

Technical and Economical Considerations in the Application of Variable-Speed Drives With Electric Motor Systems

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Abstract—In the European Union (EU), variable-speed drives (VSDs) were identified as the motor systems technology having the most significant electricity savings potential. In the EU, the identified economic electricity savings potential with the application of VSDs, by the year 2015, in industrial and tertiary sectors, are 39 and 8 TWh/year, respectively. However, only a small percentage of this potential is being used. In this paper the characterization of the current market of the VSDs is presented, including the average prices, the installation costs, and the total sales in each EU country, per power range. Selected VSD applications are presented. The key barriers to a wider application of VSDs are identified. In particular, the power quality and reliability problems associated with the use of VSDs are presented and possible technical solutions are discussed.

Index Terms—Electric motor efficiency, electricity conservation, energy-efficient motor systems, market transformation, motor drives, motor systems, variable-speed drives (VSDs).

I. INTRODUCTION

IN the European Union (EU), electric motor systems are by far the most important type of load in industry, using about 70% of the consumed electricity [2], [3]. In the tertiary sector, although not so relevant, electric motor systems use about one-third of the consumed electricity. It is their wide use that makes electric motors particularly attractive for the application of efficiency improvements. In previous studies [2], [3], the application of variable-speed drives (VSDs) was identified as the motor systems technology having the most significant energy savings potential.

This paper summarizes the results of a European wide (Portugal, France, U.K., Germany, Denmark, and The Netherlands) investigation [1] about the technical and economical considerations in the large-scale application of VSDs for electric motor systems.

The loads in which the use of speed controls in electric drives can bring the largest energy savings are the fluid-handling ap-

plications (pumps, compressors, and fans) with variable flow requirements [1]. Other applications that can benefit from the application of VSDs include conveyors, machine tools, lifts, centrifugal machines, etc. [1]. 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 VSDs have become the standard technology [7]–[10], [29].

The dominant speed control technology—electronic VSDs coupled with alternated current (ac) three-phase motors (mostly squirrel-cage induction motors)—have practically replaced other technological solutions: mechanical, hydraulic, as well as direct current (dc) motors [1], [5], [6]. The speed of the rotating field created by the induction or synchronous motor stator windings is directly linked with the frequency of the supply applied to the windings. Electronic VSDs can produce variable-frequency variable-voltage waveforms which can be used to control the motor speed and torque [7]–[10], [29].

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 motors [1].

II. ELECTRONIC VSDS APPLICATIONS

VSDs can be applied to a wide variety of loads. Examples of loads in which significant energy savings can be achieved are described next.

A. Single Pumps

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 Fig. 1. 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 fulfill 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 Fig. 2 [1]. In these pumping systems the mechanical energy is used to overcome the friction

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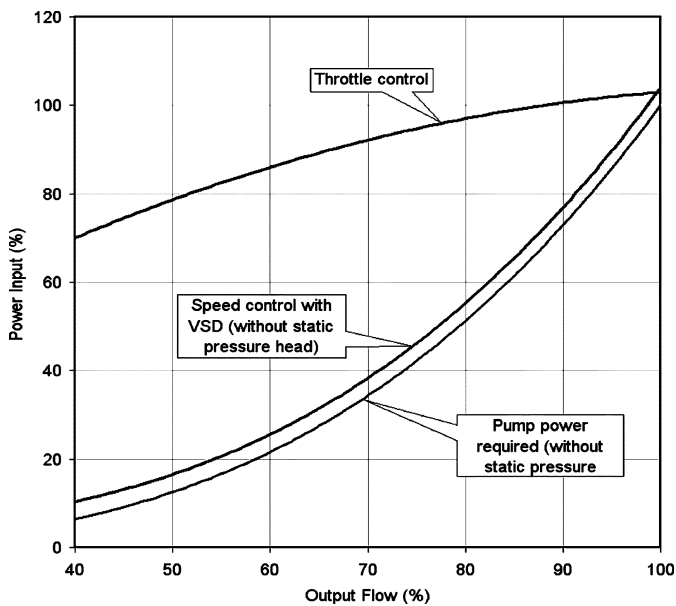


Fig. 1. Input power for different flow control methods of a centrifugal pump.

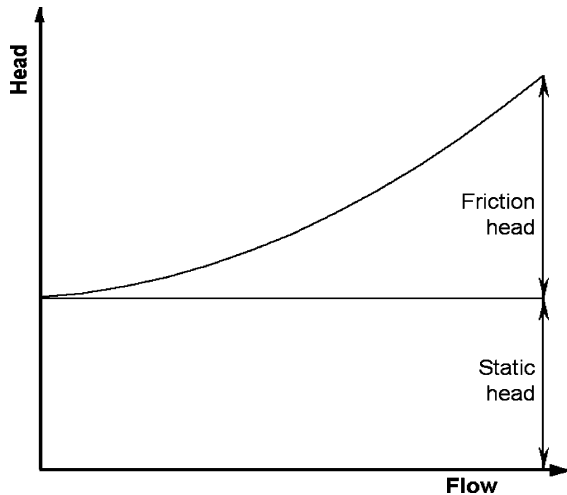


Fig. 2. Total system resistance from frictional losses plus static head losses.

in the pipes, plus the mechanical work associated with lifting the fluid against the gravity. 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 (closed circulation systems).

The overall efficiency of the pumping system depends on the efficiency of the different components of the system. Fig. 3 illustrates an example of the power absorbed by a pump system with different components. For the same output flow, the inefficient system absorbs more than twice the power absorbed by the optimized system, showing the importance of integrated motor systems design.

B. Staged Pumping Plants

In many pumping applications several pumps are used in parallel to produce the required flow. By 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), and seals stay wet and alive, also eliminating high-shock starts on the system. Fig. 4 illustrates this situation. Also, it is possible to control the “water-hammer” effect which degrades the pipes by controlled acceleration/deceleration using VSDs.

C. Fans

Savings from adding variable speed control to fans can be significant even with fairly heavily loaded motors. Fig. 5 illustrates the savings potential with a 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. The energy consumption in these loads is so sensitive to the speed that the user can achieve large savings with even modest speed adjustments. For example, in a rooftop chiller system (Fig. 6), 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 an on/off cycling control, is a more stable temperature in the controlled space and more efficient operation, by typically decreasing the fan energy in the range 25%–50%.

D. Compressors

Rotary screw and piston air compressors are essentially constant torque loads which 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 Fig. 7 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 the rated capacity, the energy savings associated with the VSD integration is about 30%.

