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Applications of variable speed drive (VSD) in electrical motors energy savings

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ABSTRACT

Most motors are designed to operate at a constant speed and provide a constant output; however, modern technology requires different speeds in many applications where electric motors are used. A variable speed drive (VSD) is a device that regulates the speed and rotational force, or output torque of mechanical equipment. Effects of applying VSDs are in both productivity improvements and energy savings in pumps, fans, compressors and other equipment. Variable speed drive technology and the importance of controlling the speed of existing motors have fascinated many attentions in the last years with the advent of new power devices and magnetic materials. This paper is a comprehensive review on applications of VSD in electrical motors energy savings. The aim is to identify energy saving opportunities and incorporated costs of applying variable speed drives to the existing applications of electrical motors. Subsequently, economic analysis, payback period and the effect of current and voltage harmonics generated by VSDs are presented. Authors are hopeful to provide useful information for future variable speed drive applications like fans, pumps, chillers, ventilators and heaters.

Contents

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Nomenclature

VSD	variable speed drive
DC	direct current
AC	alternating current
GHG	greenhouse gas
ASD	adjustable speed drive
Hp	horsepower
PWM	pulse width modulation
IGBT	insulated gate bipolar transistor
HVAC	heating, ventilating, and air conditioning
MOV	motor operating value
EMS	energy management control system

1. Introduction

In the past years, various control methods has been employed to enhance the flexibility and consistency of manufacturing processes such as controlling the speed of the equipment, changing gear ratios or pulleys, and using hydraulic drives [1]. In many cases, motors are controlled by means of a valve that regulates the flow of fuel or a vane that controls the airflow while the speed of the motor itself remains unchanged. Conventional methods, such as controlling motor by switching it on and off in two-speed motors are inefficient ways that wastes a huge amount of energy. One of the main reasons that make motor drives popular is that they save energy by changing the speed of an electrical motor and control the power that is fed into the machine. Furthermore, using motor drives reduce the amounts of carbon dioxide emissions by millions tons per year [2].

A variable speed drive (VSD) is a device that regulates the speed and rotational force, or output torque of mechanical equipment. Some examples of mechanical equipment that incorporate with VSD technology are pumps, fans, compressors and conveyors. There are many types of equipment currently in use that needs to be retrofitted because they are running inefficiently; however, manufactures are introducing VSDs technology to save the losses of mechanical equipment [3]. VSD increases efficiency by allowing motors to be operated at the ideal speed for every load condition. In many applications VSDs reduce motor electricity consumption by 30–60%. The potential for electrical motor energy savings is enormous since motor systems use more than 60% of the electrical power consumed by industry [2,4]. There are millions of motors in industries and offices around the world employed in a wide variety of applications such as motors, pumps, conveyors, ski lifts, saw mills and hospital ventilation systems. They can effectively improve the process efficiency particularly where flow control is involved.

Currently, VSD is the most effective controller and energy saver for mechanical machines in industries. Modern VSDs are affordable, reliable, flexible, and offer significant electrical energy savings through greatly reduced electric bills.

Almost all the industrial processes require adjustment for normal operation and optimum performance. Such adjustments are usually accomplished with a VSD. They are an important part of automation and help to optimize the process while reducing investment costs, energy consumption, energy cost and greenhouse gas (GHG) emissions [5].

Most motors are designed to operate at a constant speed and provide a constant output. The benefits of applying VSDs are in both productivity improvements and energy savings in pumps, fans, compressors and other equipment [6–12]. VSDs installation increases energy efficiency, saves energy consumption, improve power factor and process precision, soft start up and over speed capability. They also eliminate throttling mechanisms and frictional losses affiliated with mechanical or electromechanical adjustable speed technologies and expensive energy-wasting. Other benefits of VSDs include prolonging the life of the equipment, by adjusting motor speed to meet load requirements. Generally, energy savings translate into cost savings and reduction in GHG emissions for a given level of production [10].

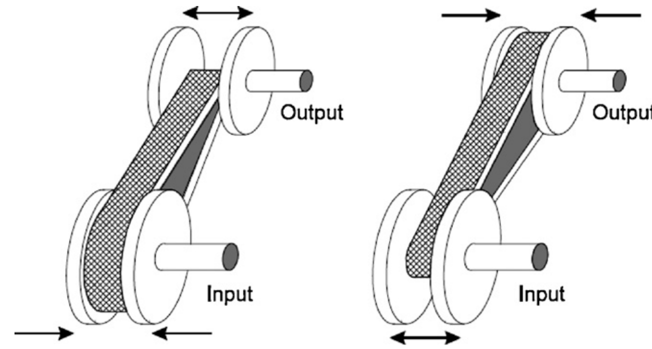

Fig. 1. Adjustable sheave belt-type mechanical VSD [14].

2. Methods of speed control

VSDs and VFDs are electronic motor speed controllers that allow the speed of any electric motor to be varied. Over the last decade, there have been substantial technological advancements in the field of variable speed drives. During this time, the market was constantly driven by the desire to reduce the amount of power squandered by motors, centrifugal pumps and fans [3]. There are several methods used in industrial sector that can be classified into three main categories: electrical, hydraulic, and mechanical drives.

2.1. Mechanical VSDs

Mechanical VSDs are still favored by many engineers for some applications due to simplicity and low cost. Mechanical variable speed control has a number of methods including belt drives, idler wheel drives, chain drive and gear box [6]. All of these methods exhibit similar characteristics. Motor operates at constant speed and the coupling ratio alters the speed of the driven load. Increasing the torque load on the output of the coupling device will increase the torque load on the motor [13,14].

