Impact Assessment of Machine tool auxiliary drives Oversizing to Energy efficiency Aspects

B. Riemer, T. Herold, K. Hameyer
Institute of Electrial Machines, RWTH Aachen University, Germany

Abstract
The paper focuses on the energy consumption of machine tool auxiliary drives. A detailed analysis of the electric power consumption of production lines in the automotive sector shows that machine tool auxiliary drives often have a low power factor. For uncontrolled induction machines this is an indicator for an operation in partial-load range and thus for an oversizing. The scope of this work is the evaluation of the energy efficiency of this auxiliary drives. Loss mechanisms of asynchronous machines are pointed out. The efficiency of asynchronous machines of different rated power will be assessed for a constant mechanical load. Beside the machine losses, ohmic losses of the lead wires are investigated to allow for a holistic assessment of the energy efficiency. The work shown in the paper was conducted within the project BEAT which is kindly financed by the Federal Ministry of Education and Research in Germany (BMBF).
Keywords:
Energy efficient production, machine tool auxiliary drives, asynchronous machine losses, lead wire losses

1 INTRODUCTION

Currently an increasing global demand on resources can be registered. The concurrent scarcity of resources, as well as the political ambition to reduce carbon dioxide emissions leads to a resulting increase in prices. Thus the manufacturing industry has to face energy efficiency as a central point. Actually a sufficient data basis for an energetic assessment of different process chains in the manufacturing industry is not available.

Within the project BEAT ("Bewertung der Energieeffizienz alternativer Prozesse und Technologieketten", engl.: Assessment of the energy efficiency of alternative processes and process chains) production lines in the automotive sector are investigated exemplarily regarding to their energetic behaviour. Therefore, the entire energy and resource flows are measured. The data acquisition of the electrical energy consumption shows an extensive energy conversion of auxiliary drives (e.g pump motors, hydraulic systems). Oftentimes in this area uncontrolled induction drives are applied. At the data acquisition a low power factor of many of these auxiliary drives was noticeable, which indicates an operation in partial-load range and thus an oversizing of the machine.

This paper presents the data acquisition of a gear wheel production line. The complete process chain, as well as a detailed overview over all energy and resource flows is presented in [1]. Furthermore, this paper pays special attention to the operation and the impact of oversized induction machines to energy efficiency aspects. For a holistic consideration lead wire losses of the investigated production line are discussed.

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2 DATA AQUISITION

The electrical power consumption of the machine tools is measured with a power quality analyzer. The sufficient accuracy of the power quality analyzer for the data acquisition is shown in [1]. To allow for an uninterruptable operation of the machine tools, the current is measured with current probes. For each machine tool the electrical power consumption was measured in two steps. In a first step the main incoming supply is recorded. To separate the electrical energy consumption of the main drive and auxiliary drives, each consumer is measured separately in a secondary step.

The power consumption is measured in normal operation mode, in stand by mode and in power off. In the normal operation mode the power consumption is averaged over several cycles. As it can be seen in Figure 2 auxiliary consumers take over 40 % of the full power. The main auxiliary consumers, e.g. hydraulic system pumps, cooling lubricant pumps and compressors, are mostly uncontrolled standard induction drives. The power factor of most of these drives is between 0.3 and 0.7 leading to high reactive power consumption.

For stationary induction drives this low power factor indicates an operation in partial-load range as it will be described in section 3.

3 STATIONARY INDUCTION DRIVES

Induction machines have been widely accepted in the range of stationary auxiliary drives. Standard induction machines have a simple construction. This leads to a low-priced

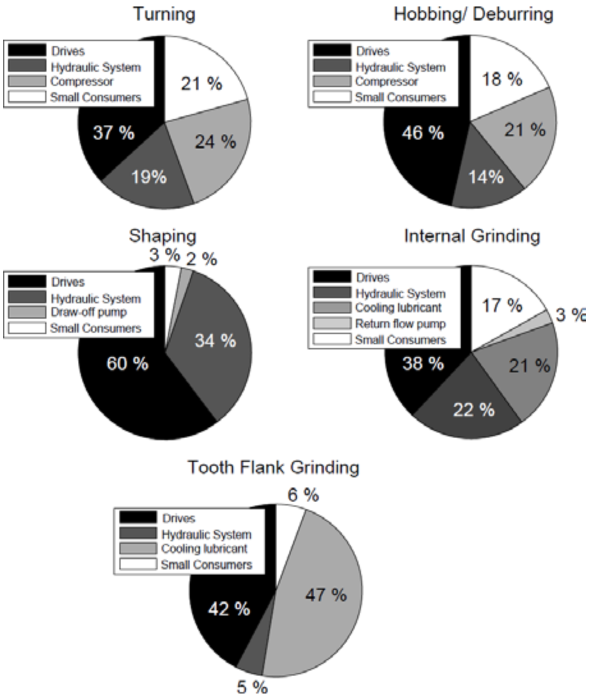
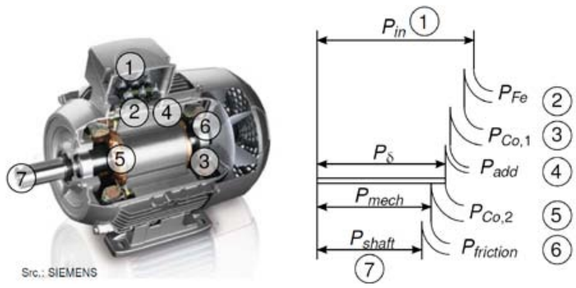


Figure 1: Power distribution of the machine tools in normal operation mode.

production. Due to their robustness, they can be applied in many different environments. For a stationary operation the induction machine can be directly connected to the grid.

