Efficiency Improvement Potential of Inverter Driven Electrical Motor Systems

Peter Scavenius Andersen, Jens Godbersen,
Ana-Mari Tataru-Kjar and Klaus Jensen

August 26, 2024

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Peter Scavenius Andersen[1], Jens Godbersen[1], Ana-Mari Tataru-Kjær[1], Klaus Jensen[1]

[1] Danfoss Power Electronics and Drives, 6300 Graasten, Denmark

Abstract. It is commonly known that controlling motor speed is the most efficient way of capacity control in e.g. HVAC systems. However, making sure that the motor itself runs in the most efficient operating point can be challenging, as it would require extensive knowledge of the motor parameters, including non-linear or saturation effects, over a wide operating envelope. Furthermore, indirect factors such as ambient temperature or ageing effects could likewise complicate matters. In this paper, it is shown that the efficiency of a converter driven motor may be increased when deviating from the operating point dictated by nominal parameters. Both asynchronous and synchronous motors are considered. Considering the volume of inverter driven motor systems worldwide, it is shown that even small improvements can bring substantial energy savings in a larger context.

Keywords: Energy efficiency, motor control, asynchronous motors, synchronous motors.

1 Introduction

A reliable and cost-efficient electric supply is fundamental for modern societies. A century ago, electricity was introduced as city lighting; later, powering water distribution, industry machines, domestic appliances, trains, HVAC installations, and recently data centers, EV charging stations, etcetera. Growth in globally consumed electrical energy over time, and how it is produced, is illustrated in fig. 1.

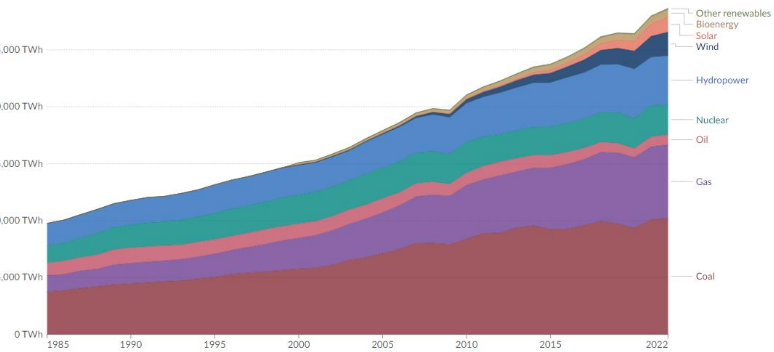

Fig. 1. Global production of electric energy by source, 1985-2022. Source: Our World in Data, 2024, [1]

It is estimated that electrical motors consume more than 40% of electrical energy worldwide [2]. With the on-going realignment of power generation from fossil based to alternative sources, combined with the electrification of the transport sector, the electric transmission and distribution grids are undergoing substantial changes, requiring large investments. Cost of electricity for the end user has also proved volatile due to geopolitical factors.

Even though electricity produced from renewables in these years is quickly growing 61% of the world's electricity is still being produced by burning fossil fuels [1] with emission of greenhouse gasses as a result. The UN Climate Panel (IPCC) has pointed at the growing concentration of greenhouse gasses in the atmosphere as one reason for global temperature rise and severe climate hazards, both presently and in the future if emissions continue at the same rate [3]. Politically there is increasing consensus that emissions must be reduced [4], and several countries have raised legislation and initiatives to both save energy, to build more renewable power production plants, and to develop technology like for example carbon capture and storage (CCS) [5]. Common for many of these programs is that the time horizon before they are effective on a global scale is counted in decades, therefore, optimizing the efficiency of electrical appliances and equipment may turn out to become a quicker path to obtain substantial emission reductions. A popular phrase is that the greenest energy is the one that is not used, and optimization of energy efficiency directly addresses this idea. An immediate step is to replace old motors with motors which complies to the latest efficiency regulations, in the EU alone this is estimated to bring energy savings up to 110TWh [6]; a further step is to use variable speed drives (VSD) which in variable torque applications, like pump and fans, can generate added considerable savings [6]. It is yet not trivial how the VSD operates the motor, if the VSD in a standard operation mode applies nominal magnetization current to an asynchronous motor the full potential for savings may not be obtained. Typically, it requires a user to interact with the VSD to activate an energy saving mode, if the VSD include this, and to be functioning optimally this mode often needs to be fed with detailed parameters of the electric motor. The process of commissioning the VSD may be cumbersome and fault prone, and it is the experience of the authors that this is not always fully performed, i.e., there remains a potential for further energy savings.

