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Efficiency trends in electric machines and drives ☆

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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.

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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.