Mechanical variable speed control usually uses a belt drive which is controlled by moving conical pulleys manually or with positioning motors as shown in Fig. 1 [14,15].

2.2. Hydraulic VSDs

Hydraulic coupling working principles are based on turbines. Changing the volume of oil in the coupling will change the speed difference between the driving and driven shafts. Volume of the oil is controlled with pumps and valves. There are two types of hydraulic VSDs including hydraulic pump and motor, and fluid coupling [13,15].

2.3. Electrical VSDs

Typical electric VSD systems are consist of three basic components: the electric motor, the power converter, and the control system. The electric motor is connected directly or indirectly (through gears) to the load. The power converter controls the power flow from an AC supply (often via a supply transformer), to the motor by appropriate control of power semiconductor switches

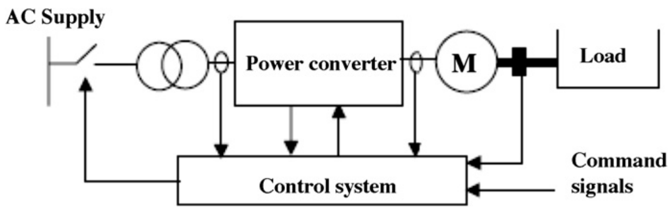

Fig. 2. Electrical VSD basic components [5]. Variable speed drives (VSDs).

(part of the power converter). Fig. 2 is the block diagram of electrical VSDs' basic components.

3. Variable speed drives

Nowadays, technology requires different speeds in many applications where electric motors are used. Electric motors using traditional control methods have mainly two states; stop and operate at maximum speed. In most motor installation, motors are sized to provide the maximum power output required. If the rotational speed is constant at its maximum value to provide the maximum designed load, the power input to the motor remains constant at the maximum value. However, if the load decreases, significant energy savings can be achieved when the rotational speed of the motor is decreased to match with the load requirement [16]. Nevertheless, the majority of motors operate only at 100% speed for short periods of time. This often results in many systems operating inefficiently during long periods of time. Consequently, there are significant energy losses during the operation time. System loss reduction can be achievable by installing VSD systems to match the speed of the motor with the related load. VSD has become very popular because of their advantages over traditional control methods. By using VSD, the speed of a motor or generator can be controlled and adjusted to any desired speed. Besides adjusting the speed of an electric motor, VSD can also keep an electric motor speed at a constant level where the load is variable [17]. There are several terms used to describe devices with capability of controlling the speed [8]:

1. Variable frequency drive (VFD) that uses power electronic components to control the motor speed by changing the frequency of input power of the motor.
2. VSD that control the speed of either the motor or the equipment driven by the motor (fan, pump, compressor, etc.). This device can be electrical or mechanical.
3. Adjustable speed drives (ASD) are devices that use both mechanical and electrical means to control the motor speed.

There are different reasons for using VSDs. Some applications, such as paper making machines, cannot run without them while others, such as centrifugal pumps, can benefit from energy savings. In general, VSDs are used to match the speed or torque of a drive to the process requirements as well as save energy and improve efficiency [14].

VSDs and VFDs are electronic devices, which match motor speed to the required speed of the application [18]. The output voltage and frequency are determined by input power of the motor. Most motors can benefit from VSD to provide different frequency outputs; whether the speed of the drive is set manually by an operator or automatically by a control system.

VSDs are an efficient and economical retrofit option that should be considered for all variable speed systems. VSDs allow the motor speed to vary depending on actual operating conditions, rather than operating continuously at full speed. Varying speed allows it to match changing load requirements more closely, and because the power draw is proportional to the cube of its speed, reducing speed can save a lot of energy. For example, reducing a fan's speed by 20% can reduce its energy requirements by nearly 50%. Installing a VSD on the fan motor allows the fan to automatically match this reduced capacity, slowing down in response to reduced demand, thereby saving energy [7].

Table 1
Potential savings from variable speed drives for fans and pumps [11,19].

Average percent speed reduction	Potential energy savings	Annual energy cost savings for a 5 Hp motor	Annual energy cost savings for a 10 Hp motor
10%	22%	USD272	USD543
20%	44%	USD543	USD1087
30%	61%	USD753	USD1506
40%	73%	USD901	USD1806
50%	83%	USD1025	USD2050
60%	89%	USD1099	USD2198

Components of VSDs.

The needs for speed and torque control are usually fairly obvious. Modern electrical VSDs can be used to accurately maintain the speed of a driven machine within ±0.1%, independent of load, compared to the speed regulation possible with a conventional fixed speed squirrel cage induction motor, where the speed can vary by as much as 3% from no load to full load.

Most adjustable frequency drives today use pulse width modulation (PWM) to create a variable output voltage, current and frequency. Some examples of potential VSD savings are provided in Table 1.

4. Components of VSDs

4.1. Rectifier

Rectifiers are used to convert alternative current (AC) to direct current (DC) [20]. There are two main topologies for medium power rectifier units: the diode and the IGBT rectifiers. The diode rectifier (also known as the six-pulse uncontrolled rectifier) is the most commonly used AC-to-DC power converter to produce a fixed DC voltage. The power circuit of the rectifier consists of six power diodes in a three-phase bridge configuration. This means the DC link voltage is fully depending on the AC supply voltage. Diode rectifiers are non-linear loads and a non-sinusoidal current is taken from the feeding line [10].

