involved market parties may further guide the development of pilot actions.

6.2. Introduction

6.2.1 Improving the Application and Potential of VSDs

VSDs, as has been shown in Section 3, can have a significant impact on energy efficiency in the EU. It is clear that the potentials are still far from being fully harnessed. This chapter summarises the barriers that cause the gap and identifies possibilities to improve the situation.

The application and potential of VSDs may be increased by:

- Increasing the market potential[7]. The previous chapters showed that in the short and medium term most energy efficiency gains can be made by decreasing the gap between the economic potential and the present market situation. Most actions focus on this gap.

- Increasing the economic potential. Section 3 showed that VSD have already become progressively more cost-effective. The present market is very competitive and pressure on prices of VSDs is high. Extra stimulation by the Commission of R&D on lower cost systems will not likely be cost-effective. Significant cost reductions though can be achieved by redesign of machines and systems that integrate speed control. This chapter will consider actions in this respect.

- Increasing the technical potential. For most of the energy-relevant applications technical applicability of VSDs is already high. The competitive market will enhance this further. Long term oriented RD&D aimed for instance at integrated design methods or new components (e.g. power integrated circuits) may help[8]. It is doubtful that additional EU actions for specific R&D on VSDs would be cost-effective. Many developments are already taking place in the US and at some large European firms. This chapter will not elaborate further on this.

[7] The present market potential includes the possibilities that can be used by market parties, confronted with present barriers such as lack of know how, etc.
[8] Possibly existing EU programmes offer generic support possibilities

6.2.2 Contents of this chapter

This chapter will assess actions and strategies by subsequently describing:

- the market process and barriers
- identification of priority market segments
- actions that are possible to promote VSD
- possible synergy of actions

6.3 The market process and barriers

6.3.1 The Flow of VSDs in the Market

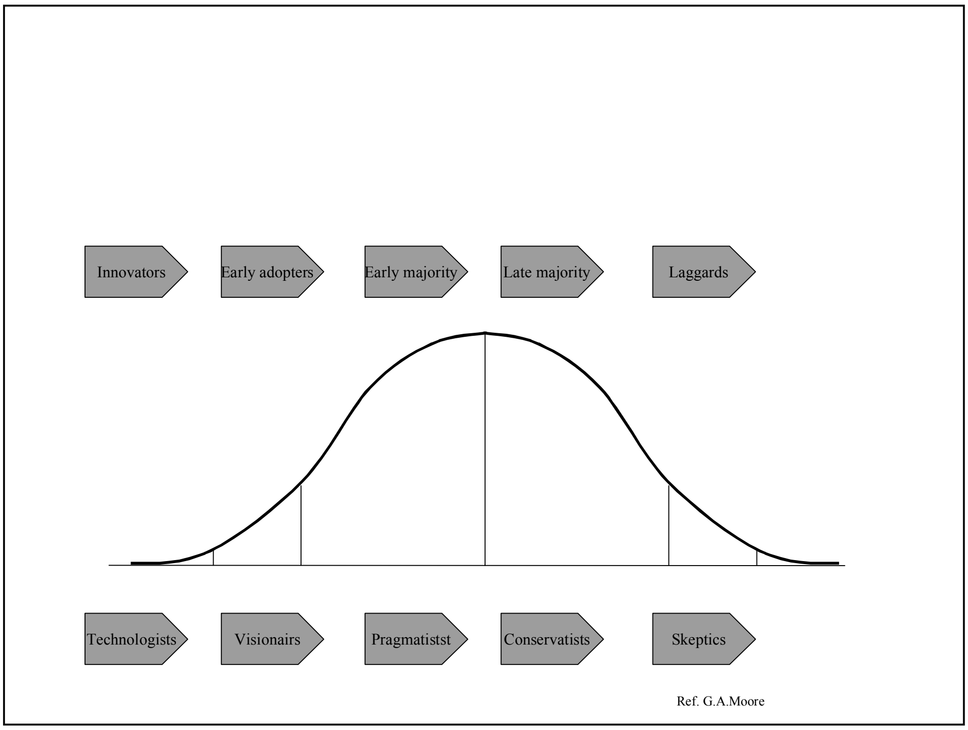
VSDs are typically considered as an extra component to 'common' systems or machines. They are acquired either:

- directly by the end-user from the VSD supplier or
- through intermediate parties such as OEM and installers

At present both channels are used. As explained in the box only a relatively small part of the potential end-users is willing to actively search for VSD related solutions; these typically are early market clients. VSDs have to move further to main market clients. Most of these will rely upon their traditional channels for motor driven system, such as system suppliers, OEMs and installers. For successful dissemination of VSDs consequently these parties will become more crucial[9]. They will have to play an important role in actions to promote VSDs.

[9] There is also an increase of sales through wholesale channels, which appeal to the low cost oriented market segment, that generally knows what it is looking for

BOX 1: The evolving market requirements, product life cycle or adoption cycle (Ref. 'Rogers[10], Moore[11] and others)



Successful products in the market succeed in appealing more or less subsequently to different types of 'customers'. The minimum requirements demanded by customers of the product increase when 'main market' customers come into sight. These customers want more standards, transparent information, more servicing and such. Many technology products start off well in direct sales to more innovative end-users, but do not succeed in overcoming 'reservations' from the majority type of end-users in the main market. Here the far majority of applications are to be found. The challenge with energy efficient drive systems is to market the product in such a way that the requirements of the main market customers are being met.

<u>Typical characteristics of 'early' markets:</u>
Clients that are looking for new solutions and big steps forward. They want state of the art technology and are rather accustomed to integrating these in their situation. Demonstrating new technologies is an important marketing issue here. Often VSD supplier and clients are in direct contact.

<u>Typical characteristics of 'main' markets:</u>
Clients here are looking for standardised 'easy' solutions, without extra efforts or risks. They are typically expecting integrated solutions through their common vendors and distributors, OEMs, system suppliers and installers. Usually they do not look for direct contact with VSD suppliers, but leave it to their OEM/installer. They are not actively seeking information, but expect clear, easy accessible information for direct decisions.

[10] Rogers, E.M.: Diffusion of innovations, 1995
[11] Moore, G.A.: Crossing the Chasm, HarperBusiness, 1999

6.3.2 Difference Between Process-Driven and Energy-Driven Applications

Though VSDs face strong growth, the general impression is that applications are driven mainly by process-related considerations (extra throughput, process control advantages, quality, etc.). The relative growth in the market segments 'driven' by energy-efficiency advantages lag significantly behind in growth and maturity. The reasons are well known, e.g.:

- Low priority for energy efficiency. This implies low financial priority, but also low willingness to put time and effort in identifying and analysing the possibilities and benefits of VSDs;

- Low visibility of benefits of VSDs in most energy-driven applications. This is due the low transparency of information on economic benefits of VSD in specific applications. It is also due to the fact that cost and benefits accrue to different parties. Many possible applications relate to in-house utilities[12]. The utility manager or technical department manager typically has to initiate the extra investment, whereas the benefits occur in other departments (as part of operational cost) and often go unnoticed;

- The market is dominated by lowest first cost decisions in competitive bidding procedures. As a consequence the OEMs or installers are not usually taking the initiative to offer higher first cost systems, since their customers might not 'appreciate' this, even with short payback time. These problems seem strongest for the energy efficiency related applications: in core processes benefits usually accrue with the same production department as where the investment is made.