In the following we will quantify the energy saving potential of VSD driven electric motors when these are controlled in the most efficient operating point compared to a standard mode with nominal magnetization current. When also considering operating conditions and applications we will scale the result to a large volume of motors.

2 Method

A data-driven bottom-up approach for estimating energy demand and potential energy savings for a pool of motor-drive systems installed in a variety of applications involves data collection for mapping the energy saving by means of energy optimizing control, load-time profile statistics and an aggregate model for the energy demand and energy savings.

2.1 Motor-drive system data collection

Data collection is done by tests on a sample of induction and synchronous motors from various manufacturers, of different power sizes, pole number and efficiency classes. Each motor-drive system was tested at pre-defined steady state *load points*, which are quantified in per unit with respect to nominal speed and torque. The number of load points may be defined according to [7, 8] or arbitrarily chosen.

At each *load point,* the efficiency was measured for *default and optimized operation points.*

An *operation point* characterizes the electromagnetic conditions of the motor at a given *load point* and is throughout this work the magnetization current, i_{ms}, for induction motor and the angle offset, $\delta\alpha_{tq}$ with respect to MTPA torque angle for synchronous motor. In Fig. 2, are illustrated default (continuous line) and optimized (stippled line) operation points for the two major motor types at one *load point (Const. torque and Const. speed)*,

Default operation point is for induction motor at nominal magnetization current, which means 1[pu] and for synchronous motors at a torque angle offset $\delta\alpha_{tq}$ of 0 degrees.

Optimized operation point can be reached in various ways [9], by varying either the magnetization current or the torque angle offset depending upon motor type. These methods are not discussed in this publication.

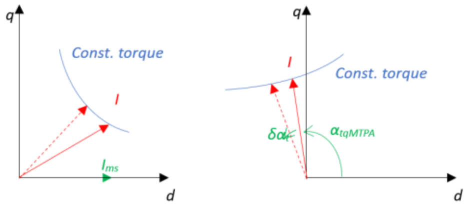

Fig. 2. Variation of electromagnetic operating point for asynchronous motor (left) and PM motor (right) by online parameter adjustment (green). Motor shaft power is constant.

To ensure data quality during measurements, besides calibration of the measurement chain including power analyzer, torque and speed transducers, increased attention was accorded to the handling of thermal conditions. Aiming at thermal steady-state at each *load point* is a time demanding approach, therefore, the motor is first brought to a near thermal steady-state by running at rated *load point* for a certain time. Following, all defined load points are tested according to a sequence which starts with *default operation point*, moves to *optimized point* and return to the *default operation point*, named *default verify*. Data averaged over a pre-defined period is stored and finally the deviation of efficiency measured at the two-default operations is verified. If the deviation is below a threshold the measurement is accepted, otherwise the test is repeated. This is illustrated in Fig. 3., where measured efficiency differences are smaller than 0.1% points.

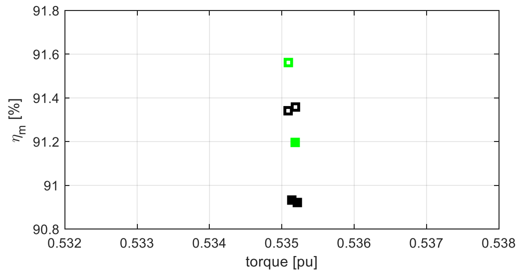

Fig. 3. Motor efficiency at default settings (black) and optimal setting of adjustment parameter (green) for two load points represented in lower and upper clusters.

2.2 Application's load-time profile

A load-time profile is defined in terms of operation time share, d_i, at specific *load points* (p_i), which are defined in terms of shaft power with respect to nominal power.