4.2. Regulator

Typically a regulator controls the VSD, enables exchange of data between VSD and peripherals, gathers and reports fault messages and carries out protective functions of the VSD [10,21].

4.3. Inverter

Inverters generate an AC by sequentially switching a DC in alternate directions through the load [22]. Nowadays, all inverters are equipped with IGBT components. The structure of IGBT results in a lack of parasitic body diode. Therefore, the IGBT required a free-wheeling diode often placed across it. PWM control is widely used for control of the IGBT switches. PWM control consists in rapidly switching on and off the IGBT switches in such a way that pulses with variable width constitute a variable waveform. The common circuit for variable speed drives is shown in Fig. 3 [10].

5. VSDs' applications

VSDs provide continuous control by matching motor speed to the specific demands of work being performed. They are an

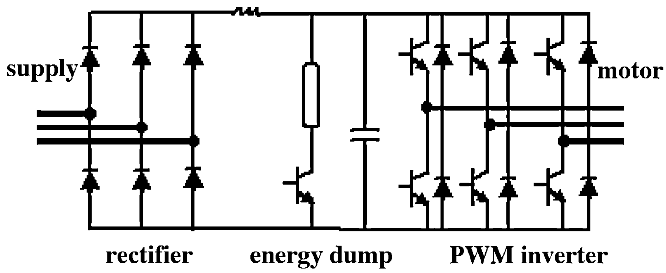

Fig. 3. Rectifier–inverter AC variable speed drive circuit [10].

excellent choice for adjustable-speed drive users because they allow operators to fine-tune processes while reducing costs for energy and equipment maintenance [21,23,24].

5.1. Electrical motors

Electrical motors convert electrical energy into mechanical energy. They play an important role as electromechanical energy is used in various manufacturing operations such as transportation, material handling and most production processes. The ease of controlling electrical motors provides a significant opportunity in meeting user demands that include the need for flexibility and precision, which is often the result of advances in technology within industry. Motors use approximately one third of the electrical energy consumption in industrial sector. They have dominated fixed speed applications for many years but with the help of VSDs they are also establishing themselves in controlled speed applications [7]. The need for energy conservation in order to save the environment is also a key driver for improving efficiency when employing VSDs [13]. Improvement in motor efficiency offers major energy saving, reduces GHG emissions and decreases the payback time [9].

Electric motors' efficiency is 90% and even more when running at rated loads; however, they are not efficient at load-following or part load operating. Conventional electric motors typically use 60% to 80% of rated input energy; even when they run at less than 50% load. It is very important to select an electric motor with suitable power in order to work efficiently. In general, motors are chosen in high capacities to meet extra load demands which lead to inefficient operation of motors at low load. Normally, motors operate more efficiently when they are performing at loads over 75% of rated load. In addition, power factor of motors decrease when operating at loads lower than 50% of rated load. These kinds of motors waste a huge amount of energy because they have been chosen for large power demands. They should be replaced with new suitable capacity motors. Hence energy saving motors should be preferred when purchasing new motors [25]. Electric motors are generally divided into two categories DC and AC motors.

5.1.1. DC motors

DC motors extensively use VSDs and position control systems where good dynamic response and steady state performance are required [5]. DC motors are commonly used in industrial applications because the speed–torque relationship can be varied to almost any useful form for both DC motor and regeneration applications. DC motors are often applied where momentarily deliver of three or more times of rated torque is required. DC motors feature a speed, which can be controlled smoothly down to zero, immediately followed by acceleration in the opposite direction without power circuit switching. They respond quickly to changes in control signals due to the DC motor's high ratio of torque to inertia. The speed of DC motor can simply be set by applying the proper voltage. Speed variation from no-load to full load (rated) can be quite small. It depends on the armature resistance [20,26].

In all applications of DC motors a mechanical switch or commutator is employed to turn the terminal current, which is constant or DC into alternating current in the armature of the machine. DC motors have usually been applied in two broad types of application. One of these categories is when the power source is DC such as automobile motors. These motors drive fans for engine cooling and passenger compartment ventilation to the engine starter motor. Another reason for using DC motors is that torque-speed characteristic is easier to tailor than all of the AC motor categories. Therefore, most traction and servo motors are using DC machines. For example, motors for driving rail vehicles are exclusively DC machines [27].

DC motors are widely used in various applications due to simplicity of construction and ease of controlling motor performance. Nowadays, although the AC machines are the preferred choice, the DC machines are still valued for their wide speed and torque range as well as high overall efficiency [13]. There are several advantages for using DC motors including simplicity of design, high starting torque, near-linear performance, ease of controlling speed and low cost drives. On the other hand DC motors are bulky and expensive and require high maintenance. They are not suitable to be used in explosive or very clean environment or high-speed operations due to commutator and brushes [26,28].

5.1.2. AC motors

AC motors work by setting up a magnetic field pattern that rotates with respect to the stator and then employing electromagnetic forces to entrain the rotor in the rotating magnetic field pattern [27]. AC motors are simple, low cost, reliable and easily replaceable with variety of mounting styles and many different environmental enclosures. Nonetheless, they need expensive speed control, are unable to operate at low speeds, perform poor positioning control and limited in range of applications [28].

5.2. Fans

An on-off switch is a simple method to control the amount of time that fans are required to operate by continuously turn them on and off; however, they are not common ways to control a process since continues on and off switching decrease the motor's lifetime considerably. Fans are the main part of a building's ventilation system. Varying a fan's speed allows it to match changing load requirements more closely, and because fan power draw is proportional to the cube of its speed, reducing speed can save a lot of energy [7].

