Energy Policy 36 (2008) 4336–4341

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Efficiency trends in electric machines and drives ☆

B.C. Mecrow *, A.G. Jack

School of Electrical, Electronic and Computer Engineering, University of Newcastle upon Tyne, Merz Court, Newcastle upon Tyne NE1 7RU, UK

ARTICLE INFO

Keywords:
Electrical efficiency
Continuous drive
Variable-speed drive

ABSTRACT

Almost all electricity in the UK is generated by rotating electrical generators, and approximately half of it is used to drive electrical motors. This means that efficiency improvements to electrical machines can have a very large impact on energy consumption. The key challenges to increased efficiency in systems driven by electrical machines lie in three areas: to extend the application of variable-speed electric drives into new areas through reduction of power electronic and control costs; to integrate the drive and the driven load to maximise system efficiency; and to increase the efficiency of the electrical drive itself. In the short to medium term, efficiency gains within electrical machines will result from the development of new materials and construction techniques. Approximately a quarter of new electrical machines are driven by variable-speed drives. These are a less mature product than electrical machines and should see larger efficiency gains over the next 50 years. Advances will occur, with new types of power electronic devices that reduce switching and conduction loss. With variable-speed drives, there is complete freedom to vary the speed of the driven load. Replacing fixed-speed machines with variable-speed drives for a high proportion of industrial loads could mean a 15–30% energy saving. This could save the UK 15 billion kWh of electricity per year which, when combined with motor and drive efficiency gains, would amount to a total annual saving of 24 billion kWh.

1. Introduction

Electrical machines have advanced significantly in recent years due to the introduction of new materials. New electrical steels have reduced losses and rare earth permanent magnet materials have provided a 'lossless' source of magnetic flux. Recent advances in construction methods have reduced winding losses, so there is a continued trend to increase efficiency. For large electrical machines efficiency is already high and so, although significant, the potential gains are limited. Greater gains are possible in smaller machines, which may be only 50% efficient.

Variable-speed drives are created when a motor is combined with a power electronic converter. By introducing variable speed to the driven load, it is possible to optimise the efficiency of the entire system, and it is in this area that the greatest efficiency gains are possible.

This paper has three major sections: Section 2 covers statistics of energy consumption and current predictions of possible savings using existing technology; Section 3 describes the current state of the art: and Section 4 covers future, longer-sighted possibilities.

2. Energy consumption

UK Energy Consumption Statistics published by the Department of Trade and Industry (2000) give a breakdown of energy consumption by fuel, by sector and by final end use, but do not explicitly reveal the energy consumed by electrical motor-driven systems. Studies promoted by the European Commission (De Keulenaer et al., 2004; European Commission Joint Research Centre on Electric Motor Efficiency, 2004; EU SAVE II Project, 2001; Haataja and Pyrhonen, 1998) state that motor-driven systems use 65–70% of all electricity consumed by industry, while in the US this is estimated at 67%. It is likely that these statistics will also be representative of the UK. Walters (1999a, b) further reports that more than half of all electricity consumed in the UK is used to drive electric motors.

De Keulenaer et al. (2004) projected that, by switching to energy-efficient motor systems, EU industry would save:

- 202 billion kWh in electricity consumption (approximately 7.5% of that consumed in all sectors);
- £3–6 billion per annum in operating costs;
- £4 billion in environmental costs;
- 79 million tonnes of CO_2 emissions (one quarter of the EU's Kyoto target.);
- 45 GW reduction in the need for new power plant capacity;
- 6% reduction in energy imports.

☆ While the Government Office for Science commissioned this review, the views are those of the author(s), are independent of Government, and do not constitute Government policy.

* Corresponding author. Tel.: +44 191 222 7329; fax: +44 191 222 8180.
E-mail address: barrie.mecrow@ncl.ac.uk (B.C. Mecrow).

doi:10.1016/j.enpol.2008.09.042

These figures refer to industrial savings alone: savings in the domestic, service and transport sectors could also make equivalent contributions.

Electricity consumed in the UK was 12.8% of the total in the EU in 2003 and so UK estimates can be extrapolated accordingly.