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, leading to typical energy savings of 15%–20%. 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. The use of VSD for temperature control (floating head operation) in the refrigeration pumps/compressors (e.g., walk-in freezer, Fig. 8) can eliminate the on/off cycling losses and decrease the temperature difference between the condenser and the evaporator, with large energy savings (typically 25%). The temperature control can also be improved, in terms of differential between internal and external temperatures.

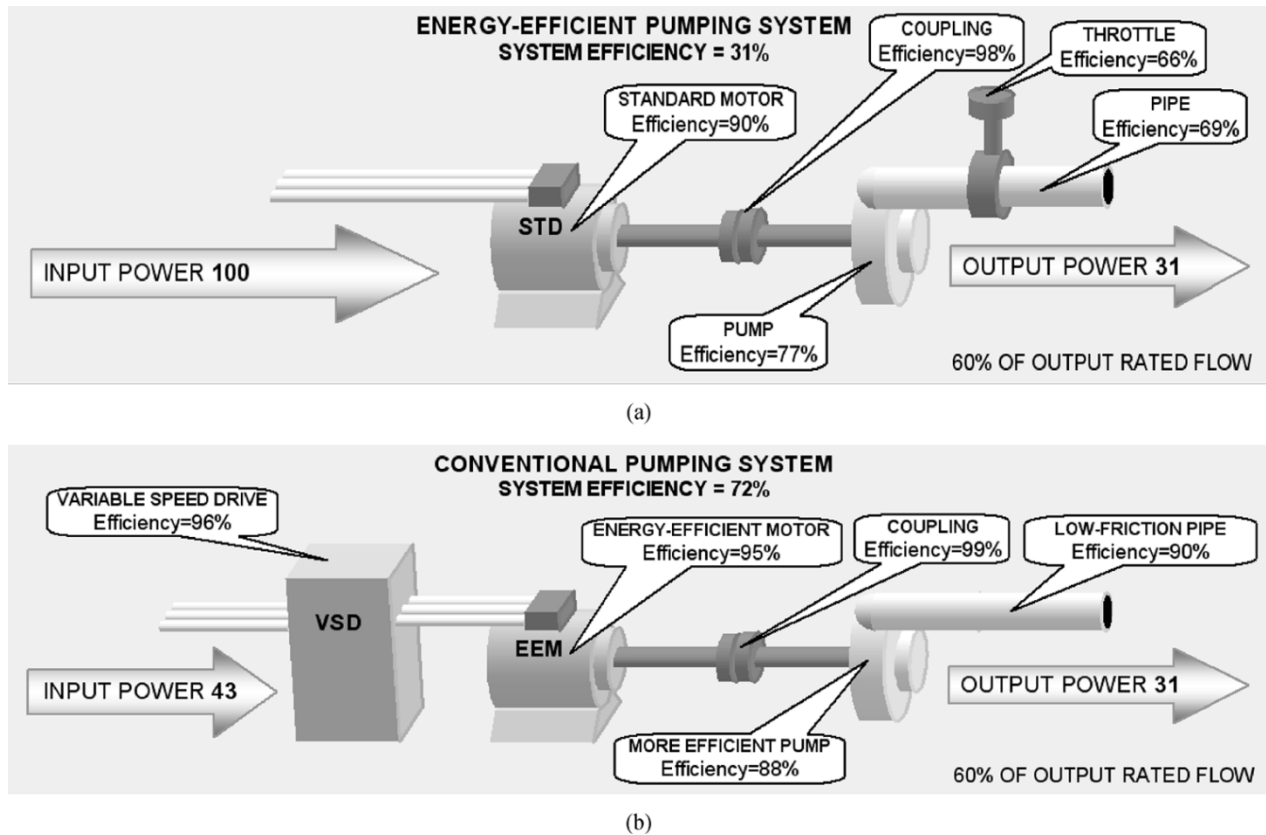


Fig. 3. Two pumping systems with same output. (a) Conventional system. (b) Energy-efficient pumping system combining efficient technologies.

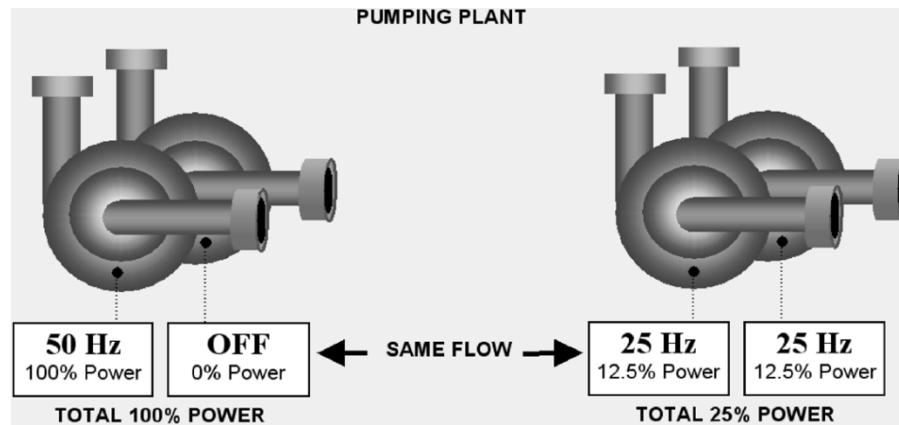


Fig. 4. Pumping plant. Useful relationship to consider with closed loop circulating independent systems where “head” is not a major factor.

E. Lifts

New VSD topologies allow the braking energy to be injected back to the source/grid—VSDs with regenerative capability.¹ 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.,

¹Conventional VSDs rely on a brake resistor connected to the dc bus to absorb power when slowing the motor down. Regenerative VSDs reconvert the energy in the rotating load back to the main power supply. This will significantly increase the overall energy efficiency of the process, increasing the energy savings. To achieve this there needs to be a complete reverse circuit, and so, regenerative VSDs are more expensive than standard types [1].

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 (Fig. 9).

In Fig. 10, possible energy savings in lifts, using different technologies, can be seen. With the use of regenerative VSD system, and efficient transmission, 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.