Table 6.1 summarises the main barriers in the VSD market for the different market parties. The difference in market maturity between process- and energy-driven applications (that use the same technology) clearly indicates that the real barriers are not technology related.

[12] *Utilities* in this report refer to production and distribution of steam, water, electricity and such within a company. Usually the head of the technical services department, further referred to as the '*utility manager*', is responsible. Many consider these services as 'free'.

Table 6.1 - Overview of barriers in the VSD market.

MARKET PARTIES	**Main barriers**
End-users : industry	
In-house Utility manager (head of technical services department)	***Low visibility***: The benefits are not easily visible. In various industries the managers are not aware of the full application potential of VSDs e.g. in motion control applications, such as conveyors, centrifugal machines, etc. In buildings this is even more so (e.g. in HVAC controls, regenerative direct drive lifts, etc.). If aware, the benefits are not always easy to sell to the superior (lack of clear information on economic benefits)
	Low priority: Time is money. Priority is given to core business. Utility departments often are reduced in capacity over recent years. They have no time to assess life cycle cost, to gather and compare information, etc.
Plant manager/production manager	***Higher initial cost***: The required extra investments compete with core business investments. The latter will be given priority.
	Perceived higher risks: Though decreasing, there are still some industries that perceive extra risk for safety and/or loss of production as a consequence of potential technical problems with VSDs
End-users: buildings	
Investor/project developer	***Low visibility***: The benefits are not easily visible and revert to other parties e.g. the users. The extra cost incurred by VSD are difficult to 'sell' to users that do not see the benefits
User	***Low priority***: The user does not feel he has any influence on decisions with regard to VSDs
Intermediate parties	
OEM	***Higher initial cost*** (sales price): Fear to offer a higher price than the competitor
	Higher initial cost (design and engineering cost): Extra design and engineering cost for OEMs in incorporating speed control
	Extra expertise: Need for additional (electronics) expertise
	Technical constraints: Though decreasing, some OEM have concern over interference, harmonics or need for additional cooling
Installer	***Lower profit margin***: Little margin to be gained on inclusion of VSDs in sales package
	Higher initial cost (installation/sales): Fear to offer a higher price than the competitor
	Higher initial cost (engineering): Extra engineering cost for incorporating VSDs
	Extra expertise: Need for additional (electronics) expertise
Suppliers	
VSD supplier	***Marketing dependency***: Lack of direct contact with the main market end-users, in particular smaller end-users. In these segments distribution depends largely on OEMs and installers.
Influencing parties	
Advisors/consultants	***Low visibility***: Lack of 'independent' information on life cycle cost
Energy suppliers/electricity distributors	***Technical constraints***: Some concern over power quality problems. Here though VSDs may be both the 'victims' or the 'villains'

In conclusion: the challenge

For many energy-relevant applications VSDs are not yet generally perceived as 'good quality for money'. This is not caused by low payback times, but rather by the feeling that it takes too much time and effort to assess possibilities and to procure VSD systems. This time is rather given to core business. VSD systems now have to appeal to markets with even more pragmatic or conservative clients. These do less focus on the 'advantages' of systems, but generally prefer:

- Standard (off-the-shelf) solutions.
- To be acquired and used without extra risks or effort.
- Not too costly. If extra cost are involved, the extra benefits should be evident, clearly visible and well competitive with core business investments
- Integrated solutions by familiar distribution channels, with preferably one single responsible supplier.

In short, more standardised and integrated VSD solutions are needed. For some applications increasingly standard-off-the-shelf' systems become available. Examples are small VSD-pump and small VSD-motor combinations and medium size compressed air systems with integrated speed control. For other systems alternative methods have to be facilitated to achieve more standardised, transparent and comparable integrated VSD solutions. Actions are needed to remove the present barriers: actions to increase the awareness of economic benefits and the importance attached by end-users to efficient VSD systems, but also actions to further trigger the supply side in meeting these main market customer requirements. End-users do not consider VSD systems as their core business and will rely upon their common suppliers in improving systems and services. As a result it will be largely the business of OEMs, system suppliers etc. to achieve the easier and more accessible integrated VSD solutions.

6.4 Identification of priority market segments for improved VSD solutions

6.4.1 Introduction

Various actions refer to VSD solutions in general. Many though need a targeted approach to maximise efficiency. This chapter identifies potentially interesting target market segments.

Many applications are important energy consumers. Growing segments are for instance VSDs in injection moulding machines, cooling towers and lifts (direct drive regenerative systems). However, from an energy point of view, these segments are less suitable for a cost-effective approach than the four by far largest energy-consuming applications of electric motor systems:

- compressors for air;
- compressors for cooling;
- (centrifugal) pumps;
- fans.

The Table 6.2 characterises these applications and selects the most appropriate segments that may form the 'beach head' in targeted actions. The characterisation is based on data from earlier tasks and on expert opinions.

Table 6.2 - Characterisation of market segments

Criteria	Pumps	Fans	Compressed air	Cooling
Energy relevance	+++	small: - other: ++	++	++
User dependency on OEMs	+	small: + HVAC: ++	++	+
Product definition possible	+ (+)	+	Small: + Large: ++	storage: ++ process: difficult air cond.: ++
Attractive for end-user	++	+	++	+
Receptive buyers	+	+	+	+
Organisation supply chain	+	+	+	+
Concentration supply chain	+ (various types of parties)	= (many parties)	+	+
Main potential[13]	Small and medium pumps for industry + HVAC	Medium fans for industry and HVAC systems	Medium and not too large sizes	Air conditioning

Following selection criteria are used[14]:

- Energy relevance: the segment should have a large number of variable load systems with significant potential for VSDs. Energy cost should be a significant part of life-cycle cost.
- Dependency of user on supplier: information on energy efficiency is difficult to obtain and assess for the user. The user has limited influence on the efficiency of the system, while energy use depends heavily on the system configuration.
- Clear product definition: scope and performances of the product can be defined
- Attractive for end-user: the segment has many applications with short pay-back time and significant energy savings (possibly in addition to other benefits)
- Receptive buyers: buyers are in principle receptive for VSDs. In principle there do not seem to be inhibiting factors.
- Well organised supply chain: the branch has an organisation, that allows for representative discussions and negotiations
- Concentrated supply side: the supply chain is competitive. Not too many different types of parties are crucially involved and the number of enterprises that dominate the market is not too large. This allows large coverage of the market with acceptable negotiation efforts. If small suppliers would dominate the segment, a time-consuming negotiation process would be needed right from the start. In a more concentrated segment at the start the support of the larger companies would suffice; the others would follow more or less automatically

[13] These applications still show a low penetration of VSDs, relative to the savings potential.
[14] Derived from requirements for negotiated agreements and joint action programmes. These type of actions are the most representative ones for actions, targeted towards a specific segment.

6.4.2 Pumps

Pumps represent the single largest energy consumer in electrical drive system. Most energy relevant applications are found in:

- Industry: small pumps for transport purposes; many pump sizes in processes
- Water supply and sewage treatment (mostly medium and large pumps)
- Buildings: small and medium sizes for HVAC systems; small pumps for water supply
- Horticulture: small pumps.

Many end-use sectors, including industry and the water supply sector, already pay much attention to VSDs with larger pumps. For medium and small pumps though, end-users generally perceive the effort of assessing this option as ‘too prohibitive’ or less attractive. This goes in particular for the industry and to a lesser extent for buildings (HVAC) and horticulture. For some other sectors integrated small pump-VSD systems are already becoming rather common e.g. for water supply in buildings.