3. Current state of the art

Industrial motor systems are dominated by induction motors running at effectively constant speed. Variable-speed drives, in which the speed of the machine is controlled by a power electronic converter, are taking an increasing size of the market and in 2004 accounted for 25% of new systems (De Almeida et al., 2005). The efficiency of the electrical system in isolation will first be considered, before progressing to the entire system where, with the addition of variable-speed drives, much larger energy savings can be made.

3.1. Generation

Large turbo-generators of 100–660 MW rating supply the vast majority of the UK's electricity. These are wound rotor synchronous machines whose efficiency is over 98%. The very high efficiency arises by virtue of their very large size, with designs only changing marginally over the last few decades as newer, low-loss materials emerge.

There is much more diversity in electricity generation from renewable resources. Most wind generators are doubly fed induction machines, fed through a step-up gearbox, but direct-drive permanent magnet generators are emerging as an alternative. With direct-drive permanent magnet systems, the efficiency of the generator is increased, and the gearbox losses are eliminated, but additional power electronic converter losses are introduced and the system costs rise due to the large mass of the low-speed generator.

3.2. Electric motors

The efficiency of an electrical machine is a complex function of machine type, size, speed of operation, loadings, materials and operating regime (Auinger, 1999, 2001; Boglietti et al., 2004; Casada et al., 2000; Rooks and Holmquist, 2002; Umans, 1989). The industrial market sector for fixed-speed machines is completely dominated by the induction motor, whose efficiency typically ranges from 76.2% at 1.1 kW to 93.9% at 90 kW (European Commission Joint Research Centre on Electric Motor Efficiency, 2004). Other market sectors, such as white goods, power tools, etc. mainly utilise smaller, commutator machines, whose efficiency is typically 50% or less.

The principal sources of loss in a mains-supplied induction machine are:

- *stator winding loss*, which is the dominant source of loss in small machines. It comprises around 60% of the total full-load loss in the sub-1 kW range, falling to 25% at 1 MW and above.
- *lamination iron loss*, due to hysteresis and eddy currents, which accounts for approximately 20% of full-load loss. This loss does not generally decrease during operation at reduced load, thereby giving low efficiency in machines operating at light load.
- *rotor winding loss*, due to losses in the aluminium cage rotor, which are strongly load-dependent and amount to approximately 20% of full-load loss.
- *stray losses*, which are due to a number of effects, including induced eddy currents in the stator frame. These are insignificant in machines of less than 10 kW, rising to almost 20% of loss in machines of 1 MW.
- *friction and windage*, including bearing loss, which is less than 5% of total loss in machines of 10 kW, rising to 20% in machines of 1 MW.

Efficiency band classifications (I–III) have been developed in accordance with IEC 34-2 (1996), in which the highest efficiency, Class I, is typically 3% greater than that of the standard Class III as the total losses are reduced by about one quarter. This improvement is generally down to a combination of lower-loss electrical steels and increased conductor cross-sectional area. The materials cost of the motor is increased by a few percent, with a typical 20% premium on selling price and the payback period for the customer can be as little as 6 months for a continuously loaded motor. It is estimated (De Keulenaer et al., 2004) that adoption of high-efficiency electric motors within existing systems alone would save the UK 3 billion kWh per annum.

The EU introduced the efficiency bands in the mid-1990s but, unlike the USA, which used legislation, a voluntary agreement between all of the motor manufacturers in the EU was produced, covering all 2- and 4-pole induction motors rated at 1–90 kW and dividing motor efficiencies into three bands. It was expected that the Class III (i.e. lowest) band would be removed by 2002 so that all motors sold in the EU would be in the improved-efficiency bands I and II. However, this does not seem to have happened. Clearly, there is an urgent need to review the position. A recently published briefing note from the Department for Environment, Food and Rural Affairs' Market Transformation Programme (2006) recommends that the existing scheme be extended to cover a wider range of motor ratings. It also proposes more accurate testing procedures in order to label motors with higher efficiencies than the current Class I level.