F. Centrifugal Machines and Machine Tools

In high-inertia loads (e.g., machine tools) and/or high-speed loads (e.g., centrifugal machines), with frequent accel-

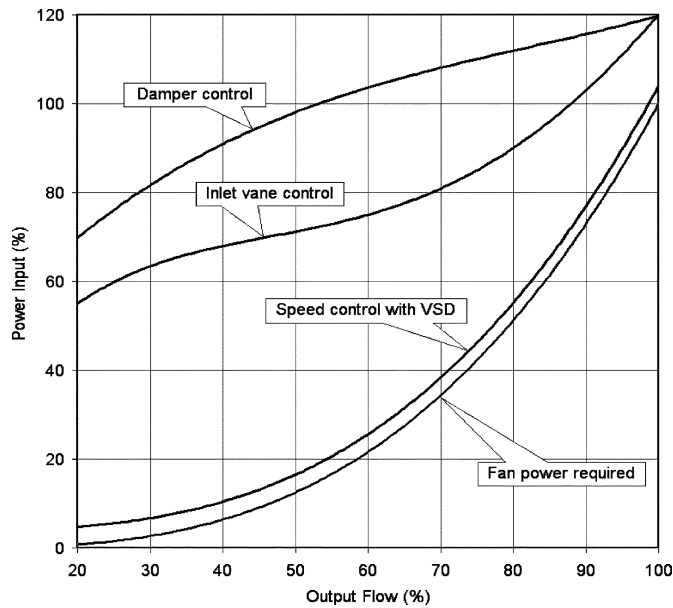


Fig. 5. Input power for different flow control methods of a centrifugal fan.

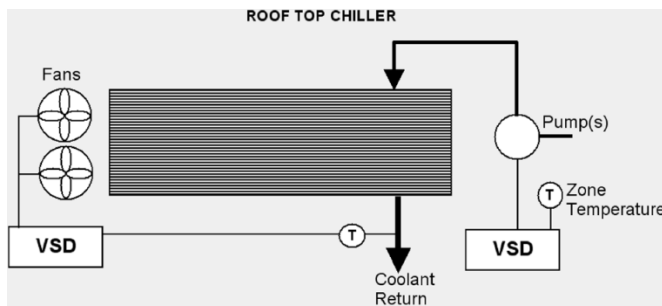


Fig. 6. Application of VSDs on a rooftop chiller.

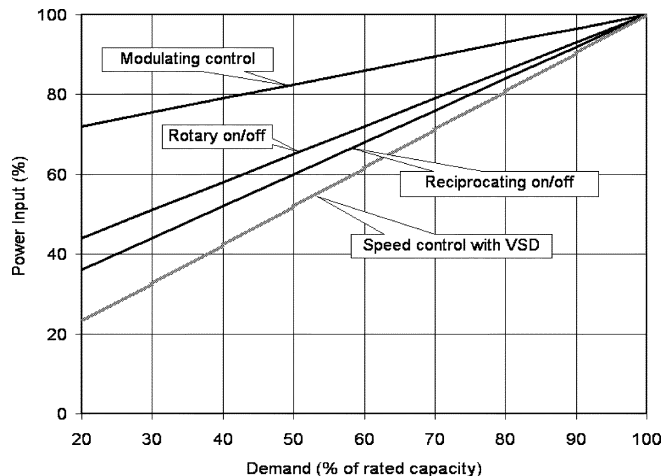


Fig. 7. Energy saved by using a VSD on a rotary screw air compressor [1].

ating/braking operation, it is possible to save significant amounts of energy. When running, this type of loads has a large amount of kinetic energy, which in a braking process, can be regenerated back to the grid, if a regenerating VSD is used. Examples of this type of loads are high speed lathes with an automatic feeder or high-inertia saws.

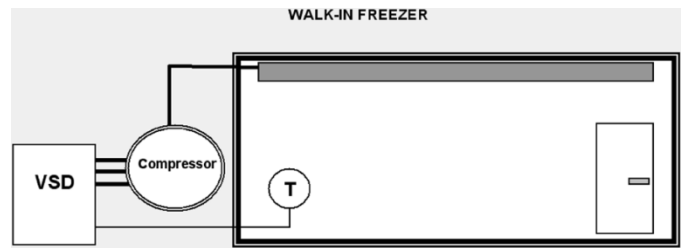


Fig. 8. Application of VSDs on a variable-speed refrigeration compressor.

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 necessitates a fast stop. To explore the energy saving potential, the braking energy can be re-injected to the grid instead of dissipating in a resistance. Another important aspect is the acceleration process. As can be seen in Fig. 11, if the motor is simply turned on [Fig. 11(a)], without any speed control, the rotor losses will be higher than if is used a pole-changeable motor [Fig. 11(b)]. A more efficient acceleration technique uses a VSD [Fig. 11(c)], that will significantly reduce the energy consumption, compared to the other mentioned techniques.

G. Conveyors

In the constant torque devices (e.g., horizontal conveyors, Fig. 12), 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 is changed, it is possible to reduce the speed (the torque is the same), and, as can be seen in Fig. 13, significant energy savings will be reached, proportional to the speed reduction.

III. TECHNICAL BARRIERS TO THE USE OF VSDS

The three-phase induction motors fed by VSDs based on voltage-source inverters with pulsewidth modulation (VSI-PWM) may have to support three main additional motor stress factors that are described next, namely, internal temperature increase, partial discharges, and breakdown of the stator windings insulation system and bearing currents [11].

A. Internal Temperature Increase

The internal temperature increase is mainly due to the harmonics increase which leads to an increase of iron and copper losses and, therefore, the overall losses will increase typically between 15%–35% with load factors higher than 60% [6], [11]. Based on the Arrhenius law, a 10 °C increase in the operating temperature will lead to a 50% and 35% decrease for the insulations and lubricants lifetime, respectively. In a totally enclosed fan-cooled (TEFC) 35-kW motor with a 90% nominal efficiency, an increase of 7.5% in the losses lead to a 2.3 °C increase in the operating temperature [11]. Besides increasing the motor losses, the 5th, 11th, and 17th harmonics, although present in low values, will reduce the starting torque [1], [7], [29]. Note that sophisticated control techniques have been developed in modern VSI-PWM VSDs to minimize harmonics,