For any load-time profile, various weighted indicators can be defined, such as weighted power, weighted efficiency, and weighted loss reduction. Weighted power P_w is defined by rated power P and the load-time profile as follows,

$$P_w = P \sum_i p_i \, d_i \, , \quad P_{in\,w} = P \sum_i \frac{p_i}{\eta_i} \cdot d_i \qquad (1)$$

A weighted energy efficiency, η_w, can be calculated by using efficiency, η_i, relative shaft power, p_i, and time share, d_i, at each load point (i) of the load profile as follows:

$$\eta_w = \frac{p_{out\,w}}{p_{in\,w}} = \frac{\sum_i p_i \, d_i}{\sum_i \frac{p_i}{\eta_i} \cdot d_i} \qquad (2)$$

Lowercase p denotes per-unit values. The *weighted loss reduction*, δp_{loss} achieved by means of energy optimized control is calculated in per unit to nominal shaft power by:

$$\delta p_{loss} = p_{out\,w} \left(\frac{1}{\eta_w} - \frac{1}{\eta_w + \Delta\eta_w} \right) = \sum_i p_i \, d_i \left(\frac{1}{\eta_w} - \frac{1}{\eta_w + \Delta\eta_w} \right) \quad (3)$$

where $\Delta\eta_w$ is the weighted efficiency improvement achieved by *optimized operation* compared to *default operation*.

2.3 Large- scale evaluation

For a large-scale evaluation over a volume of specific motors N with specific rated power P, the total *absolute* power difference would be an expansion of (3) over the range j of rated power, i.e.

$$\Delta P_{loss} = \sum_j \left(N_j \, P_j \sum_i p_i \, d_i \left(\frac{1}{\eta_w} - \frac{1}{\eta_w + \Delta\eta_w} \right) \right) \quad (4)$$

This would require a unique knowledge of the individual motor in the volume, in terms of rated power, default and optimized efficiency. Such a detailed level of information is typically only available for a limited sample of motors. Considering large volumes, a simplified approach would be to use the weighted efficiency (1) as representative for the entire volume, from which the total absolute power difference would thus be defined as

$$\Delta P_{loss} = P_{total} \left(\frac{1}{\eta_w} - \frac{1}{\eta_w + \Delta\eta_w}\right) \sum_i p_i \, d_i \qquad (5)$$

3 Preconditions and assumptions

In this section we will provide some preconditions and assumptions for the calculations provided in section 2.2. The aforementioned load points have been chosen in the (speed, torque) grid as shown in **Fig. 4**. P1..P3 are present on a quadratic torque function at 0.5, 0.75 and 1 times nominal speed while P4..P5 are part load at nominal torque and speed, respectively.

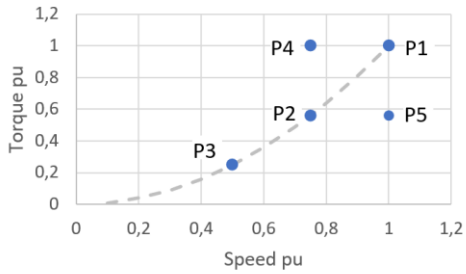

Fig. 4. Definition of load points as function of per-unit speed and torque.

Choosing a generally representative load-time profile is not trivial since applications vary greatly in their nature. Since a large part of the installed motors run either pumps or fans, the chosen load-time profile is inspired on these cases. A widely referenced load profile for circulator pumps is given by [10] and is thought to represent fan systems as well. However, to consider other applications for use here, duty cycles are biased slightly towards nominal load. This would also partially consider e.g. servo applications where the magnetization current is in general fixed at nominal value.

In summary, an assumption in the following would be a general load profile as represented by the aforementioned load points P1 – P5 with the distribution as provided in table 1:

Load point	P1	P2	P3	P4	P5
p.u power *p*	1	0.42	0.125	0.75	0.56
Duty cycle *d*	0.1	0.25	0.35	0.1	0.2

Table 1. Definition of load-time duty cycles of individual load points.