3.3. Power electronic converters

Power electronic converters are used to supply a variable frequency supply to an AC motor, thereby enabling variable-speed operation. Power converters have conduction and switching losses in the power devices, losses in passive components and auxiliary cooling systems. The loss is a function of device type, switching frequency, voltage and current level, but for industrial systems the converter has a typical full-load efficiency, which rises with power rating from around 80% below 1 kW to over 97% at 150 kW (Rooks and Wallace, 2004). Efficiency levels are rising as newer, low-loss, faster-switching devices emerge.

3.4. Variable-speed drives

For the purposes of this paper, an electric drive will be classified as the combination of a power electronic converter, electrical machine and electronic controller. The EU-funded SAVE II Project (De Almeida et al., 2005) identified large-scale application of variable-speed drives as the motor systems technology having the most significant energy-savings potential. Savings within the electrical drive system alone are projected to be 6 billion kWh per annum in the UK (De Almeida et al., 2005).

Variable-speed drives have been adopted as standard within process control applications, where their variable speed gives greater functionality and is often essential for the application. However, for the bulk of applications a fixed-speed drive can be employed and involves a lower initial capital cost, but generally with much lower system efficiency.

3.5. Complete system

3.5.1. Industrial

The greatest potential for fuel savings are in closed-loop fluid-pumping applications (pumps, compressors, fans) with variable flow requirements (De Almeida et al., 2005). Pumps and fans of this type are often run well below their rated power level, in which case fixed-speed machines are run in an 'on/off' manner (as in the operation of a pump in a central heating system). However, the power requirement is related to the cube of the flow, and so running a pump continuously at half speed will produce the same flow as running one at full speed for one half of the time, while only requiring one quarter of the energy.

De Almeida et al. (2005) showed that the following typical energy savings would result from replacing fixed-speed machines with variable-speed drives:

- *fans*: 25–30%;
- *compressors*: 15–20%;
- *lifts*: up to 81% when regenerative braking is included.

The efficiency improvements within the driven load (i.e. pump, fan, etc.) are expected to save the UK 15 billion kWh per annum, which when combined with the motor and drive efficiency gains, amount to a total annual saving of 24 billion kWh.

3.5.2. Household

There have been extensive studies of the household sector, both in the USA (Kubo et al., 2001; Little, 1999) and the EU Save II Project (2001). In Europe, the electricity consumption of a central heating pump is up to 600 kWh per annum, which is comparable to the complete lighting system of a household, or that of a fridge/freezer. Through the adoption of efficiency standards and technical measures, such as speed control, more efficient motors and seasonal switches, it is predicted that energy requirements could be reduced by more than a factor of three by 2020.

Japan is leading many aspects of innovation in motors and drives for household applications. Morimoto et al. (2002) focuses on refrigeration and air-conditioning systems, which make up over 40% of Japan's electric power consumption. By moving from induction machines to permanent magnet synchronous machines, a reduction in motor loss of over 60% is reported. This improvement is due to a combination of innovative construction techniques and the use of power electronic converters, which have made it possible to use the more efficient permanent magnet machine and is in addition to the large gains, which a variable-speed system produces.

3.5.3. Transport

Electric motors and drives are becoming increasingly dominant in the following modes of transport:

- *Sea*: Electric ship propulsion of military vessels, ferries and cruise liners is now commonplace, with the ship's engine driving a generator, which in turn feeds propeller motors. The propeller can now be pod-mounted and hydrodynamic efficiency improved, resulting in system gains of up to 15% (ship-technology.com).
- *Air*: In the 'more electric' aircraft, hydraulic and mechanical systems are being replaced with electrical alternatives along with the introduction of electric climate control. Direct energy savings result from more efficient pumping systems, and indirect savings in fuel due to reduced aircraft mass.
- *Road*: Hybrid electric vehicles are able to supply fuel economy advantages over conventional vehicle drive trains (Williamson et al., 2006). For example, the Toyota Prius achieves 65.7 mpg on a Department of Transport combined driving cycle test. Both this and the Honda Insight use high-efficiency permanent magnet drives, which represent current state of the art in high-efficiency drives
- *Rail:* Most new rail systems are electrically driven, with induction motor drives. Efficiency of the drive is high, but could be further increased with permanent magnet drives. Magnetic levitation can be used to reduce drag losses and increase speed, but involves very high capital investment.