Following market segments seem attractive for EU action:

- Small pumps in industry. Standard-off-the-shelf solutions are available: integrated motor-VSD and/or integrated pump-VSD systems. Also pumps with separate VSDs may be purchased. Main actors are the end-users and the (pump) system supplier.
- Medium size pumps for industry and HVAC systems, and to a lesser extent water supply and sewage treatment. In this segment VSDs are offered as addition to or part of a system. Main actors in industrial pumps are technical departments in industry and pump system suppliers. For HVAC systems: see under fans.

The supply sector seems interested in participating in EU actions[15]. In industry, end-users are scattered. Since the larger industries are important users and have a significant demonstration effect, these will be an appropriate end-user group to be involved in EU pilot actions.

6.4.3 Fans

The most common energy relevant applications are:

- Small fans for ventilation in houses and buildings. For this application brushless DC drives are widely used. VSDs do not offer a significant saving potential here
- Small and medium fans in HVAC systems. For various ‘single fan’ system with smaller capacities integrated motor-VSD systems are considered an option as drive. These integrated systems are not yet very common though.
- Fans of all sizes in industrial processes and cooling towers. Especially for medium sized fans in this segment energy improvement potential is still high; so far only a moderate

[15] See also the indications provided in the SAVE pump study

penetration of VSDs has occurred. Larger fans are already more often equipped with VSDs and/or well designed.

HVAC systems offer the most relevant segment for targeted actions in this application field. These systems involve various applications of VSDs in fans, cooling and pumping. There would be many market parties involved: fan manufacturers, system suppliers, installers and engineering consultants. Concentrated[16] end-use sectors are ‘available’ for a multi-national targeted action e.g. chains of banks and government buildings.

6.4.4 Compressed air

The major segments in compressed air are to be found in industry and hospitals:

- Small compressor systems (<about 10 kW): these are often used only a limited number of hours and therefore do not have a relevant energy potential
- Medium size systems (10 – 300kW), usually consisting of 2-3 compressors. If VSDs are applied then usually to one compressor only. There are many variable load situations.
- Large compressors, usually tailor-made and well designed with relatively low efficiency improvement potential.

The medium size segment between 10-300 kW is an interesting segment for action. The system suppliers may well influence the market and be receptive for EU actions, since they are already actively involved in energy efficiency campaigns in USA, the Netherlands and other countries. The EU may consider extending these efforts, since most involved companies would be the same. It may be considered to start with a specific range where systems are relatively easy to compare (see box 3 for illustration of such an approach). This will be cost-effective and may gain confidence within the sector. The range may be expanded later.

6.4.5 Cooling

There is a wide variety of applications:

- In industry many process specific uses: these are difficult to ‘standardise’
- Cooling for storage is more ‘standard’ and may offer possibilities for joint OEM actions. However the number of crucial parties is relatively large and includes also engineering consultants and system suppliers. Energy relevance is moderate compared to various other subsegments.
- Air conditioning systems
- Cooling as part of HVAC systems: see under fans.

Air conditioners may be an attractive target segment for action. Also cooling systems for storage are an important sector, though with moderate energy relevance. As a consequence of the Montreal protocol and the Kyoto agreements, the sector has to give high priority to the

[16] In the sense that few parties control large numbers of applications

introduction of alternative refrigerants and may at present be less receptive to other initiatives that involve much effort.

6.4.6 In conclusion

Various segments are interesting for targeted actions. For successful dissemination of VSD systems in these segments, all need more standardised systems. There are differences:
- in some segments more or less standard off-the-shelf integrated systems are available: small pumps and air conditioners. These can be relatively easy characterised with regard to efficiency.
- in other segments systems are more complex and should first be more 'standardised' and made more comparable: compressed air, HVAC and cooling systems.
- integrated motor-VSD systems have to be considered separately. At present they apply to small capacity motors and as a pilot action may appeal best in segments where they offer relatively simple alternatives for electric motors, without many interaction with the load or other surrounding system components. Small single fan systems for ventilation may be an interesting pilot segment.

6.5 Possible actions to promote VSD

6.5.1 Overview

This section describes possible actions. Many actions do not focus on VSDs as such but on systems that integrate VSDs. The benefits of VSDs mainly come from a proper integration in systems, processes and machines.
Some actions apply to all VSDs, others should be tailor-made for specific segments. Section 6.6 gives an indication of the cost-effectiveness of actions and discusses synergy between actions.

6.5.2 Negotiated Agreements with End-Users

6.5.2.1 Introduction

Various countries have good experiences with long-term voluntarily concluded agreements between the government and sectors in industry or in the built environment (hospitals, schools, offices, etc.). There are different forms of 'negotiated' agreements.

6.5.2.2 General Energy-Efficiency Related Agreements

These aim to improve the energy efficiency in the sector with a specified percentage over a defined number of years. An evaluation in the Netherlands illustrated the effectiveness of long term agreements. They significantly increase the 'drive' for energy efficiency by putting energy higher on the agenda. They also lead to significant increase of energy efficiency as compared to autonomous developments.

BOX 2: Elements of a negotiated agreement.

Negotiated agreements at least encompass elements such as:

Preparatory scans/audits to assess possible improvement measures and to elaborate implementation schemes. Audits are repeated regularly to account for (process) changes.

- Implementation of measures. These include technical projects, organisational measures and good housekeeping. One of the essential measures is the implementation of structural energy management (including policy, organisation, procedures, monitoring)
- Monitoring of progress and results. Confidentiality of process data may be accounted for through the involvement of a third party that aggregates the monitoring data of individual participants to a higher level (e.g. per industrial sector). This enables the government to assess the results and progress, while at the same time protecting confidential plant specific data.

Such agreements per sector require a minimum level of coverage in a sector for sufficient impact and support. They also require a sufficiently strong ‘organisation’ of the involved sectors e.g. in sector associations. This type of agreement appeals to enterprises since it is goal instead of means oriented. It enables participants to determine their own path towards this goal. Negotiated agreements should be supported by a series of actions and/or incentives, offered ‘in return’ by the government. Such actions should facilitate the process and offer generic support tools. In the Netherlands e.g. energy audit methodologies and monitoring procedures were developed.

VSDs are often addressed, but represent just one out of many energy-efficiency options that compete. Some barriers still apply, notably the high effort needed to assess the potential of VSDs in their specific situation. Where such negotiated agreements are in place, dissemination of VSDs would significantly benefit from almost all cost-effective VSD related actions described in this report. Actions that make VSD benefits more transparent and visible will be extra effective (and recommendable) within such agreements, e.g. easy audit tools on utility systems, decision support tools, guidelines, etc. With little extra effort, existing negotiated agreements may also provide a platform for many VSD related pilot actions.

6.5.2.3 Negotiated agreements on utilities (electricity, steam and/or water)

The EU recently supported the start of the Green Motor programme that plans agreements with enterprises on improvement of electrical drive systems. VSDs would likely be a major issue in these agreements. This type of agreements can encompass all or most of the utility systems. They would place these higher on the agenda and make them clearly visible for management. It would almost certainly be an effective action in promoting the application of VSDs over a wide range of applications. The US has similar experience with partnerships on motor systems between DOE and industrial enterprises.