5.3. Pumping systems

Pumping systems account for nearly 20% of the world's energy consumption by electric motors and 25–50% of the total electrical energy usage in industrial facilities. Significant opportunities exist to reduce pumping system energy consumption through smart design, retrofitting, and operating practices. In particular, many pumping applications with variable-duty requirements offer great potential for energy savings. The savings often go well beyond energy, and may include improved performance, reliability, and reduced life cycle costs. Most existing systems require flow control of bypass lines, throttling valves, or pump speed adjustments as shown in Fig. 4. The most efficient way is pump speed control. When a pump's speed is reduced, less energy is imparted to the fluid and less energy needs to be throttled or bypassed. Speed can be controlled in a number of ways, with the most popular type of VSD [9]. There are many types of pump prime movers available such as diesel engines and steam turbines, but the majority of pumps are

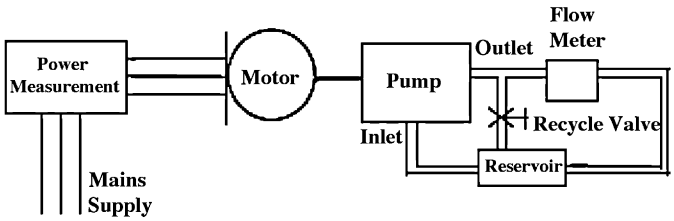

Fig. 4. Pump schematic with traditional control [7].

driven by electric motors [20]. The schematic of pump using VSDs is shown in Fig. 5.

Variable speed pumping has become more popular in recent years due to improvements in speed control technology for pumps and the reduction in the initial cost of such devices [2]. A centrifugal pump runs with AC induction motor which is a single speed device due to the fixed frequency of the applied power to the motor. VSD allows the frequency of the power to be controlled and the speed of the motor's shaft to be adjusted [29].

5.4. Heating, ventilating and air conditioning (HVAC) systems

Building ventilation systems are designed to operate at maximum load conditions; however, they operate at full load only for short periods of time which results in inefficient operation during long periods of time. Most inefficient operations in buildings are encountered in heating, ventilating and air-conditioning systems that are normally sized to meet peak load conditions, which are experienced only for short periods of day. The efficiency of such systems can be improved by varying the capacity to match actual load requirements. In variable torque applications, the power consumption (to drive the pumps or fans) is related to the cube of the speed. The most common method is to modulate the speed of the motors of pumps, fans and air conditioning systems to vary their capacity using VSDs [30].

The load in HVAC systems varies throughout the day and from day to day. Typical HVAC systems run at partial-load conditions during most of operation time. Therefore, methods of reducing the output level to matches with demands are required [31]. According to the study conducted by Nadel et al. [32], VSDs can save 15–40% of energy in HVAC application. Qureshi and Tassou [33] have reviewed the VSD in refrigeration application to reduce energy consumption.

VFDs are used to vary a pump and fan speed in HVAC systems in buildings as it is shown in Fig. 6. In these applications, speed control is used to regulate the flow of water or air because speed adjustment is an energy efficient method to control the flow. Performance of the VFDs has developed due to rapid improvements in semiconductor technology such as improvement in electrical characteristics, ability to handle higher power levels, easy programming of desired control, steadily response, increasing reliability, ruggedness and decreasing size of units [34].

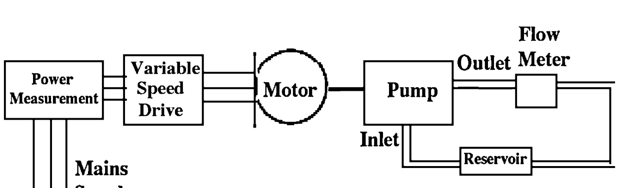

Fig. 5. Pump schematic with variable speed drive [7].

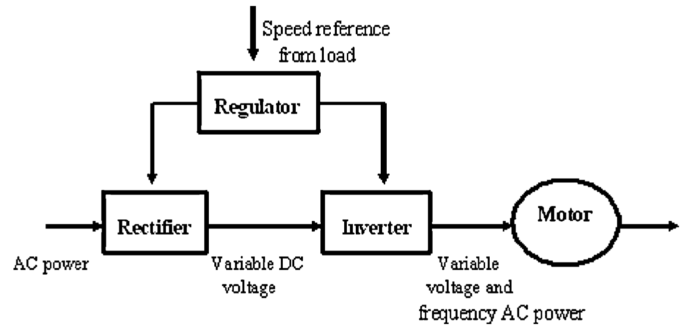

Fig. 6. Components of a variable speed drives [11].

5.5. Air compressor system

Air compressor is the mechanical device that takes in ambient air and increases its pressure. The compressed air system utilizes a huge amount of electrical energy. Fig. 7 is a graph that shows the running cost of a compressed air system is far higher than the cost of a compressor itself [35]. A VSD air compressor is an air compressor that takes advantage of VSD technology. This type of compressor uses a special drive to control the speed of the system, which in turn saves energy compared to a fixed speed system. VSD is the most effective way to improve the compressors and compressed air systems. They provide energy savings of more than 30% in compressor applications [36,37]. The benefits of using VSD technology in compressors are reducing power cost, decreasing power surges (from starting AC motors), and delivering more constant pressure. However, the down side of this technology is the heavy expense and sensitivity of drives to heat and moisture [38]. For many facilities this is equivalent to thousands, or even hundreds of thousands of expenditures. A properly managed compressed air system can save energy, reduce maintenance, decrease downtime, increase production output, and improve product quality.