3.6. Market barriers

By far the largest barrier is one of initial capital cost. Within the industrial sector, the majority of motor and drive purchases are made by the original equipment manufacturer (OEM) and not by the end user. The OEM is concerned predominantly with selling cost, rather than lifetime cost and therefore has little motivation to improve efficiency.

When replacing an industrial fixed-speed motor with a variable-speed drive, the initial capital cost may be larger by a factor of three or more. The cost per kW of power reduces with power rating (De Almeida et al., 2005) up to around 70 kW, above which it is relatively constant.

Household applications are particularly cost sensitive, but brushless drives are beginning to penetrate the market, such as an LG direct-drive washing machine (Cho et al., 2004) and a Dyson vacuum cleaner (Drives and Controls, 2004) (currently available only in Japan). Interestingly, these products are marketed more for their increased functionality rather than their higher efficiency.

Within the industrial sector, there is still a need to inform and educate the end users. There is still a widely held belief that by purchasing a motor rated higher than the application demands, the motor will last longer and be more reliable. In practice, an over-rated motor tends to have higher iron loss, magnetising loss and friction, which will substantially reduce the efficiency. There is a strong analogy with cars of large engine size: their fuel consumption is almost always inferior to the lower powered alternatives.

4. Future advances to 2050 and beyond

The function of an electrical drive is to transfer electrical energy to mechanical energy and vice versa. This is currently achieved almost exclusively via a magnetic field. The first question to ask is: 'Are there any new processes of energy conversion that may replace this method in the next one hundred years?' The answer is simple: none are known of at the time of writing. Competing systems, such as electric fields are several orders of magnitude less power-dense or, in the case of ultrasonic motors, very inefficient. So, unless there is a truly major breakthrough, electric motors will continue to use the same basic concepts for the foreseeable future.

4.1. Key challenges

It is clear that the key challenges to increased efficiency lie in four areas:

- increase the adoption of variable-speed, high-efficiency systems, with a revision of efficiency bands and possibly legislation replacing voluntary agreements;

- extend the application areas of variable-speed drives through reduction of power electronic and control costs;
- integrate design of the drive and the driven load to maximise system efficiency;
- increase the efficiency of the electrical drive.

4.1.1. *Extension of application areas*

The main barrier to further market penetration is capital cost, which is dominated by the power electronic cost in the sub-100 kW range. Reliability is also a concern for some applications. Unlike electrical machines, which are dominated by material cost, power electronic systems are a much less mature technology, which is dominated by processing and packaging costs. Therefore, with advances in these areas, the cost of power electronic converters will continue to fall substantially.

By 2050, it is possible that power electronic converters will be substantially cheaper than the machines they drive and will also be highly efficient. Once this happens, a high proportion of line-connected electrical machines could be replaced by variable-speed drives, in which the average user has no awareness of (or indeed interest in) the contents of the system, only its flexibility and functionality. Energy savings will occur in traditional fan, pump and compressor applications as entirely new markets emerge. Penetration into the consumer market will replace commutator machines, which generally operate at around 50% efficiency, with brushless permanent magnet drives of 80–90% efficiency and high functionality.

Perhaps the largest new market will be in automotive drive trains, initially in hybrid vehicles and later in fuel-cell or battery-powered vehicles. CO_2 emissions from a fuel-cell-driven vehicle are very low, but production of the fuel itself may be an inefficient process. Efficiency of the electric-driven train is increased by operating at higher voltage levels than the 42 V system proposed by manufacturers. It should be noted that there is a trend to increase this voltage for hybrid vehicles to improve efficiency, recognising that safety issues have also to be addressed.

4.1.2. *Integrated system design*

Blaabjerg et al. (2005) state how, within power electronics, semiconductor devices have hitherto been the main technology drivers; circuit topologies have stagnated, while performance, control and system integration has become the main challenge for the future.

A simple example of the need for integrated system design may be found in a pump. Most industrial pumps are designed for 1500 rpm, because that is the speed of the line-connected motor. If a variable-speed drive is employed, there is complete freedom to choose any speed up to over 100,000 rpm. As the speed changes, different pump technologies can be chosen and the size of the system can be drastically reduced (Drives and Controls, 2004). The torque from the electric motor is reduced and therefore loadings and electromagnetic losses can be reduced. The motor and power electronics can be integrated into the impeller, with sophisticated control systems ensuring maximum efficiency.