Elements for these agreements will be similar to those mentioned in box 4 though specifically targeted towards utilities. Conditions for success include:

- The possibilities for positive exposure of the participants (publicity, image)
- Participation of leading enterprises that provide good examples for others to join in
- The availability of supporting and facilitating actions, such as financial incentives, user friendly utility auditing tools, decision support tools, monitoring tools, databases, information material, etc. Since such tools will not likely be generated through autonomous market forces, EU stimulation actions will be needed. The EU may expand from existing tools, such as EURODEEM, the JRC audit method, etc.

6.5.3 Information 'in' Products: Testing, Labelling, Standards, etc.

As described, there is a dire need for more transparency of performances and efficiencies of integrated VSD systems. Information may range from labels and nameplate information to classification, certification and life cycle costs in bidding forms. The most relevant are described below.

6.5.3.1 Testing, certification, labelling and standards for VSDs

Differences between VSD do not pose a major market barrier. The energy effect of selecting a better VSD is only very small relative to the potential of the application of a VSD. Actions with regard to testing and labelling of VSDs as such therefore are not recommended as cost effective.

6.5.3.2 Testing, certification, labelling and standards for machines and systems using VSD

For many prospective users (and suppliers!) of systems for compressed air, ventilation, pumping, cooling, etc., assessing benefits and performances and comparing system configurations is time consuming and difficult. The energy performance of these systems highly depends on system design and on the specific applications (load pattern, operation and maintenance) and less on the efficiency of VSDs or other components as such. This makes labelling, certification and fixed standards therefore generally[17] very difficult (if at all possible) and costly. On the other hand however, the importance of user-friendly and comparable information makes it worthwhile to consider alternatives. These may be found in expanding on experiences in 'joint action' programmes with OEM sectors, as described in the next section.

[17] May be with the exception of a few specific systems; this study will not consider this further though.

6.5.3.3 Joint action approach

The core of the approach is to have specific OEM sectors or system suppliers work jointly on a more standardised system characterisation. Together with end-users, test laboratories and other relevant market parties, they develop more transparent performance indicators that enable quick assessment and easy comparison of overall system efficiencies. The Box 3 list typical steps in joint action.

BOX 3: Typical joint action elements.

Possible steps in joint action with OEM and/or system supply sectors:

- Defining the scope of systems and products considered and/or the priorities herein
- Improving transparency and comparability of performances of systems. Obviously suppliers would like to stress their competitive differences; however experience shows that on a number of (energy) relevant performance indicators a high degree of standardisation in definitions and indicators is possible. The stakeholders (including end-users) identify the most relevant parameters and agree on guidelines in definition and specification. This could include agreements on life cycle costing information in bids.
- Defining benchmarks and reference cases
- Agreeing on methods for benchmarking and/or verification
- Making available guidelines and tools (software) to facilitate easy comparison of different systems and system configurations. These generally will be used by the suppliers, installers and consultants.
- Identifying areas for comparative testing for those situations where the market will benefit from better information. This may result in co-operative testing programmes.

Example: In the Netherlands the compressed air sector is involved in such an approach. Parties involved in one or more steps are: the suppliers branch association, an independent test institute, the energy sector and a facilitating agency. When appropriate end-users and consultants were involved. Steps are:

- as a first step a joint brochure was developed with guidelines and references for efficiency. This brochure was used by the sector in joint promotion campaigns on energy efficient compressed air systems
- the positive experiences in collaboration enabled a second step: a joint software tool for standardised comparison of systems and system configurations. This tool is meant for suppliers, installers, consultants and (larger) end-users.
- the energy sector joined the effort by preparing a subsidy scheme that intends to give a bonus to efficient systems, proportional with the extra system efficiency above a reference line. This line is developed by an independent test institute based on aggregated efficiency data from suppliers
- applicants for subsidy need to install measuring facilities to check efficiencies. The independent test institute may assist or check. As a start the larger half of the capacity range has been taken (for cost-effectiveness reasons). Later this may be extended downward.
- if feasible in future this may even lead to some form of ‘labelling’ for efficient systems

Many elements are comparable with 'market procurement'. However, the initiative here lies with the suppliers. As a consequence suppliers will likely be less defensive. Also the initiative may have a more structural influence on the sector in improving their services. Examples of such joint approaches can be found with the compressed air sectors in the USA and the Netherlands. The SAVE-study team on compressed air systems[18] also discusses the value of a 'bottom up' approach with many similar elements.

Joint action may appeal to sectors that seek to improve quality and image of their products. The interest of a sector may be enhanced if joint action would be accompanied by other incentives that increase market perspectives for the sector, such as agreements with end-users, financial incentives, etc. The approach enables sharing cost and risks in improving the quality of products and services. It also enables pre-competitive marketing of new profiles for the services or product groups (e.g. 'efficient compressed air supply'). The actions in the Netherlands led among others to a joint information campaign; many suppliers also advertised more aggressively with energy-efficiency improvements. The step-wise approach in this process is an important success factor. It gives this action an evolving nature that may lead to many variations in approach. Also the 'returns' for the sector were important: facilitation of tools such as guidelines and software. An independent agency facilitated the process, which proved effective since a large number of parties is involved, none of which would likely have taken the full initiative. It may also have been helpful in overcoming reservations between competitors.

Joint actions will be good step-up towards further actions: negotiated forms of classification or labelling of systems, joint testing programmes, etc. The study team recommends to considers facilitating and supporting joint actions in selected market segments, in addition to the Green Motor programme. This would include making available tools, guidelines and such. It should be reminded that these actions are not cost-effective for VSDs as such, but should focus on a system approach. The relevant segments for such an approach are compressed air systems, HVAC and possibly medium sized pumps for industry. It is further recommended that labelling and standards be considered only after such joint action programmes.

6.5.4 Negotiated Agreements with Suppliers

6.5.4.1 Voluntary agreements with VSD suppliers

Agreements with suppliers, where possible, could lead to more efficient systems and the phasing out of less efficient products. The EU agreement with motor manufacturers is a good example. For VSD suppliers this does not seem relevant. In general efficiencies of VSDs are high and market barriers do not relate to differences between VSDs but rather to their integration in the systems.

[18] CAS Draft final report for the SAVE programme, August 2000

6.5.4.2 Voluntary agreements with OEMs and/or installers

A negotiated agreement with a suppliers sector aimed at more energy efficient machines and systems should start with similar steps as mentioned under ‘joint action approach’. Also sufficient ‘returns’ to the sector should be in place, such as supportive actions as described elsewhere in this chapter. In addition although there would be a strong need for consensus on targets to be achieved, timing of phasing out less-efficient systems, tools and procedures for monitoring and actions in case of non-compliance and such. Furthermore the need for a clear and indisputable definition of performance requirements and measurements would be higher than with most other actions. These conditions may be difficult to achieve at present[19].

Given these difficulties and the cost involved, it is recommended to consider ‘joint action programmes’ with selected sectors as an alternative. If successful and if needed these may be stepped-up to more comprehensive negotiated agreements.

6.5.5 Procurement, Contests and Awards

6.5.5.1 Co-operative procurement

Co-operative procurement involves forming a buyer group that defines performance requirements for improved energy efficient systems and subsequently challenging the supply sector in offering these services in a cost competitive way. An influential buyer group may jointly offer a sufficiently attractive market perspective for suppliers to meet the challenge. The perspective also includes demonstration effects to other potential buyers.

For VSDs as such, procurement does not seem cost effective. Efficiency is high in almost all VSDs. However for integrated systems, procurement may be a trigger for an OEM sector. The buyer group would define the elements of the improved system or service and the relevant performance indicators. They should also express their willingness to adhere to these indicators in their call for bids.