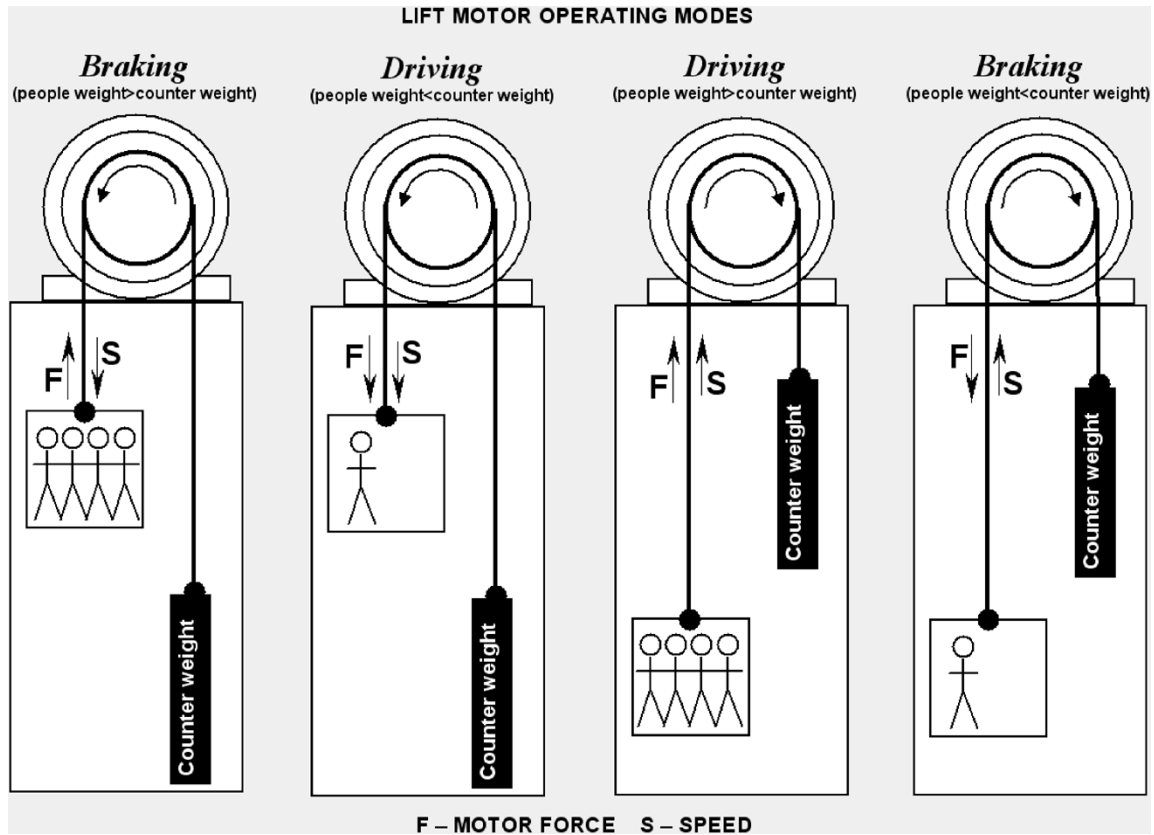


Fig. 9. Lift motor operating modes.

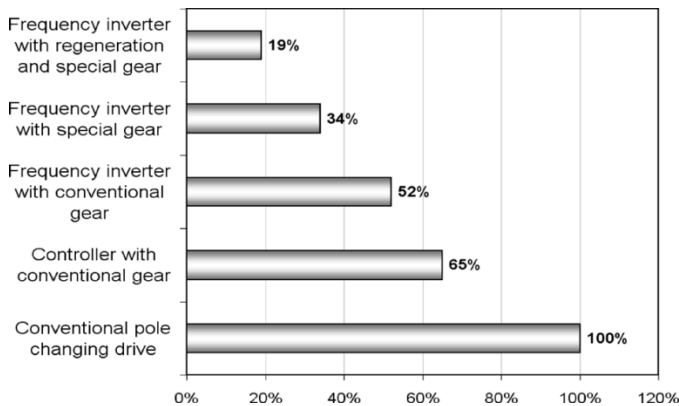


Fig. 10. Average energy consumption of lifts, percentage [1].

particularly on the motor side [1]. In the case of self-cooled motors (e.g., TEFC type), the temperature increase can be also due to the reduction of motor speed and, thus, the cooling airflow. Therefore, it is important to properly size the motor for loads requiring speeds lower than nominal, as can be seen in the Fig. 14. For low speeds (below 70% of the nominal speed) an external ventilator may be required to avoid motor overheating.

B. Partial Discharges and Breakdown of the Insulation System

Because of the nature of the VSI-PWM output voltage waveform, characterized by high dv/dt (in a 400-V VSD with insulated gate bipolar transistors (IGBTs), the pulse rise time

is 70–100 ns and the dv/dt is typically 2500–9000 V/ μ s [7], [11]) and high frequency (2–20 kHz [11]), and the motor and cable impedance difference, wave reflection effects² occur in the power cable between the VSD and the motor [11], [13], [18]. The insulation voltage stress can be particularly serious if the length of cable between the VSD and motor exceeds 50–100 ft. Because of the consequent superposition of the output and reflected pulses, this effect can lead to very high peak voltage transients (2–5 times the normal pulse values with a 0.2- μ s rise time [11], [13], [18]) in the motor terminals. In these instants, the voltage transient can lead to the partial discharge effect in the air cavities of the motor insulation system between coils and phases or between phases and slot surfaces [21]–[24]. The air cavities will increase, and the insulation systems becomes weaker until short circuit occurs. If the voltage transient exceeds the insulation dielectric strength, short circuit can occur without the partial discharge effect. Even dv/dt without reflection effects can stress the insulation because it allows the circulation of capacitive parasitic currents through the insulation. The effect of voltage transients is critical in the initial turns of the windings because of the nonlinear voltage distribution [25], [26].

Because of the temperature increase, partial discharge, and voltage stress, the insulation system of older motors (in particular) with long cable runs may have a significant shortened life-time when fed by VSI-PWM VSDs.

²The reflection effects increase with the cable length and PWM frequency.