6. Harmonics

Current and voltage harmonics in the AC supply are created by VSD (as a nonlinear load) connected on the power distribution system. Harmonics pollute the electric plant, which cause problems if harmonic level increases beyond a certain level. Harmonic currents provide useless power [39,40]. The effects of harmonics are

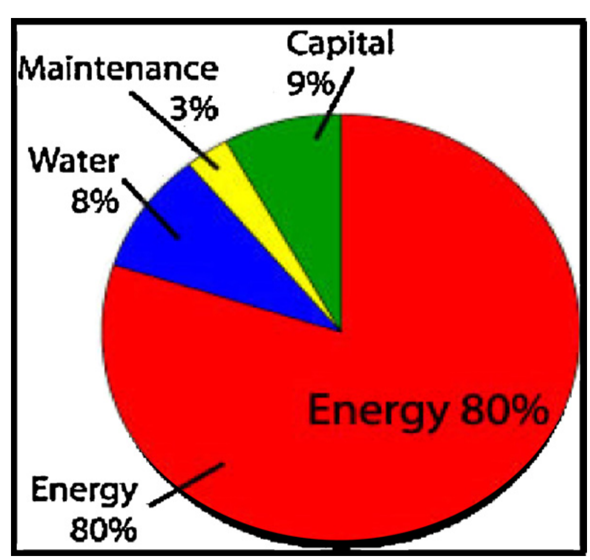

Fig. 7. Cost components in a typical compressed air system [35].

overheating of transformers, cables, motors, generators, and capacitors [8,11,41,42]. Large harmonics lead to increase factory downtime and operating costs. There are significant changes in waveform distortion at different speeds and torque levels in the operation of VSDs. Current waveform distortion is injected back into the power supply system creating several problems such as increase in the electrical losses on the network side of the transformer, decrease efficiency of motor, nuisance tripping of circuit breakers, malfunction or failure of electronic circuits, erroneous reading of metering devices, de-rating of fuses as a result of additional heat generated, and decrease life expectancy of equipment [24,39].

Current and the voltage harmonic distortion have devastating effects on a power distribution system and its connected equipment. Present methods to reduce harmonics are line reactors, multi pulsed systems, tuned or broadband passive filters, and active filters. They are often only moderately effective, too costly, and somewhat unreliable. The harmonic filter is an innovation in passive harmonic mitigation. It is an easy to apply harmonic filter capable of reducing VSD harmonics with none of the inherent problems of conventional filters [43]. A harmonic filter has various functions such as reducing neutral currents, transformer loading, peak phase or average phase current, system losses and distribution transformers while increasing system protection and capacity [39].

7. Installation costs of VSDs

Installation costs of VSDs are relatively expensive. The cost ranges between $3000 for a 5 Hp motor and $45,000 for a custom-engine 300 Hp motor. The costs increase drastically for larger versions. VSD installation time takes 10–70 labor h, depending on system size and complexity; however, payback period ranges from few months to less than 3 years for 25–250 Hp models. Each VSD is capable to drive more than one motor; hence some costs can be consolidated. In addition, savings from reduced maintenance and longer equipment life contribute significantly to achieving a rapid payback and long-term savings. Many electric utilities offer financial incentives to reduce the installation costs of VSD [44]. Table 2 shows the installation cost, cost savings and payback period of VSDs [24,45].

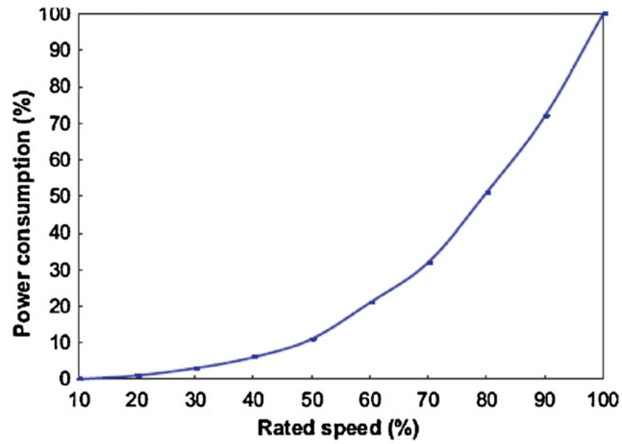

Fig. 8. Relationship between motor power reduction and rated speed [35].

The cost of an adjustable speed motor varies depending on the particular features and durability. Per-horsepower cost decreases significantly with size, from an average of about $640 per horsepower for a 20 Hp application to about $150/ Hp for a 20,000 Hp application [46]. As an example a 10 Hp, 460 V drive with line reactor costs about $1300, while installation time, materials and start-up costs over $500 [47].

8. Energy savings through VSDs

Employing VSD is the best way to reduce energy consumption of electrical motors. Energy consumption of electric motors constitute up to 75% of total plant's energy consumption. About two-thirds of the motors in industry are applied in fans and pumps which do not need constant motor speeds [11]. A small change in motor speed can cause a significant change in energy consumption as shown in Fig. 8. Using VSD systems provide the opportunity to save about 15–40% of the energy and extend equipment lifetime by allowing gentle start-up and shutdown [35].

Energy savings of motors when installing VSDs can be calculated from either Eq. (1) or (2) [48,49]:

$$\mathrm{AES_{VSD}} = n \times P \times 0.746 \times H_{\text{avg-usage}} \times S_{\text{SR}} \tag{1}$$

Table 2
Installation cost, cost savings and payback period of VSDs [24,45].