[19] Other conditions for success include e.g.: a well organised sector at EU level with at least some experience with collaboration, a competitive sector with market dominance by a limited number of players, mainly OEM supplied drive systems with significant energy-efficiency potential, systems that are clearly defined with regard to scope and complexity, significant energy-efficiency potential and a branch with compelling reason to embark on such a scheme (better image, increased markets, etc.)

BOX 4: Essential steps in a procurement approach.

Essential steps in a procurement approach include:

1. Identification and motivation of leading buyers. The EU Green Motor programme that is presently being developed may offer the network for starting such a buyer group.
2. Defining the scope of the systems under consideration and establishing performance requirements.
3. Defining benchmarks or reference efficiencies, as well as indicators to measure and compare performances. Also tools and means to perform such assessments and measurements should be made available.
4. Inviting the supply sector to develop and offer the improved services and systems

This approach in principle seems possible for well-defined systems (see 6.4) such as :

- small integrated pump-VSD systems (up to a few kW) for industry. The buyer group may be the larger industries. If these put these systems on their preferred vendor lists it will likely have a significant demonstration effect to other industries. To enable competition also small integrated motor-VSD systems and pumps with separate VSDs for the same applications have to be included in performance comparison;
- small integrated motor-VSD systems (for fans and possibly pumps). For small-pumps: see above. For fans a large number of end-users would have to be involved, which makes this segment more difficult for procurement;
- air conditioning. Again the large number of users needed will make this a difficult effort.

Mobilising a significantly large buyer group will be difficult and require much effort at the least, given the low priority the prospective buyers attribute to such (small) systems.

It is recommended as an alternative to start for these three segments with other steps, such as:

- more clearly define and standardise performance indicators that enable easy differentiation between system efficiencies;
- develop guidelines for end-users and intermediate parties (such as system suppliers, installers and engineering consultants) on application of these systems. It will include defining and describing economic guidelines on when to apply such systems.

These actions can be a joint effort of the suppliers branch, selected larger end-users and other crucial market parties. The relevant parties have been indicated in section 6.4. The involvement of the sector will enhance their willingness to participate in improving the systems further. If successful and needed this effort may at the end-users side grow into a more elaborate procurement action. The publicity on the success of the mentioned steps will be instrumental in motivating a larger buyer group.

For more complex systems, such as compressed air systems, procurement seems even more difficult. It will take much extra effort and negotiation to establish efficiency standards. For these segments it is recommended to consider the alternative of joint actions with the supply sector as sketched in section 6.5.3.

6.5.5.2 Contests and awards

Contests and awards could be a bonus for suppliers of integrated VSD systems with an energy-efficient design. The marketing value of an award could provide an extra drive for system suppliers and installers to improve system design through integration of speed control. Comparing different systems however, as described, poses a major problem. Therefore contests and awards should be considered mainly as support action to 'joint action' and only when standards and base line situations have been defined for system comparison. Contests and awards may be an alternative to 'procurement'. They do not require forming a buyer group. It requires a significant promotional effort to have effect though. This will only be possible for a few clearly defined comparable systems (possibly air conditioners or small pump/VSD systems). Its cost effectiveness as a stand-alone measure will probably be low.

6.5.5.3 Energy performance information

Another 'driving' force for procurement of more energy-efficient systems in general is a method that is used, e.g. in the Netherlands, for buildings. In this system (called 'EPN[20]') new building designs are rated. Each energy efficient measure adds points. The total for a building gives an indication for overall energy efficiency of the design. Many VSD related systems are included in a list of possible measures with which points can be obtained. This system enables comparison of building designs with respect to energy efficiency; also minimum standards can be set. This system is now being expanded to other market segments and to existing buildings.

Such a performance indicator may help in making system performances more visible and comparable. As a measure solely for VSDs it will not be cost effective. If in place, it may be used to differentiate between energy performances of e.g. HVAC systems, lifts, etc.

6.5.6 Information for Dissemination, Training and Education

In general the role of information and training in innovation has three aspects:

- Information ('what has happened?') to create awareness and attention;
- Knowledge ('what is happening?'), showing the relevance for the own situation;

[20] EPN is the Dutch acronym for Energy Performance Information

- Know-how (‘what and how to do now?’), enabling the action.

In early market information campaigns focus on creating attention for innovative systems. These clients will in general actively fit this into their own situation.

Creating further attention for energy saving potentials of VSDs will still be relevant. The focus of the actions, though, should shift more towards the present types of prospective users[21]. These generally require brief, transparent, easy accessible and practical information on standard ‘accepted’ technology[22]. They want application specific information, preferable with references from similar type of clients. They also want to be able to easily compare options and systems. They usually expect their ‘common’ suppliers to take the initiative in providing information. So the problem with information and training is not availability, but accessibility and suitability for relevant parties.

Table 3 lists information tools that seem effective in tackling the present barriers. Information and training are cost-effective tools in dissemination of VSDs. In contrast with information campaigns in early markets, the focus in communication now should be:

- No special seminars, training sessions, etc. but integration of the relevant material in main stream workshops and training sessions for the target groups. These focus on prime business concerns; energy and VSDs are brought in as an ‘extra’. Present clients are generally not adverse towards energy-efficiency, but will not often actively look for information on energy-efficiency;
- Integration of VSD aspects into workshops on system engineering, mechanical engineering, building design, etc. Important target groups for training and information are engineering consultants, installers, OEMs and dealers;
- Common/accepted technology applications, standard options and best practices within the industry branches of the prospective users of VSDs (branch orientated)[23];
- Short, easy and practical information, including transparent information on economics.
- Bringing in system approach and life-cycle cost in an easy and practical way;
- Using the proper channels for dissemination of materials. For the present type of prospective clients this could be through system suppliers, installers, etc. Articles, presentations and press releases should focus on branch magazines and workshops. Also intermediate parties (engineering consultants, installers, OEMs) should be targeted through their own branch magazines and communication channels.

[21] And focus more on directly applicable information, guidelines on when to apply, etc.
[22] At the moment it takes much effort for prospective buyers to assess the relevance for their specific application and make this visible to the management. This hampers buying decisions.

[23] This ‘vertical’ orientation (that is that clients look for reference in their own branch) contrasts with communication in early markets, where clients usually look for new innovate options. These typically will not be found in their own branch, so they look elsewhere (referred to as ‘horizontal’ or cross-branch orientation).

Table 6.3 - Overview of relevant information actions.