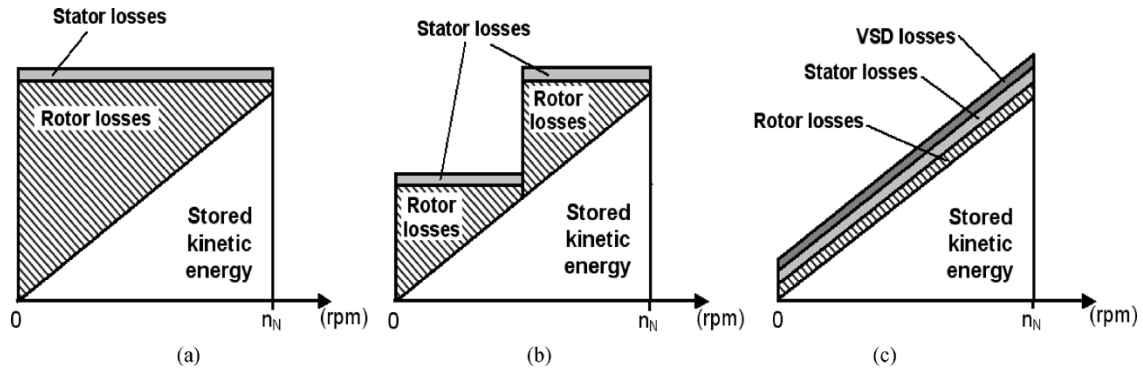


Fig. 11. Energy consumption for an acceleration period. (a) Standard motor. (b) Pole-changeable motor. (c) VSD.

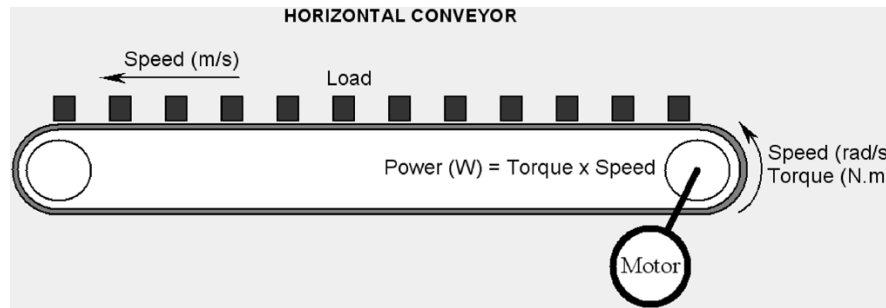


Fig. 12. Power required by a conveyor.

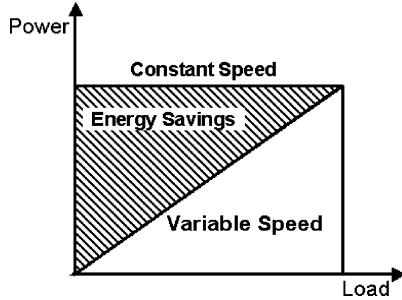


Fig. 13. Energy savings in a conveyor using speed control, in relation to the typical constant speed.

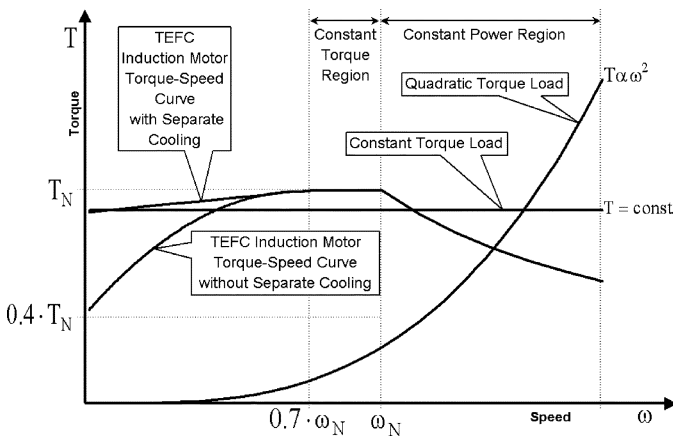


Fig. 14. Motor torque and power limitations in totally enclosed fan-cooled induction motors fed by a VSI-PWM VSD, assuming motor constant nominal operation temperature (switching frequency > 5 kHz, field-weakening point at nominal frequency) [30]. Torque-speed curves for different types of loads.

C. Bearing Currents

Because of the induction motor parasitic capacitances between the windings and frame, windings and rotor, rotor and frame, and inside the bearings, high-frequency currents can circulate in the bearings of motors fed by VSI-PWM VSDs [11], [13]–[17], [19]. The currents have two main different modes, but the same primary cause which is the common-mode voltages generated in the VSD output due to the unbalance of the three output PWM voltage waveforms. The first current mode is a consequence of the generated voltage between the shaft and the ground due to the referred parasitic capacitances. The presence of a shaft-ground high-frequency voltage leads to the circulation of capacitive and resistive high-frequency currents through both bearings. The second high-frequency current mode is a consequence of the voltage between the shaft ends, induced by the circulation of a high-frequency common-mode currents in the windings and between them and the frame. The presence of a voltage between the ends of the shaft leads to the circulation of a capacitive and resistive high-frequency current through the closed circuit formed by both bearings, shaft, and frame. In both current modes, the constant circulation of resistive and capacitive currents, although its low amplitude, leads to the accelerated degradation of the lubricant, balls, and races. If instantaneous electric contact occurs between the balls and races of one or both bearings, and a significant voltage exists between the shaft ends or between the shaft and ground, an electric discharge (characterized by an high current density) occurs leading to severe damages [due to electric discharge machining (EDM)] in the balls and races surfaces (fluting, pitting). The described effects can be worse if voltage transients occur in the voltage

waveforms applied to the motor. These currents can, therefore, significantly decrease the lubricant and bearing lifetime.

D. Harmonics and Electromagnetic Interference

Current harmonics in the VSD input stage can also feed back into the power bus grid, and can disrupt other types of equipment in the premises. Harmonics can also cause supplementary losses and temperature rise of all the elements in the supply system (rotating machines, transformers, cables, capacitors banks). In the case of three-phase diode rectifiers being used in the input stage, the negative sequence harmonics (5th and 11th) are particularly worrying in terms of increase of the losses. Harmonics can also produce 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 [1].

E. Mitigation Strategies

Manufacturers should specify the maximum transient voltage and dV/dt , which the motor windings can withstand. To mitigate the described undesirable problems, common-mode and high-frequency filters and special shielded cables [27] (acting as a distributed filter) can be used between the VSD and the motor, keeping the link between as short as possible [1]. Common-mode voltage cancellation electronic devices connected between the VSD and the motor can be also a good solution [16]. Also, proper grounding and shielding should be made. Several alterations can be made in the motor to increase its reliability. For example, use of magnetic wire with reinforced insulation, use of impregnation techniques that minimize the air cavities in the insulation system, use of insulated bearings in both sides (e.g., with external insulation coating or ceramic balls [20]), connection of the shaft to the ground using a contact brush and install an electrostatic shield in the stator slot openings connected to the ground [11], [14], [15].