	Mfg. ASD estimated cost	200 Hp constant speed	Additional costs of ASD purchase
6-Pulse 200-Hp drive	$31,000	$20,000	$11,000
12-Pulse 200-Hp drive	$46,000	$20,000	$26,000
6-Pulse 200-Hp drive	$51,000	$20,000	$31,000
Plus rebate per installed ASD	−$7200	$0	$7200
ASD post installation annual savings			
Use motor operating value (MOV) vs. check valve	−$2.500	$5000	$2500
Additional maintenance cost	$0	$2000	$2000
Man-hours to adjust limit switch	$0	$3600	$2000
Energy cost of maintaining flow set-point ($0.45 or $0.35 × 2000 cubic of water × 365 days)	$33,215	$42,705	$9490
Total of annual energy savings			$17,590

Actual costs for installing an ASD	6-Pulse	12-Pulse	18-Pulse
Estimated costs of varying pulse ASDs	$31,000	$46,000	$51,000
Less: rebate	−$7200	−$7200	−$7200
Less: energy savings	−$17,590	−$17,590	−$17,590
Net costs for installing an ASDs	$6210	$21,210	$26,210

Estimated time to recoup remaining initial costs		Number of years
6-Pulse 200-Hp drive-ASD	$6210/$17,590	−0.4
12-Pulse 200-Hp drive-ASD	$21,210/$17,590	−1.2
6-Pulse 200-Hp drive-ASD	$26,210/$17,590	−1.5

Table 3
Incremental costs of VSDs [35,53].

Motor power (Hp)	Increment cost (US$)
3	2216
5	2461
7.5	3376
10	3349
15	4176
20	5316
25	6123
30	6853

$$AES_{VSD} = (1 - S_{SR}^3) \times 100\% \quad (2)$$

The annual cost savings is related to annual energy savings and price of the fuel. The annual bill savings of motor when using VSDs can be calculated using [50–52]:

$$\text{Annual Bill Savings } (ABS_{VSD}) = ABS_{VSD} \times C \quad (3)$$

The payback period is the function of the incremental cost of VSDs divided by the annual bill savings of VSDs in a particular year. Incremental prices of VSDs are shown in Table 3 [35]. Thus Payback period can be expressed mathematically from the following Equation:

$$\text{Payback period (years)} = \frac{\text{Incremental cost } (IC_{VSD})}{\text{Annual bill savings } (ABD_{VSD})} \quad (4)$$

It is estimated that replacing conventional motors with adjustable speed motors in appropriate applications would result in saving 41% of the energy used in industrial motors. Power consumption actually drops far more than the drop in motor speed, so the savings can accumulate quickly. For example a 10% reduction in shaft speed results in a 27% decrease in power consumption [11].

9. Quantification of energy savings through VSDs

Study on quantification of energy savings of VSDs has been conducted on San Francisco refinery. VFD installation on the primary feed and product transfer pumps saved energy by reducing losses through flow control valves. The result was 500,000 kWh/month energy saving, and the cost reduction shared by the refinery and contractor from the variable speed pumps was €/$340,000. The total savings accounted for €/$750,000 [9].

Lönnberg [54] has applied VSD in pumping systems in a hospital and has shown huge saving potentials as pumps in a hospital have to operate 24 h for the whole week. It is estimated that US$11,855/year can be saved using VSDs just for pumps in a hospital.

In another project at the metal plating facility in Burlington, Vermont; General Dynamics Armament Systems has installed ASDs along with an energy management control system (EMS). As a result, electricity savings was around 443,332 kWh. The project implementation cost was around $99,400, and saved $68,600 annually, providing a simple payback period of 1.5 years. The installation also reduced CO_2 emissions by 213,000 kg/year, improved overall productivity, controllability, product quality, and reduced wear of equipment, thereby reducing future maintenance costs [55].

A study conducted in china by Nadel et al. [37] has evaluated the potential of energy saving through VSDs. The annual energy saving has been recorded as high as 40 billion kWh annually. It was proved that the percentage of energy savings in VSD applications typically ranges from 20 to 40% and the payback period can be recovered in 1–3 years.

Another example of using ASDs has been recorded in the pumping of machine coolant at an U.S. engine plant. Pressure at the pumps was reduced from 64 psi to 45 psi, average flow cut in half, and power usage reduced by over 50% with no adverse effect on part quality or tool life. Reducing the coolant system pressure resulted in reducing the misting of the coolant, reducing the ventilation requirements and cleaning costs. ASDs could also be used in draft fans on coal-fired boilers, instead of dampers. The average electricity savings exceeded 60% annually [56–58].

Table 4
Overview of energy savings potential for motor systems in the EU [60].

Savings potential (billion kWh/year)					
EU-15	EU-25	France	Germany	Italy	UK
45	50	8	10	7	6

Table 5
Estimated technical savings in TWh by 2015 in industry and in the services sectors by using VSDs [41].