Information tool	Description
Advertising, brochures, technical leaflets, etc.	In early market information campaigns the focus is on raising awareness of the energy saving possible, which clients will then be able to relate to their own circumstances. Information material will be cost-effective in supporting other actions and in making available information on results of the action programmes.
Guidelines.	Information (tools) for more transparency and standardisation in market campaigns, bids, system comparison, design, engineering, installation, distribution and such. They will help lowering cost for OEMs and other intermediate parties. Examples: selection guidelines for end-users, guidelines for engineering or installation, etc.
Training and workshops	Short practical information and training sessions in which VSDs are offered as an integral part of a wider workshop or training programme. Main focus would be on system suppliers, engineering consultants, OEMs, installers and dealers. To a limited extent, end-users may be reached e.g. in short afternoon workshops on prime business concerns. Experiences with short workshops, sometimes with hands-on exercises, show they attract much interest without much cost. Some can be commercially exploited after start-up. Though the focus needs to be on the supply side, sessions could be open to some prospective buyers. Topics: application screening, electronics for mechanical engineers and engineering consultants, etc.
Decision support tools	User friendly software tools for more standardised comparison of efficiency and economics of system configurations. Many suppliers do have software tools. However these are not independent, use different assumptions and rely on the quality of data input. These have limited impact in dissemination of VSDs. However, software tools may be far more effective with the following considerations: - more standardisation in assumptions and calculation methods; - if independent from specific manufacturers/suppliers; - if supported and used by the supply sector. This enables more standardisation. The cost-effectiveness of this software will depend on becoming more or less a standard in these channels (rather than only a tool for a few specialised consultants). Suppliers and installers will be the main users of the software in their contacts with clients. End-users will generally rely upon the suppliers. Comparability of systems is more important than detailed answers. The software on compressed air systems is established along these lines and is becoming more and more a standard. There are various systems that may form the base for such tools.
Audit tools for in-house utilities	User friendly tools to assess in-house utility systems. A tool is being developed for SAVE by JRC. This may be the basis for further actions such as (subsidised) independent on-site audit schemes. Good experiences exist with a more or less standard audit methodology on energy management for consultants. A similar approach may be considered for utilities, e.g. by training interested consultants and installers. Where possible these audits should become an integral part of wider audits already used in the market. Trained consultants may consider forming an association or developing a published list of trained persons. This gives prospective clients some form of certification.
Executive summary formats for bids	A standardised and agreed upon format with easy accessible information on (life cycle) cost and benefits. This should provide brief transparent information to less technically trained people. This format could be developed in co-operation with or by suppliers.
Databases for product selection	Support tool for product selection. With the ongoing extension of EURODEEM experiences will be gathered. Also in the US good experiences exist with databases.
Benchmark and reference information	Reference efficiencies for quick comparison by management. This could include aggregated data from cases or reference efficiency levels of specific systems groups, based on aggregated data of suppliers. Also comparative data from user groups may be relevant.
User groups	Groups of end-users (technical managers or utility managers), that meet regularly, exchange experiences and assess options for improvement in their utility systems. This is done with independent guidance. These groups help lower barriers for other participants to also use new systems (more confidence and references). Social commitment to the group proves an extra ‘drive’ to implement measures
Internet	Support site as focal point for actions with regard to electrical drive systems. It may consist of an EU web site or linked national sites and gives access to resources, case studies, tools and such.

The EU role would be starting and facilitating action programmes. It is recommended to have a communication action programme with various elements as indicated in the Table 3 to support the other actions. Especially decision support tools, guidelines, training workshops for intermediate parties and supporting articles seem essential and cost-effective.

6.5.7 Demonstration and Pilot Actions

There is an abundance of demonstration projects available with VSDs in many types of applications. Priority should be given to making the information from these cases more accessible. It could provide a base for information on efficiencies and economics, as well as for practical guidelines. Also databases from EU countries, CADDET etc. may provide useful information. Further technical demonstration should only be considered in case of important gaps in information. Some gaps may exist for the target segments for standard VSD solutions. This may be the case for some applications of VSDs in lifts, materials handling and materials processing.

Pilot tests of some of the more complicated actions mentioned in this chapter will likely be effective, such as joint action programmes and negotiated agreements with end-users. The latter action is already started in the 'Green Motor' programme.

6.5.8 Financial and Fiscal Instruments

Subsidies and tax incentives are used throughout the EU. In some cases the energy sector provides subsidies for VSD systems. There are many applications where VSDs are economically attractive. Subsidies and tax incentives would render these even more attractive. However, it should be considered that subsidies may increase the budget for technical departments and in some cases may raise attention from management ('higher on the agenda'). If properly used in decision making, in convincing the management, they may have a significant role in accelerating the dissemination in initial phases of market development. The schemes should be easy and transparent to have effect. Some schemes are found too cumbersome or are not effectively used in the decision making. Also for subsidies the 'split cost responsibility' may sometimes occur: the money does not go the department that makes the investment. Also technical staff may not be fully aware of the fiscal incentives or cannot properly present the project to the fiscal experts in companies.

OEMs have asked to have some subsidy schemes carried out directly through them; however the difficulties in e.g. controlling the legitimacy of using subsidies renders this option not feasible. OEMs though may offer services to facilitate clients in preparing subsidies, for instance by making available prepared subsidy requests as part of their bids to clients.

For the present purpose, subsidies may be considered as a short term measure in stimulating OEMs and system suppliers in offering improved services and integrated systems. They may enhance joint actions of a suppliers sector. The effect is illustrated by a planned subsidy scheme of the energy sector in the Netherlands (see Box 3).

Reduced VAT rate on VSDs is another option. In some member states renewable energy equipment already has a much reduced VAT rate, and the same principle can be applied to energy-efficient equipment with a large savings potential such as VSDs. Accelerated depreciation of the VSD investment may also be allowed, in a way similar to computer equipment, in order to make its application more cost-effective.

6.5.9 Outsourcing and DSM Services

6.5.9.1 Energy services by system suppliers or installers

Many suppliers offer 'energy services' to the end-user. The contents may differ e.g.:

- Maintenance contracts for specific installations;
- Operation and maintenance contracts;
- Energy contract management (load management) e.g. by energy companies;
- No cure-no pay consultancy services on energy cost reduction (not very common);
- Energy management as part of facility management;
- Exploitation of co-generation installations;
- Full outsourcing (built, operation, own, maintain) of utility installations and performance contracting. The supplier takes responsibility for guaranteed outputs of defined quality, defined quantity and agreed upon timing.

The first three types are directed towards ease, comfort and lower cost. The others also aim at increased energy efficiency.

Only the latter gives full responsibility for investments and energy cost to one party. The most common energy services as yet do not comprise full outsourcing. For VSD systems this type of outsourcing may tackle various barriers: clients do not have extra investments but only have a yearly service cost budget, it takes less time and effort for the client to assess the systems and cost and benefits accrue to the same party (the supplier of services). The latter makes energy-efficiency in utilities more clearly somebody's core business.

For outsourcing to be more widely used, the following constraints should be tackled:

- Increasing need of good performance indicators to measure and compare offered services;

- Proper inclusion of energy costs in contracts to avoid 'split' responsibilities and to create a drive for the supplier towards investing in efficient systems;
- Dealing with high transaction costs[24] and high risks for the service supplier. Consequently at present services are offered only for large energy consumers with contracts of some 100 kEuro upward;
- Limited experiences with full outsourcing of energy services. The effects are not yet fully known.

These services may significantly contribute in dissemination of efficient systems with VSDs. Outsourcing of in-house utility systems is already offered in the market place. It is recommended that the EU consider a few (limited) actions in this respect:

- Monitoring the effects in case studies and making the effects visible (as a pilot action);
- Facilitating the elaboration of guidelines for outsourcing e.g. on what to be included, how and what to be measured, etc. This makes outsourcing more transparent to end-users and lowers the cost of suppliers;
- Facilitating selected sectors in defining and agreeing upon 'performance indicators'. This may be done e.g. by representative groups of clients and the suppliers sector. Where relevant an independent third party may be involved in control measurements.

Such limited pilot actions could be cost-effective, when carried out as extension of the Green Motor programme[25].