Some manufacturers developed low voltage VSDs (up to 800 kW for 400 V) with three-level voltage control method technology (see Fig. 15) [31]. This technology reduces the stress for the motor winding insulations and the bearing currents which helps in applications with long motor cables and significantly increases the motor lifetime. The likely applications of this technology are high speed elevators, positioning, synchronization, centrifuges, press and cutting machines, paper production, printing machines, simple spindle drives, and all applications where long motor cables are required [31].

Manufacturers are now producing integrated motor/VSD units as a single package (up to 15 kW). This product overcomes many of the barriers associated with the application of VSDs, e.g., motor properly matched to the VSD, reduced overvoltage on the motor due to the short length of the connection and minimization of the radiated radio-frequency interference [1].

IV. RIDE-THROUGH CAPABILITY OF VSDS

VSDs are often susceptible to voltage disturbances such as sags, swells, transients, and momentary interruptions (outages). Depending on the application, and the characteristics of the disturbance, the VSD-controlled process may be momentarily

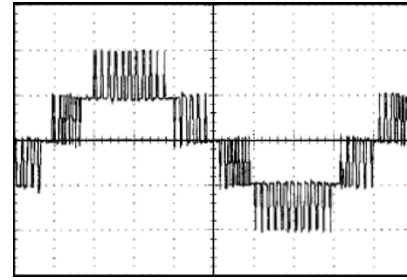


Fig. 15. Output line-to-line voltage of a VSI with PWM and three-level control method [32], [33].

interrupted or permanently tripped out. This can result in costly down time [6], [12]. The most demanding processes in the modern digital economy need electrical energy with very high reliability (nine “9s”) in order to provide peak performance. Between 1993–1999, the Electrical Power Research Institute (EPRI) carried out a study in the U.S. in order to characterize the power quality on low voltage distribution networks. This study concluded that 92% of disturbances in power quality were voltage sags with amplitude drops up to 50% and duration below 0.5 s. Fig. 16 shows the typical distribution of sags and micro-interruptions under 0.5 s.

The situation in Western Europe is very similar to the one observed in the U.S. In industry and commercial sectors more than 90% of the disturbances are under 1 s. Therefore, a ride-through capability with a duration of 1 s would decrease dramatically the down time of VSD-based equipment [6].

In continuous process systems such as metal casters, paper machines, winders, extruders, etc., any interruption can halt the entire manufacturing flow, with very costly implications. Industries with critical production processes have reported losses ranging from \$10 000 to \$10 000 000 per disruption event.

VSD ride-through alternatives include the use of the load inertia, topology modifications, and energy storage technologies [6], [12].

In the load inertia technique, the VSD software control must be modified such that when a power disturbance causes the dc-bus voltage to fall below a specified value the inverter will adjust to operate at a frequency slightly below the motor frequency, causing the motor to act like a generator, maintaining the dc bus at a specified level. There are no delays to start accelerating the motor as soon as the ac power line returns to normal, assuming the load can handle it. Commercial drives are available on the market with this feature with 2 s of ride-through capability for sags down to 80% of the nominal voltage [6], [12].

The more advanced hardware modifications include boost converter ride-through capability and the active rectifier VSD front-end.

The boost converter ride-through is used to maintain the dc-bus voltage during a voltage sags and can be integrated between the rectifier and the dc-link capacitors. This technology can provide ride-through for sags up to 50%. In the case of an outage, the boost converter will not be able to provide ride-through, and the drive will trip [6], [12].

A VSD with active rectifier VSD front has an active PWM rectifier. By this method, ride-through for sags up to 10% can be provided at full load. By derating the rectifier by a factor of 1.5,

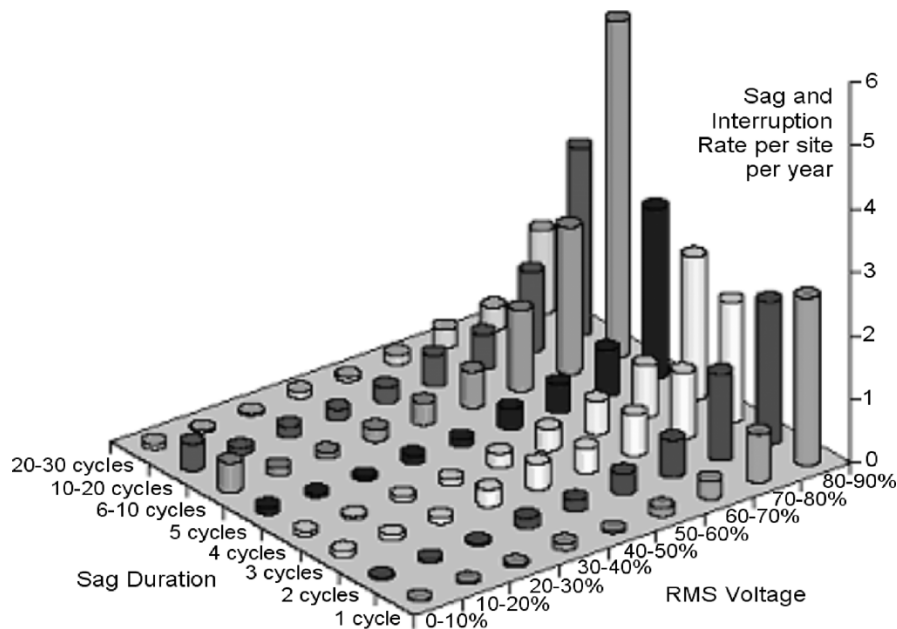


Fig. 16. Distribution of sag and micro-interruption in low-voltage networks in U.S. [29].