Industry type	Savings (TWh) by VSDs
Basic chemistry	15.5
Food, beverage, and tobacco	8
Iron and steel	6.3
Machinery and metal	6.4
Non-metallic mineral	7.4
Paper and cardboard	15.4
Other industries	11.9
Total industry in EU	71
Total services	24.6

Yu and Chan [59] have reported load-based speed control for all-variable speed chiller plants to optimize their environmental performance. Thermodynamic-behavior of chiller system models has been developed and the environmental performance has been assessed (in terms of annual electricity and water consumption) for typical constant speed and all-variable speed chiller systems operating for the cooling load of an office building. By applying load-based speed control to the variable speed chiller plant, the total annual electricity and water have been reduced by 19.7% and 15.9%, respectively. In addition using VSDs has reduced power consumption from 13,500 W to 365 W. Keulenaer et al. [60] has showed the energy savings of VSDs in motor applications for European countries. The results are presented in Table 4. Almeida et al. [61] have estimated energy savings for motors using VSDs for selected industries. The results are presented in Table 5.

10. Conclusions

VSDs are reliable and cost effective means to control the speed of electrical motors. Installing VSDs on electrical motor applications improves the efficiency of the systems and saves a huge amount of energy. They require little maintenance, provide the most energy efficient capacity control, have the lowest starting current of any starter type, and reduce thermal and mechanical stresses on motors and belts. In addition, they protect the motor while keep the process running, reduce pump failure caused by pump cavitations, and reduce maintenance on piping and valves. Applying VSDs to the HVAC systems and compressed air provide excellent opportunities to reduce the energy consumptions. VSDs are an option to match the required loads thus savings energy and improve the economical features of motors.

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References

[1] Schachter N. Energy efficient speed control using modern variable frequency drives. Available online at: http://www.cimentec.com [retrieved on 26th October 2010].

[2] Solomon S. Understanding variable speed drives (part 2), 1999. Available online at: http://ecmweb.com [retrieved on 14th October 2010].

[3] VFD. Variable frequency drive; 2010. Available online at: http://www.rowan.edu [retrieved on 18th October 2010].

[4] Eknath SY. Variable speed drive. Available online at: http://www.energymanagertraining.com [retrieved on 26th October 2010].

[5] Rashid MH. Power electronics handbook. Canada: Academic press; 2001.

[6] ABB. A guide to using variable speed drives and motors in hospitals and healthcare centers; 2010. Available online at: http://www05.abb.com [retrieved on 28th October 2010].

[7] Al-Bahadly I. Energy saving with variable speed drives in industry applications. WSEAS Int.; 2007.

[8] Carrier. Operation and application of variable frequency drive (VFD) technology. New York: Carrier Corporation Syracuse; 2005.

[9] Euro Pump. Variable speed pumping a guide to successful applications. U.S. Department of Energy, Energy Efficiency and Renewable Energy. Available online at: http://www1.eere.energy.gov [retrieved on 21st December 2008].

[10] Mustaffah S, Azma S. Variable speed drives as energy efficient strategy in pulp and paper industry. Master thesis. Malaysia: University Technology Malaysia; 2006.

[11] Saidur R. A review on electrical motors energy use and energy savings. Renewable and Sustainable Energy Reviews 2009;14:877–98.

[12] Shepherd W, Hulley LN, Liang DTW. Power electronics and motor control. Cambridge University Press; 1995, 539 pp.

[13] Okaeme N. Automated robust control system design for variable speed drives. PhD thesis. UK: University of Nottingham; 2008.

[14] Barnes M. Practical variable speed drives and power electronics, Technology & Engineering. Australia: Perth; 2003, 286 pp.

[15] ABB. Guide to variable speed drives; 2010. Available online at: http://www05.abb.com [retrieved on 18th October 2010].

[16] Saidur R, Mahlia TMI. Energy, economic and environmental benefits of using high efficiency motors to replace standard motors for the Malaysian industries. Energy Policy 2010;38(8):4617–25.

[17] Saidur R, Rahim NA, Ping HW, Jahirul MI, Mekhilef S, Masjuki HH. Energy and emission analysis for industrial motors in Malaysia. Energy Policy 2009;37:3650–8.

[18] Olson MR, Lonnberg M. Variable frequency drives for energy savings in hospitals. Hospitals Engineers & Facilities Management 2005;2.

[19] APS. Energy efficient motor applications. Available online at: http://www.aps.com [retrieved on 28th October 2010].

[20] Sueker KH. Power electronics design: a practitioner's guide. Newnes, 2005.

[21] Jayamaha L. Energy-efficient building systems: green strategies for operation and maintenance. New York: McGraw-Hill Professional; 2006, 305 pp.

[22] LLC. VFD fundamentals; 2003. Available online at: http://www.kilowattclassroom.com [retrieved on 18th October 2010].

[23] APEC. Electric motors-alignment of standards and best practice programs within APEC. final report; 2008.

[24] Leonard III Abbott. Power quality and cost analysis of industrial electrical distribution systems with adjustable speed drives. MS thesis. USA: California State University; 2006.

[25] Kaya D, Yagmur EA, Yigit KS, Kilic FC, Eren AS, Celik C. Energy efficiency in pumps. Energy Conversion and Management 2008;49:1662–73.

[26] Salam Z. Power electronics and drives; 2003. Available online at: http://www.energymanagertraining.com [retrieved on 27th October 2010].

[27] Kirtley J. Electric motor handbook, chapter one, technology & engineering. McGraw-Hill; 2004, 404 pp.

[28] Boley BL. Overview of motor types tutorial; 1997. Available online at: http://www.oddparts.com [retrieved on 27th October 2010].

[29] Viholainen J, Kortelainen, Ahonen T, Aranto N, Vakkilainen E. Energy efficiency in variable speed drive (VSD) controlled parallel pumping; 2010. Available online at: http://www1.cetim.fr [retrieved on 4th November 2010].