Even in 2006, very sophisticated programmable controllers could be purchased for a few pence. It is clear that the level of 'intelligence' within the drive will rise dramatically in the future and that there will consequently be a huge increase in the functionality and controllability of even the most basic of products.

As higher-temperature power electronics become possible, the power electronics will become embedded in hostile environments, such as internal combustion or jet engines. This will allow electrical actuation and significant efficiency improvements in our major CO_2-producing systems.

4.1.3. *Drive efficiency*

The key to improving motor efficiency lies in new materials and construction methods.

Winding loss is reduced by increasing the conductivity of the winding. In the case of induction machines, recent advances in production methods are starting to allow the replacement of aluminium rotor cages with copper (Kimmich et al., 2005), reducing machine losses by around 8–10%. Copper is already used for stator windings and is unlikely to be replaced by a more conductive material at room temperature. Superconducting electrical machines have been researched for over 30 years, but with the advent of high-temperature superconductors, they are now close to introduction (Kalsi et al., 2004; Singh et al., 1999), both as generators and in ship propulsion systems. Superconductors have hitherto been considered only suitable for DC current and are therefore used as a field winding producing a very high flux density. Air-gap windings are employed, with an ironless stator, thereby also eliminating iron loss. However, substantial eddy currents are induced in the AC windings because they sit in the full magnetic field. Losses in very large generators can be reduced by up to 50% and the additional energy requirement of the cryogenic cooling system is relatively low. The generator efficiency may therefore rise from 98% to over 99%, but, perhaps more importantly, the generator is much smaller, which reduces the very large civil engineering cost associated with a power station.

The superconducting properties of magnesium diboride were discovered in 2001 (Nagamatsu et al., 2001) This material typically operates at 24–30 °K, placing it between conventional and high-temperature superconductors. It is much cheaper to produce and it is easy to form into wires than other superconductors (Das, 2002; Fang et al., 2005; Musenich et al., 2004), and is being developed for AC applications. If both technical and financial criteria are met, it may have a role in future high-efficiency electrical machines.

Eddy current losses in the soft iron material of a machine's core can be reduced by either increasing the resistivity of the core material or reducing the amount of flux, which eddy currents can enclose. The former is achieved by the introduction of up to 6% silicon into the lamination material, which also reduces the coercivity and hence hysteresis loss. There will certainly be further incremental improvements in this area. Amorphous iron (Johnson et al., 1981) reduces the thickness of the laminations and therefore the eddy current loss. Because of the crystal structure resulting from very rapid cooling, the hysteresis loss is also exceptionally low. However, the material is both expensive to produce and limited in flux density. Soft magnetic composites (Hultman and Jack, 2003) replace the laminations with 100 μm diameter iron particles, which are pressed together. This material has very low eddy current loss, but current products have greater hysteresis loss. So iron loss is only reduced at very high frequency. Soft magnetic composites have, however, been shown to offer significant efficiency gains because of their three-dimensional shaping properties. New tooth shapes are possible, with much shorter winding lengths, thereby reducing winding loss (Jack et al., 2000). Future soft magnetic composites will incorporate special high-temperature powder coatings, which will lower hysteresis loss and make the material more attractive for energy-efficient systems.

Electromagnetic design tools have advanced greatly with the application of the finite element method. However, further advances will continue to develop. Greater understanding of stray loss mechanisms is required at the design stage in larger machines. Improved understanding and modelling of iron loss mechanisms within the machine are also needed to replace the empirical scaling that continues to be adopted by manufacturers today. Eddy current loss mechanisms in high-speed machines will be addressed and new machine topologies will continue to emerge.