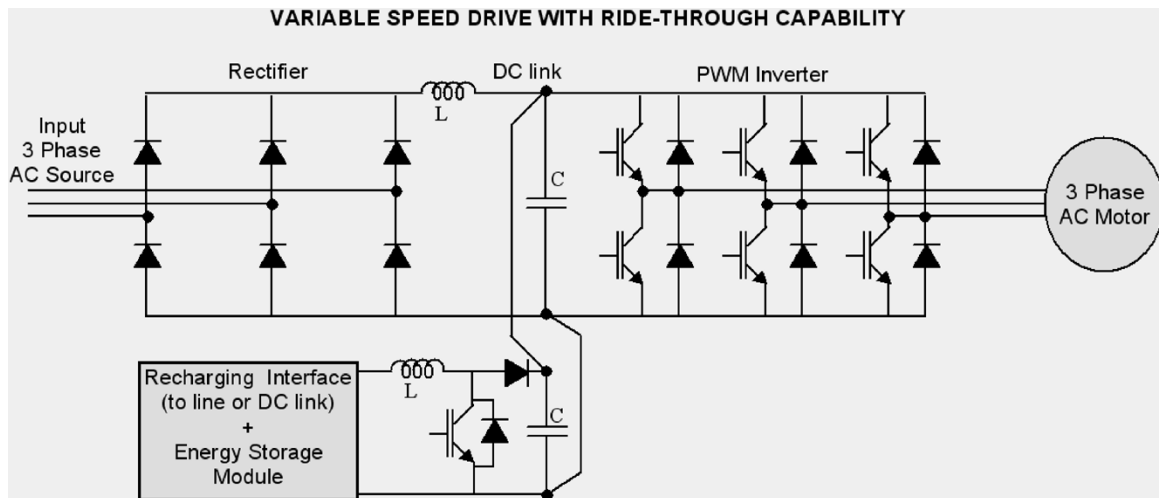


Fig. 17. Use of energy storage as an add-on module for VSD with ride-through capability [6], [12].

the ride-through capability can be extended to sags of up to 40% at full load. This technology has several advantages, namely, the VSD unity power factor, low distortion (compliance to IEEE 519 distortion limits), and regenerative braking capability [6]. The main disadvantages are the high cost and larger size of the VSD package.

Energy storage technologies which can provide full power VSD ride-through capability include battery backup systems, capacitors, supercapacitors, motor-generator sets, flywheels, superconducting magnetic energy storage (SMES), and fuel cells.

By adding conventional capacitors to the dc bus, additional energy needed for full-power ride-through during a voltage sag can be provided to the motor. This technique is simple and rugged. However, it can only provide limited ride-through for minor disturbances, the cost is relatively high, and a large cabinet space is needed.

Higher performance can be achieved by including in the circuit layout a booster supplied by an energy storage module (Fig. 17). The energy storage capacity is a function of the duration and of the voltage decrease of the maximum disturbance for which it is intended to provide ride-through capabilities.

For critical processes requiring full power (full speed and torque) ride-through of up to 5 s, supercapacitors (or ultracapacitors) are the most cost-effective approach for VSDs up to 100 kVA, whereas flywheel technologies are the most suitable for VSDs between 100 kVA–10 MVA [6], [12]. Supercapacitors have experienced a significant increase in energy density and a decrease in price in the last decade. A VSD can be designed with integrated supercapacitors, or an add-on module. The main advantages of supercapacitors are the ride-through capabilities for deep sags and full outages, long life cycle, fast recharge rates, easy state and charge monitoring, and minimal maintenance needs. The main disadvantages are the additional

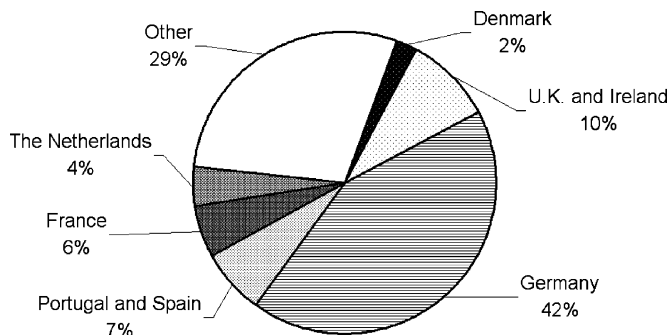


Fig. 18. Distribution of the VSD market in terms of the total number of units sold per each country [1].

hardware and space requirements, though much less than with standard capacitors.

V. MARKET CHARACTERIZATION

The presented characterization of the VSDs current market in the EU includes the number of units sold in each country, the average retail prices and total cost of VSDs per unit and kilowatt and per power range. The information was collected, through several sources (questionnaires, trade associations, large manufacturers, etc.) in each country of the study (Denmark, U.K. and Ireland, France, Germany and Austria, The Netherlands, Portugal, and Spain). These 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 studies [1]–[3] and EU statistics [4]. The base year for the market characterization was 2002. Fig. 18 shows the disaggregation of the VSDs market by country in the EU. Fig. 19 shows the number of VSD units sold in the EU per power range. This figure shows that the VSDs market, in 2002, was dominated by low-power drives in the range of 0.75–4 kW, representing about 76% of the total units sold in the considered countries. The number of VSD units sold in the EU in 2002 was 1.8 million units, representing a total value of over 1 billion € (Euro³).

Induction motors are by far the dominant type of motor used with VSDs, but other more advanced motor designs are entering the market (e.g., brushless dc and switched reluctance motors), particularly in the low-power range.

As can be seen in Fig. 20, the prices per kilowatt W decrease with the increase of the power, but more sharply in the low- to medium-power ranges. In fact, the prices per kilowatt decrease until the 30–70 kW range, then they stabilize in the higher power ranges. Fig. 20 also shows the total cost (unit cost plus installation) per kilowatt. This curve is influenced by the fact that the higher the power, the lower the installation costs per kilowatt.

VI. SAVINGS POTENTIAL

The estimated motor electricity consumption in the EU by 2015 is 721 TWh in industry and 224 TWh in the tertiary/commercial 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. In the economic saving potential the cost-effectiveness constraints are considered. Only the power ranges with a cost of saved electricity (CSE) lower than the average price of kilowatt-hours in the sector of application are considered. In the technical potential no economic restrictions are considered. Table I summarizes the technical and economic savings potential in the industrial and in the tertiary sector with the application of VSDs.

The identified economic electricity savings potential (assuming VSD constant prices) with the application of VSDs, by 2015, would translate into 19 Mton CO₂ savings, contributing to the goal of reducing the greenhouse gas emissions in the EU. Table I also shows the technical and economic potential CO₂ and Euro savings in industry and tertiary sector, with the application of VSDs, by 2015.

VII. ACTIONS TO PROMOTE VSDS

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. 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, original equipment manufactureres (OEMs), and installers. For successful dissemination of VSDs these parties will become more crucial. They will have to play an important role in actions to promote VSDs. Though VSDs face strong growth, the general impression is that applications are driven mainly by process-related considerations (extra throughput, process control advantages, quality enhancements, 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, low visibility of benefits of VSDs in most energy-driven applications, and the market is dominated by lowest first cost decisions in competitive bidding procedures. The difference in market maturity between process-driven and energy-driven applications clearly indicates that the most barriers are not technology related [1].