6.5.9.2 Energy services by the energy sector/Demand Side Management

Energy distribution companies can supply energy services within the framework of Integrated Resource Planning and/or Demand Side Management. These include for instance consultancy, load management or performance contracting. The main reasons for energy companies to pursue these actions are a better relation with clients, participation in environmental programmes and more efficient supply and distribution (demand side management, peak shaving etc.). The availability of an attractive regulatory framework appears to be a key condition for the large scale implementation of DSM programmes by the electricity distributors. The energy sector initiatives are often supported by financial schemes for clients. A widely adopted model is the application of a "public benefits" surcharge on all kWh sold. The collected funds are used to finance DSM schemes. Electric utilities may be rewarded based on the performance of their DSM schemes.

[24] In assessing the situation, in acquisition, in engineering, in administration, etc.

[25] The pilot action could include following steps: forming a potential buyer group, defining the contours and performance criteria for the services, elaborating a prospectus with typical end-use situations, establishing criteria for suppliers, tendering, selection, contracting, evaluation and dissemination. Rather homogenous and concentrated sectors for a (multi-national) pilot action may be banks, government buildings or applications in industry such as compressed air.

The liberalisation of the energy sector in Europe causes a rapid change of the sector. In practice the further development of energy efficiency services in this sector seems to be hampered by the priority the sector has to give to the liberalisation. The profile of future energy efficiency services by the sector at present is rather unclear. However, the experiences in the USA show that some types of DSM schemes may survive in a liberalised market.

6.6 Combined strategies

6.6.1 Overview and Type of Actions

What market parties should be given priority?

Market parties will only buy or integrate VSDs if they perceive a favourable balance between alleged benefits and expected efforts (including money, time and risks!). Actions may improve this balance on the benefit or effort side.

The end-user is mainly driven by cost-efficiency considerations, some also by a 'green' image. Energy for them is no core business, but part of the operational cost. Their interest in more efficient in-house utilities may be influenced to some extent by negotiated agreements. These will increase importance attached to electrical drive system efficiency. All other actions towards end-users will need to focus on the 'effort' side by making the systems easier and more common. The end-user will not do so himself, others should do the job.

The VSD supplier has a natural interest to market the systems. No extra impulses are needed. He may improve on more accessible information for the buyer or offer a higher margin to resellers, such as OEMs, system suppliers and installers. No action from the EU will be needed in this.

The OEMs, engineering consultants and installers hold the key to an easy and 'low effort' system or service for the end-user. As yet the 'drive' to market integrated VSD systems is not yet high. Many OEMs still consider the cost too high and or the market benefits too low. Given their crucial role in disseminating VSDs, an action programme should well address these parties. Also engineering consultants determine to a large extent whether VSDs will be integrated in system designs such as HVAC, etc..

In conclusion: a mix of measures is needed, directed especially to:
- the end-user, to increase the importance and awareness of more efficient VSD systems;
- the intermediate parties, to improve the services offered to the clients (total solutions, that do not require extra effort from the end-user). Actions should focus on joint programmes that enable a better quality; in return supporting measures and other incentives will be needed to motivate the sectors.

What actions are most effective?

Table 4 summarises the various actions and gives a brief indication on their cost efficiency Most actions though will be cost-effective especially when carried out simultaneously with others. The following considers combinations of actions with significant synergy. This should be treated with care though, given the difficulty in predicting effects.
Most actions are system related and not solely for VSDs as such. The present market requires a system approach. Most energy benefits with VSDs also result from their integration in systems.

Table 6.4 - Indicative summary of cost-efficiency of various actions in disseminating VSD.

Overview of actions				
The actions	*Cost*	*Likely cost-efficiency*[26]	*Time to effect*	*VSD applications that (may) benefit*
Negotiated agreements - on energy efficiency - on utilities	 medium medium	 limited good	 medium medium	 all all
Procurement/contests/awards	high[27]	medium		only possible for some priority subsegments (see 6.4)
Labelling/testing/standards: - for VSDs - for systems with VSD -	 high high	 low low	 medium long	 not relevant not considered feasible
Joint action of OEM sectors	medium	good	medium	priority segments
Information/training - decision support tools and databases - guidelines, formats, cases - training material - articles, PR, internet	 medium limited limited limited	 good good medium/good good	 medium short short short	 per application type all all all, mainly as support to other actions!
Technical demonstration projects	medium	limited	medium	in present market little added value
Subsidies/fiscal incentives	medium	Limited[28]	medium	to be considered if specific financial barriers occur with other actions
Negotiated agreements with: - VSD suppliers - OEM sectors -	 medium medium	 low medium[29]	 medium medium	 all priority segments
Outsourcing: - guidelines - case material	 limited limited	 good[30] good	 short medium	

[26] The effect refers to the effect specifically on VSD dissemination.
[27] If considered over all relevant segments. All segments will have to be tackled separately. Procurement actions as part of joint action though may be more cost-effective. These involve from the start the OEM sector in transforming their entire product range. Procurement then is just a means to enhance this transformation process.
[28] Experiences in the US and other countries have shown that subsidies/fiscal incentives may be influential to increase penetration of VSD
[29] Effect will be significant on sector as such, also as step-up for other system improvement actions
[30] Effect difficult to predict. May help in facilitating more services to be supplied in start-up phase

6.5.2 The Alternative Action Packages

The study team distinguishes between three basic approaches. None of these will likely do the job alone; however they can be considered as extremes in which, depending on preferences of the policy makers, a balance should be found.

The ‘awareness’ approach - Another approach in innovation is making information and know-how available. This aims to increase awareness with relevant parties. The assumption in this approach is that the main barrier is lack of information and know how. This approach could be adopted in two ways:
- as a sole action package of information and training, it would likely increase demand to some extent. However it would in itself not likely result in a real shift in character of demand (towards life cycle orientation), nor in a services approach by the supply chain;
- as support to actions in other approaches, providing user-friendly information on application and economics. It would also have ‘promotional’ value for participants (better reputation, ‘green’ image).

Information actions are a requirement in both other approaches.

The ‘demand stimulation’ approach - This approach focuses on increasing market demand. The core would obviously be negotiated agreements with end-users on utilities. This step is planned in the Green Motor programme. End-users will only embark on such agreements if the EU offers extra actions, such as:
- Promotional activities that improve the reputation and image of the clients;
- Supporting activities that ease implementation, such as audit tools, decision support tools, case materials, subsidised audits, etc..

This approach will likely be cost effective. There is some risk though that market demand, though increasing, may not really change in character. A change in character, notably towards a life cycle cost approach, requires other responsibilities of market parties and departments with regard to procurement and implementation of services.

The ‘improved services’ approach - The focus in this approach is stimulating and facilitating system suppliers and installers to develop product or service packages that better suit present market demand. The suppliers have to shift from product seller towards provider of a total solution (integrating VSDs). These could range from integrated VSD-pump systems to more comprehensive ‘built, own, operate and maintain’ services for utilities. This approach does not wait until ‘split cost’ responsibilities with the end-users have changed, but gives more possibilities to suppliers to influence life cycle cost. Ideally energy-efficiency will become more a part of the core business of suppliers.

Core of the actions would be 'joint actions' with the supply sectors (system suppliers, OEMs, installers, engineering consultants and possibly energy distribution companies). These actions will focus on target segments[31]. It will not be necessary for the EU to make a detailed selection of narrowly defined subsegments; the sectors may suggest this themselves as part of the co-operative actions[32]. Supporting actions would be needed on two accounts:

- enabling OEMs and others to implement the actions at reasonable cost. This requires tools that may be used in marketing of new energy-efficient concepts (decision support tools, information materials, guidelines, etc.);
- increase the market perspective for improved services e.g. through actions with end-users, such as negotiated agreements on utilities, user groups, procurement, etc. This is essential, since at present the market perspectives for improved services apparently are not yet considered sufficiently promising to massively embark on improved services.