4 Results

4.1 Individual motor evaluation

Fig. 5 shows two examples of how for each load point, the optimal operating point was found by a sweep of dedicated VSD parameter as indicated in **Fig. 2**. Left plot is for asynchronous motor where the magnetization current is varied, and default value is 1 per-unit. Right plot is for synchronous motor, where the torque angle offset is varied, and default is 0 degrees. It is noted how the variation of efficiency is larger for the asynchronous motor.

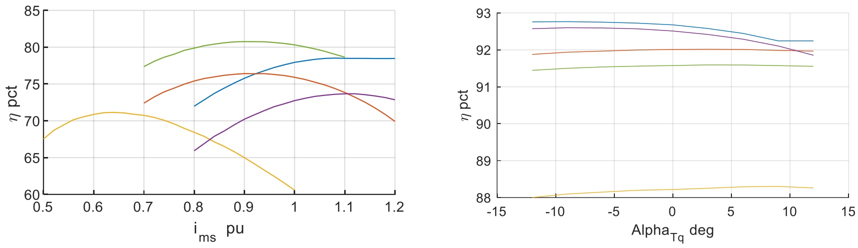

Fig. 5. Motor efficiency with different settings of VSD parameter for asynchronous motor (left) and permanent-magnet motor (right). P1: blue, P2: red, P3: yellow, P4: violet, P5: green.

For each motor type, the efficiency increase in each operating point is obtained as the difference between efficiencies at the optimum and the default value of the tuning parameter. The results are shown in **Fig. 6** for asynchronous (left) and synchronous (right) motors.

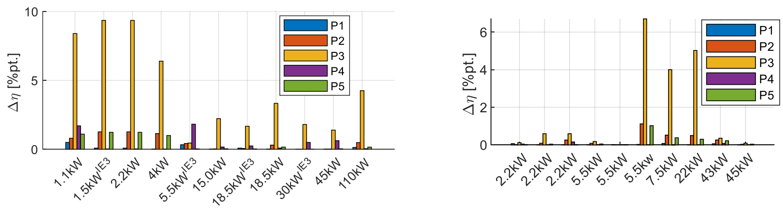

Fig. 6. Motor efficiency improvements obtained on range of tested motors. Left: asynchronous motors, right: synchronous motors.

The list of tested motors can be found in Appendix 1. It is seen that the improvements are more consistent for the asynchronous motors. In most cases, the highest potential is found with the lowest load point P3, however, some motor designs may already have been optimized for partial load operation, in which case the greatest efficiency potential is shifted to other load points. Such an example is the 5.5kW IE3 motor. In the case of synchronous motors, the improvements exceeding 2 points are a hybrid or reluctance motor type.

Using table 1, the individual load point efficiency improvements can be collapsed into a single weighted value using Equation 1. **Fig. 7** shows these values in orange, superimposed on the weighted defaults motor efficiency for the range of tested motors.

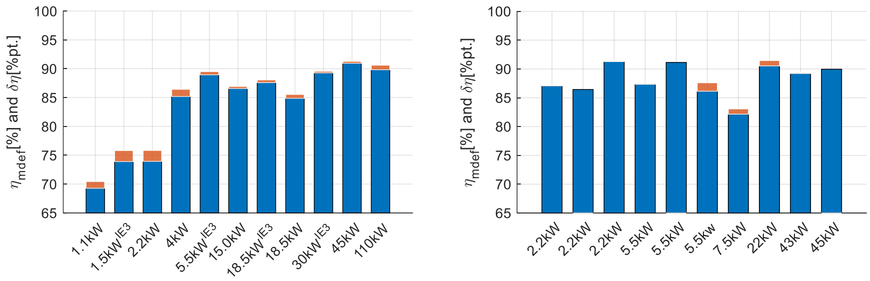

Fig. 7. Default weighted efficiency (blue) and weighted improvements (orange) on the range of tested motors. Left: asynchronous motors, right: synchronous motors.