In most AC electrical machines the windings have to supply two components of current—one to produce the torque and another magnetising component to produce the magnetic field. When the field is produced by a permanent magnet the winding losses are substantially reduced and so, providing full magnetic flux is required under all operating conditions, permanent magnet machines are substantially more efficient than other AC machines. In the 20 years until 2006 the cost of rare-earth permanent magnet material dropped very dramatically, and the volume of production (mainly from China) rose exponentially. The percentage of electrical machines which employ high-performance permanent magnets has consequently risen sharply. Very large permanent magnet machines are now being developed for propulsion (Parker and Hodge, 1998) and generation purposes (Veersteegh, 2004) and this will form a substantial part of the market over the next few decades. For many fan and pump type loads, where field weakening is not required, it may soon become cost-effective to replace induction machines with permanent magnet machines in the general drives market and substantial efficiency gains will result. However, it should be noted that the cost of magnets has risen once more—future cost and availability will be a critical factor determining the penetration of permanent magnet machines in this sector.

Power electronic converters are a less mature product than electrical machines and therefore should see larger efficiency gains over the next 50 years. The conduction and switching loss in silicon-based power electronic devices will decrease, but not by orders of magnitude. Silicon carbide, gallium nitride and diamond offer gains in this area, along with higher-temperature operation, but all semiconductors have a bulk resistance and will therefore have significant conduction drops. Interestingly, the flow of charge through a vacuum, as employed in old valve technology, overcomes this problem. It is possible that, if this process could be successfully miniaturised, such techniques may produce very low-loss power electronics in the distant future. It has also been postulated that micro-electromechanical devices could have a role to play by effectively miniaturising the mechanical switch. However, these possibilities are purely speculative and the likelihood of this advance occurring must be rated low.

Power electronic converters need passive energy storage devices in the form of capacitors and inductors. The size, cost, reliability and efficiency of these devices can all be problematical, and in due course may dominate the power electronic converter performance. There have been some major gains in this area, but there is a need for further development.

Packaging of the converter remains a major challenge for the future. While signal-level electronics moved away from single discrete devices more than 30 years ago, this has not yet been the case with power electronics. Integration of the power and control electronics into a single hybrid or even chip will become commonplace. Further integration of the passive components remains a longer-term aim. Although there have been a number of attempts at limited integration with the motor, these have been hampered by thermal issues, since the motor can run hotter than the electronics. Advances in high-temperature semiconductors, including silicon carbide devices may overcome this problem.

Integrated design can reduce lead length, and hence reduce parasitic inductance and capacitance effects. This in turn permits higher switching speeds, lower losses, and smaller passive components. Developments of this nature in switched power supplies are somewhat in advance of variable-speed drives, but many of the same advantages can be encompassed by new, ultra-high-speed electrical machines.

4.2. *Key engineering and scientific advances*

The following key advances are required:

4.2.1. *Electrical machines*

- New soft magnetic materials giving lower iron loss at low cost.
- Low-cost, high-temperature, high-energy magnets.
- High-temperature insulation and magnet systems ($>400\,^{\circ}$C).
- New construction methods, including segmented stators, and cast copper rotors where appropriate.
- Bearing systems for ultra-high-speed operation.
- Reliable high-temperature superconducting designs at moderate cost.
- Improved design tools.

These advances will happen, though perhaps on a continuous incremental basis.

4.2.2. *Power electronics and control*

- Cost reduction.
- New devices, materials and technology to produce increased switching speeds and reduced conduction drops.
- Increased integration.
- Reduced size of passive components.

Considerable advances will occur: significant possibility of technology breakthroughs causing fundamental advances in power electronic devices and passive components.

4.2.3. *Integrated systems*

- New fan, pump, compressor, etc. designs for maximum efficiency where there is complete freedom of speed.
- Intelligent control methods.

5. Conclusions

By adopting known, proven concepts, it is possible to dramatically increase the efficiency of systems driven by electrical machines and reduce total electricity consumption by over 7%. There is a trend for increasing efficiency within the electrical machine itself, but the greatest gains are at system level when the machine is combined with a power electronic converter to create a variable-speed drive. The main barriers to this lie in the initial cost of a variable-speed drive, even though in many cases the payback period is short. Future advances in technology will reduce the capital cost of the drive, and therefore existing markets will grow and new markets will open up. In the future, electric drives will become integral to the propulsion of road transport vehicles, and so the need for maximising their efficiency will become even more pressing than it is today.

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