The 'prescriptive' approach - Activities could also aim at developing standards and minimum efficiency levels. The OEM sector would likely be more defensive in defining norms, labels, etc. As mentioned this would be a very costly approach, only feasible for selected specific systems. Control measures and sanctions in case of non-compliance, are cumbersome and would add extra cost and efforts.

6.7 In conclusion

The study team recommends a mix of the first and second approach. The Green Motor programme offers a good basis for integration of actions for dissemination of VSDs. It is recommended to add one or more pilot actions with the supply side in specific target segments that aim at enabling improved services and/or systems ('joint actions'). Various segments have been identified as options for this pilot scheme. The discussions with the various sectors on the Green Motor programme and on this report may be taken as a basis for further pre-selection of subsegments and as step-up for negotiations. Specific recommendations for (further) individual actions are included in the previous section.

The proposed actions require a high degree of commitment of the parties involved and a close collaboration with market parties. It is essential that the actions be developed and implemented in close co-operation with the crucial market parties. To this end the European Commission could consider an advisory committee with relevant trade associations of the involved market parties for further development of pilot actions.

[31] Priorities are described in section 6.4

[32] Provided it is relevant within the criteria as mentioned under 6.4. This enables the sector to build up co-operation in selecting 'easier' subsegments as a start.

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APPENDIX A - QUESTIONNAIRE FOR CHARACTERIZATION OF VSDS MARKET

SAVE II VSDs Study

Task 1, Characterisation of current market for Variable Speed Drives

This questionnaire is designed to ensure that all the collected market data can be computer-processed.
Please note the following guidelines:

1 The countries that this questionnaire apply to, must always be indicated.
2 Please fill in as many of the tables 1 through 6 as possible. All possible data are of interest, if the fields for "Data category" are checked.
3 The "Number of units" is the most important information, that should always be indicated.
4 The "Total sales in ECU" can be indicated as an average value, based on end-user prices.
5 If used on a company/supplier-level, several sets of tables can be used for a single country, if the fields for "Data category" are checked.
6 The spreadsheet can be used as it is, to report the collected data back to the task leader. (A printed out answer is also welcome).
7 Write all values as values without unit (ECU, %, …).
8 Write all check-marks as the small letter "x".
9 At least one application %-value of the total number of units should be indicated per power range.

Please indicate the countries that this set of tables apply to.
More than one x is allowed.

EU Country	check
Austria	
Denmark	
England	
France	
Germany	
Portugal	
Spain	
The Netherlands	
(Sweden)	
(Luxembourg)	
(Italy)	
(Ireland)	
(Finland)	
(Belgium)	

Legend:

47	is a data input field for values.
x	is a data input field for check-marks.

Table 1 Technology: **AC induction motor drive**
Design form: **Discrete drive**

	Main information		Application Indicate % of total number per power range per application.								Data category Check only one category per power range.					
Power range	**Number of units**	**Total sales in ECU**	Air compressor	Fan	Materials handling	Materials processing	Pump	Refrigeration compressor	Other applications	No data	1998 total domestic sales	1998 sales, one supplier	1999 total domestic budget	1999 budget, one supplier	Estimated	Other statistics
0,75kW <= P2 < 4kW																
4kW <= P2 < 10kW																
10kW <= P2 < 30kW																
30kW <= P2 < 70kW																
70kW <= P2 < 130kW																
130kW <= P2 <= 500kW																

Table 2 Technology: **AC induction motor drive**
Design form: **Integrated motor/drive**

	Main information		Application Indicate % of total number per power range per application.								Data category Check only one category per power range.					
Power range	**Number of units**	**Total sales in ECU**	Air compressor	Fan	Materials handling	Materials processing	Pump	Refrigeration compressor	Other applications	No data	1998 total domestic sales	1998 sales, one supplier	1999 total domestic budget	1999 budget, one supplier	Estimated	Other statistics
0,75kW <= P2 < 4kW																
4kW <= P2 < 10kW																
10kW <= P2 < 30kW																
30kW <= P2 < 70kW																
70kW <= P2 < 130kW																
130kW <= P2 <= 500kW																

Table 3	Technology:	**Brushless DC drive**														
	Design form:	**Discrete drive**														
	Main information		**Application** Indicate % of total number per power range per application.								**Data category** Check only one category per power range.					
Power range	**Number of units**	**Total sales in ECU**	Air compressor	Fan	Materials handling	Materials processing	Pump	Refrigeration compressor	Other applications	No data	1998 total domestic sales	1998 sales, one supplier	1999 total domestic budget	1999 budget, one supplier	Estimated	Other statistics
0,75kW <= P2 < 4kW																
4kW <= P2 < 10kW																
10kW <= P2 < 30kW																
30kW <= P2 < 70kW																
70kW <= P2 < 130kW																
130kW <= P2 <= 500kW																

Table 4	Technology:	**Brushless DC drive**														
	Design form:	**Integrated motor/drive**														
	Main information		**Application** Indicate % of total number per power range per application.								**Data category** Check only one category per power range.					
Power range	**Number of units**	**Total sales in ECU**	Air compressor	Fan	Materials handling	Materials processing	Pump	Refrigeration compressor	Other applications	No data	1998 total domestic sales	1998 sales, one supplier	1999 total domestic budget	1999 budget, one supplier	Estimated	Other statistics
0,75kW <= P2 < 4kW																
4kW <= P2 < 10kW																
10kW <= P2 < 30kW																
30kW <= P2 < 70kW																
70kW <= P2 < 130kW																
130kW <= P2 <= 500kW																

Table 5	Technology:	**Switched reluctance drive**														
	Design form:	**Discrete drive**														
	Main information		**Application** Indicate % of total number per power range per application.								**Data category** Check only one category per power range.					
Power range	**Number of units**	**Total sales in ECU**	Air compressor	Fan	Materials handling	Materials processing	Pump	Refrigeration compressor	Other applications	No data	1998 total domestic sales	1998 sales, one supplier	1999 total domestic budget	1999 budget, one supplier	Estimated	Other statistics
0,75kW <= P2 < 4kW																
4kW <= P2 < 10kW																
10kW <= P2 < 30kW																
30kW <= P2 < 70kW																
70kW <= P2 < 130kW																
130kW <= P2 <= 500kW																

Table 6	Technology:	**Switched reluctance drive**														
	Design form:	**Integrated motor/drive**														
	Main information		**Application** Indicate % of total number per power range per application.								**Data category** Check only one category per power range.					
Power range	**Number of units**	**Total sales in ECU**	Air compressor	Fan	Materials handling	Materials processing	Pump	Refrigeration compressor	Other applications	No data	1998 total domestic sales	1998 sales, one supplier	1999 total domestic budget	1999 budget, one supplier	Estimated	Other statistics
0,75kW <= P2 < 4kW																
4kW <= P2 < 10kW																
10kW <= P2 < 30kW																
30kW <= P2 < 70kW																
70kW <= P2 < 130kW																
130kW <= P2 <= 500kW																

APPENDIX B - PROFILES OF CONTRIBUTORS

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NOVEM

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