[30] Beggs C. Energy management and conservation. Elsevier Ltd.; 2002.

[31] Gao X. Energy consumption of HVAC variable speed pumping systems. PHD thesis. USA: The University of Alabama; 2002.

[32] De Almeida A, Bertoldi P, Leonhard W. Energy efficiency improvements in electric motors and drives. Springer; 1997.

[33] Qureshi TQ, Tassou S. A., variable-speed capacity control in refrigeration systems. Applied Thermal Engineering 1996;16(2):103–13.

[34] Teitel M, Zhao ALY, Barak M, Eli Bar-lev, Shmuel D. Energy saving in agricultural buildings through fan motor control by variable frequency drives. Energy and Buildings 2008;40:953–60.

[35] Saidur R, Rahim N, Hasanuzzaman M. A review on compressed-air energy use and energy savings. Renewable and Sustainable Energy Reviews 2009;14:1135–53.

[36] ABB. Products for compressor applications Powerful, reliable, efficient solutions; 2009. Available online at: http://www05.abb.com [retrieved on 3rd October 2010].

[37] Nadel S, Wang W, Liu P, Mckane A. The China motor systems energy conservation program: a major national initiative to reduce motor system energy use in China. China: Lawrence Berkeley National Laboratory; 2001. Available online at: http://industrial-energy.lbl.gov [retrieved on 17th July 2010].

[38] Community of Green Energy, Renewable Power, Electrical Machinery, Automation, Process Control (CGREAP). Variable speed air compressor; 2009. Available online at: http://www.inverter-china.com [retrieved on 3rd October 2010].

[39] Thota S. Harmonic filters overview—part one; 2003. Available online at: http://powersupplies.frost.com [retrieved on 29th November 2010].

[40] Wildi T. Electrical machines, drives, and power systems. 6th Ed. Columbus: Prentice Hall; 2005.

[41] AlmeidaAnıïbal T, de Almeida, Fonseca P, Bertoldi P. Energy-efficient motor systems in the industrial and in the services sectors in the European Union: characterization, potentials, barriers and policies. Energy 2003;28:673–90.

[42] Bingham RP. Harmonics—understanding the facts; 2010. Available online at: http://www.dranetz-bmi.com [retrieved on 28th October 2010].

[43] UNICO. Harmonics filter; 2010. Available online at: http://www.unicous.com [retrieved on 18th October 2010].

[44] VFD. Variable frequency drive; 2010. Available online at: http://www.energy.ca.gov [retrieved on 4th November 2010].

[45] Zabardast A, Mokhtari H. Effect of high-efficient electric motors on efficiency improvement and electric energy saving. DRPT 2008, 6th–9th April, Nanjing, China.

[46] Nesbitt L. The impact of industry characteristics on the diffusion of adjustable speed motors across manufacturing industries. MA thesis. USA: University of Denver; 2008.

[47] Martino FJ. Payback analysis for variable frequency drives; 2003. Available online at: http://www.powerqualityanddrives.com [retrieved on 30th August 2009].

[48] Abdelaziz EA, Saidur R, Mekhilef S. A review on energy saving strategies in industrial sector. Renewable and Sustainable Energy Reviews 2011;15(1):150–68.

[49] Saidur R, Mekhilef S. Energy use, energy savings and emission analysis in the Malaysian rubber producing industries. Applied Energy 2010;87:2746–58.

[50] Hasanuzzaman M, Rahim NA, Saidur R, Kazi SN. Energy savings and emissions reductions for rewinding and replacement of industrial motor. Energy 2011;36(1):233–40.

[51] Saidur R, Madlool NA, Hossain MS, Rahim NA. A critical review on energy use and savings in the cement industries. Renewable and Sustainable Energy Reviews 2011;15(4):2042–60.

[52] Saidur R. Energy savings and emission reductions in industrial boilers. Thermal Science 2011;15(3):707–21.

[53] Saidur R, Hasanuzzaman M, Yogeswaran S, Mohammed HA, Hossain MS. End use energy analysis in a Malaysian public hospital. Energy 2010;5(12): 4780–5.

[54] Lönnberg M. Variable speed drives for energy savings in hospitals. World Pumps 2007:20–4.

[55] Christina G, Worrell E. Energy efficiency improvement and cost saving opportunities for the vehicle assembly industry. In: LBNL-50939-Revision; 2008.

[56] Price A, Ross MH. Reducing industrial electricity costs—an automotive case study. The Electricity Journal 1989;(July):40–51.

[57] Saidur R, Atabani AE, Mekhilef S. A review on electrical and thermal energy for industries. Renewable and Sustainable Energy Reviews 2011;15(4):2073–86.

[58] Saidur R, Mahlia TMI. Impacts of energy efficiency standard on motor energy savings and emission reductions. Clean Technology and Environmental Policy 2011;13(1):103–9.

[59] Yu FW, Chan KT. Environmental performance and economic analysis of all-variable speed chiller systems with load-based speed control. Applied Thermal Engineering 2009;29:1721–9.

[60] De Keulenaer H, Belmans R, Blaustein E, Chapman D, De Almeida A, De Wachter B, Radgen P. Energy efficient motor driven systems Tervurenlaan 168b10, B-1150 Brussels, Belgium: European Copper Institute; April 2004.

[61] De Almeida AT, Fernando JTE, Ferreira, PF. VSDs for electric motor systems, handbook; 2000. 109 pp. Available online at: http://www.scribd.com [retrieved on 3rd December 2010].