4.2 Large-scale evaluation

Contextualizing the findings in section 4.1 is done by considering annual production volume of VSDs of a single manufacturer: Danfoss Power Electronics and Drives.
In 2022, an accumulated rated power of 32 GW was sold, where VSDs smaller than 55 kW amount to a significant fraction. Now assuming a single weighted efficiency improvement could be achieved across this range of sold power, an expanded case of equation (5) is used to calculate the reduction in *electric power produced* required to run these installations.

$$\Delta P_{el} = \frac{P_{total} \cdot k_{on}\, k_{load}}{\eta_d\, \eta_g} \left(\frac{1}{\eta_{m,def}} - \frac{1}{\eta_{m,opt}} \right) \tag{6}$$

where k_{on} is a further factor taking into account that most systems are not continually operating. $k_{load} = \sum_i p_i\, d_i$ can be calculated from table 1 to 0.44 and η_d , η_g are drive and grid efficiencies, respectively.
As seen from **Fig. 7**, motor efficiency in general varies with power size, but a representative value based on this sample volume is 87%. Likewise, a representative weighted efficiency improvement is found from the sample volume at 0.6 points.

Drive efficiency varies less, typically around 93% in part load and up to 97% at nominal load, and not so dependent on nominal power. In the following, a representative drive efficiency of 95% is used.

Finally, efficiency of the grid varies greatly worldwide, typically in the range of 85% to 95%. [11]. Here, a value of 93% is used.

Using these assumptions, *reduction in produced electrical power required to operate the systems sold in 2022 by a single drives manufacturer, provided that all motors run at their optimal efficiency at all times* is

$$\Delta P_{el} = \frac{32\ GW \cdot 0.9 \cdot 0.44}{0.97 \cdot 0.93} \left(\frac{1}{0.87} - \frac{1}{0.876} \right) \cong \text{ 110 MW} \tag{7}$$

which corresponds to approximately 1 TWh annually.

5 Conclusion

In this work we have shown that if VSDs always operates electric motors at optimum efficiency a considerable residual energy saving potential gap can be closed. Retrofitting old motors with new highly efficient ones and installing VSDs can by itself save large amounts of energy but ensuring that the VSD is operating the electric motor in the most efficient operating point can bring further savings. The precondition for energy optimum operation is that the VSD has the feature to do so and that it is commissioned and set up correctly.

The saving potential with asynchronous motors are more conspicuous as for synchronous motors, as well as the saving potential with old motors are greater as compared to motors complying to the latest efficiency regulations. Using the production numbers from one drive manufacturer and by considering the time-weighted load profiles for various typical applications and motor sizes used around the world, the savings amount to 1 TWh when operating motors optimally as compared to a standard operation mode. Assuming the same can be anticipated for all drive manufacturers, it is apparent that on a global scale it is crucial that VSDs are being commissioned for energy optimal operation wherever applicable.

6 Appendix 1

Table 2 provides an overview of the motors tested in this study. They are listed in order of appearance left-to-right in figures 6 and 7 and separated into asynchronous (upper) and synchronous motors (lower).

Manfacturer	Nominal power	Poles	Efficiency class
Efafec	1.1 kW	4	IE1
ABB	1.5 kW	4	IE3
ABB	2.2 kW	4	IE2
Grundfos	4 kW	2	IE2
ABB	5.5 kW	2	IE3
ABB	15 kW	4	IE2
ABB	18.5 kW	4	IE3
Siemens	18.5 kW	4	IE2
ABB	30 kW	4	IE3
ABB	45 kW	4	IE2
Seydelmann	110 kW	4	IE2

Manfacturer	Nominal power	Poles	Motor type
Unknown	2.2 kW	20	PMSM[1)]
Ber-Mar	2.2 kW	4	PMSM
Danfoss	2.2 kW	10	PMSM
Lafert	5.5 kW	8	PMSM
Nidec	5.5 kW	4	PM reluctance[2)]
Sisme	5.5 kW	4	Line-start PM[3)]

KSB	7.5 kW	4	Reluctance
Nidec	22 kW	4	PM reluctance
VEM	43 kW	4	PMSM
Wonder	45 kW	4	PMSM

Table 2. Overview of motors tested.

Notes:

1) PMSM describes motors whose main torque component is created by permanent magnets but may have a smaller contribution from reluctance torque.
2) PM reluctance are motors whose main torque component is created by reluctance and a smaller contribution from permanent magnets
3) The VSD used in test did not have a motor parameter detection feature for this particular motor type.

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