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 the core business. Pragmatic or conservative users usually prefer: 1) standard (off-the-shelf) solutions; 2) to be acquired and used without extra risks or effort; 3) not too costly—if extra costs are involved, the extra benefits should be evident, clearly visible and competitive with core business investments; and 4) integrated solutions by familiar distribution channels, with preferably one single responsible supplier [1].

In short, more standardized and integrated VSD solutions are needed. For some applications increasingly standard off-the-shelf systems become available. Examples are

³1 € (Euro) = \$1.17 U.S., 6 October 2003.

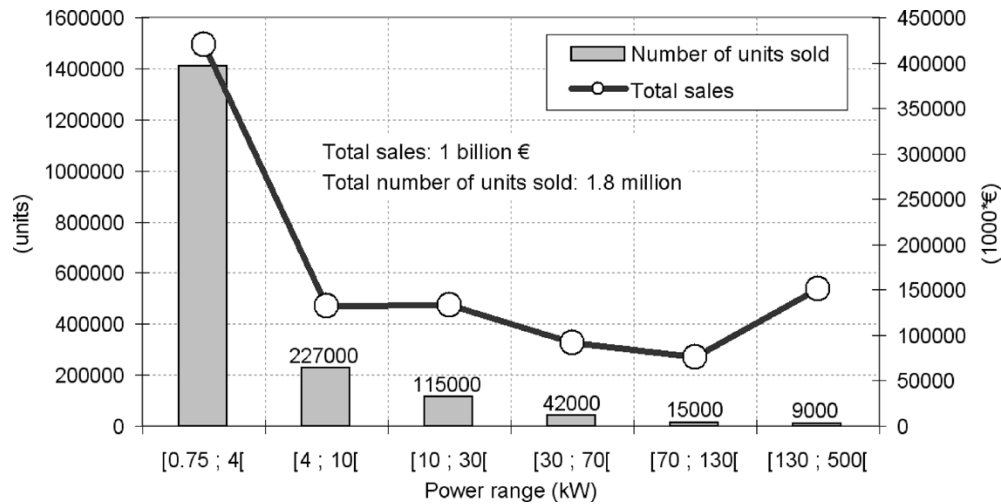


Fig. 19. Number of units sold in the EU and sales value per power range, in 2002.

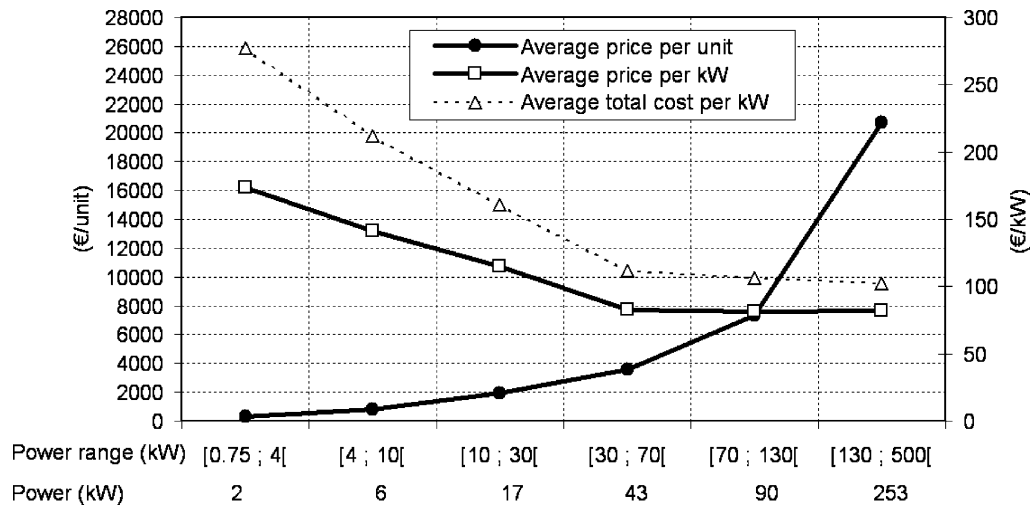


Fig. 20. Average unit costs and average per kilowatt costs, for the different power ranges in the EU.

TABLE I
ESTIMATED SAVINGS POTENTIAL BY 2015 [1]

	Technical potential	Economical potential	
		Constant prices	5% per year price decrease
Total Industry (TWh per year)	62	39	43
Total Tertiary (TWh per year)	22	8	11
Total (TWh per year)	84	47	54
⁶ Savings (Mton CO ₂ per year)	33	19	22
⁷ Savings (10 ⁶ € year)	5600	2050	3500

¹ Considering average CO₂ emission of 0.4 kg CO₂/kWh generated.² Considering average electricity prices of 0.05 and 0.1 Euro/kWh in industry and in the tertiary sector, respectively.

small VSD–pump and small VSD–motor combinations and medium-size compressed air systems with integrated speed controls. For other systems alternative methods have to be facilitated to achieve more standardised, transparent, and comparable integrated VSD solutions. Most 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 [1]. Actions are also needed to increase the awareness of economic benefits and process improvements by end-users, associated with the use of efficient VSD systems.

VIII. CONCLUSION

VSDs are a very relevant growing market, although only 25% of new motors are equipped with VSDs. They allow one to control with precision the speed and torque of induction motors, increasing its application spectrum. When integrated in variable-speed motor systems, they have significant economical and technical advantages. Huge energy savings, and the associated reduction in environmental emissions, are possible through the massive application of VSDs in a wide variety of loads in the different sectors of the economy.

However, there are several barriers, both technical and non-technical, which prevent a larger scale adoption of VSDs. Because of lack of knowledge of the VSDs economical and tech-

nical advantages in industrial and commercial sectors, actions to promote awareness of those advantages should be implemented.

VSDs may introduce problems related to the motor efficiency and reliability, power quality, and EMI. For the majority of these problems, solutions are now available and new improved ones are under investigation, which can avoid or mitigate these problems.

With proper installation and proper motor construction, VSDs can be a very cost-effective technology that can lead to better process control, less wear in the mechanical equipment, less acoustical noise, and significant energy savings.

More recently, with recent hardware advances, VSDs can also integrate the ride-through capability to overcome the majority of power disturbances, which is a valuable feature in continuous process systems such as metal casters, paper machines, winders, extruders, etc., avoiding very costly down time

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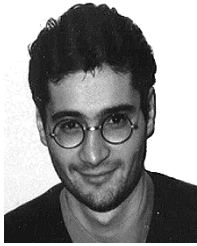


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