3.1 Operation of an induction machine



(a) (b)

Figure 2: Schematically depicted power flow of an induction machine [2].

This section describes the operation of stationary induction drives which are directly connected to the grid. The paper concentrates on squirrel cage induction machines as depicted in Figure 2 (a). Only fundamental waves are considered for electrical quantities, therefore the power factor is equal to cos φ.

Figure 3 depicts a simplified current locus of an induction machine. This locus is valid for an operation range, where the current displacement inside the rotor bars can be neglected. This is the case for small slip frequencies. In the considered operation range from the nominal operation point (see Figure 3: OP) to partial load, the slip will decrease. Values for the nominal slip are smaller than 5% depending on the rated power of the machine. It can be seen that the power factor depends on the point of operation of the machine.

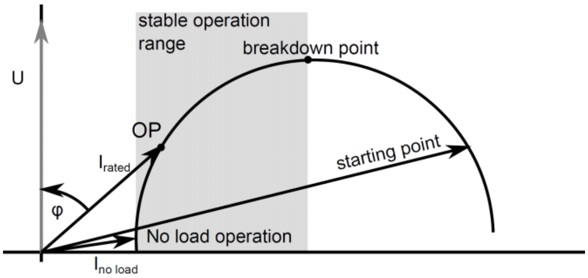


Figure 3: Simplified current locus of an induction machine.

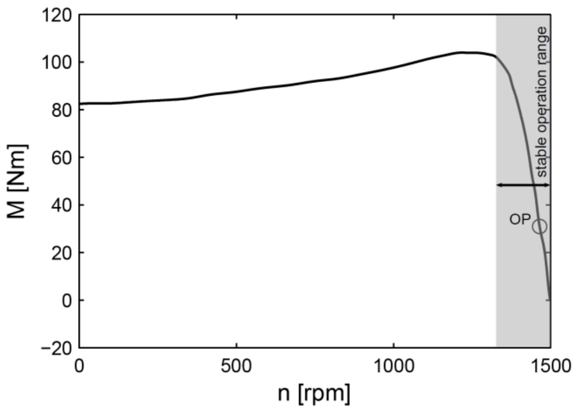


Figure 4: Typical Torque-Speed characteristic of an induction machine.

A typical torque speed characteristic of an induction machine is depicted in Figure 4. The speed depends on the loading. In the partial load range the speed comes up to the synchronous speed n_{syn}.

3.2 Efficiency of induction machines

Figure 2 (b) depicts the power flow of an induction machine. Different loss mechanisms have to be regarded. Inside the stator winding losses, iron losses and load dependent additional losses occur. Ohmic losses in the three-phase winding are defined by:

$$P_{co,st} = 3 \cdot I_1^2 \cdot R_1, \tag{1}$$

with the resistance R_1 and the current I_1. The load dependent additional loss term considers losses in the active part of the iron and other metal parts of the machine. According to DIN-EN 60034-2 [3] load dependent additional losses are defined by:

$$P_{add,rated} = P_{in} \cdot \left[0.025 - 0.005 \cdot \log_{10}\left(\frac{P_{mech}}{1\text{kW}} \right) \right]. \quad (2)$$

Equation 2 is valid for induction drives of a rated power $1\text{kW} < \text{P}_{\text{mech}} < 10{,}000\text{kW}$. For different loads than the nominal load additional losses can be calculated by:

$$P_{add} = P_{add,rated} \cdot \left(\frac{I_1}{I_{1,rated}} \right)^2. \quad (3)$$

Classical iron losses of the stator can be assumed as constant over the considered operation range. Iron losses are specific losses which increase with an increasing amount of stator iron, and so with an increasing rated power of the induction machine. Stator losses are frequency dependent. The rotor of an induction machine is only penetrated with a field alternating with the slip frequency of a few Hz and will be neglected. Then, the only considered electrical losses inside the rotor are ohmic copper losses, which are defined as:

$$P_{co,2} = P_{mech} \cdot \frac{s}{1-s}, \quad (4)$$

with the slip:

$$s = \frac{n_{syn} - n}{n_{syn}}. \quad (5)$$

Modern induction drives are classified into efficiency classes IE1 to IE3 according to IEC 60034-30 [4]. Figure 5 depicts the efficiency of induction drives of efficiency class IE1 and IE2 for different numbers of pole pairs p.

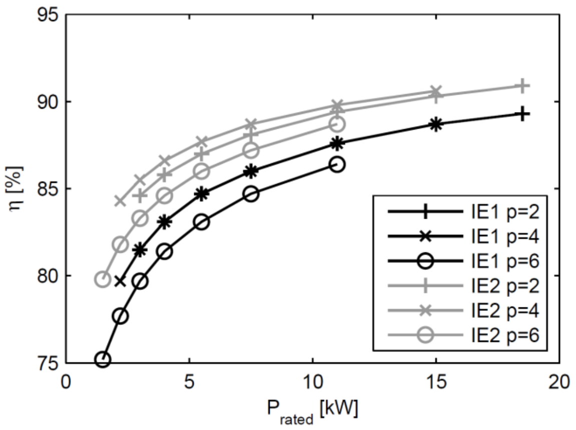


Figure 5: Efficiency of standard induction machines of different rated power and pole pair numbers [5].

The efficiency of induction drives increases with an increasing rated power. The efficiency of an induction machine is nearly constant up to an operation of 3/4 rated load. This can be seen in Figure 6. The depicted efficiency characteristic and the mechanical power are calculated from manufacturer data sheets [5]. Behind the marked range the efficiency decreases up to zero in no load operation. Due to the fact that machines with higher rated power have a higher efficiency, it seems to be possible that an oversized machine will have lower losses than a smaller machine operating in the nominal point. Therefore in the following section induction machines of different rated power will be compared at operation at constant load.

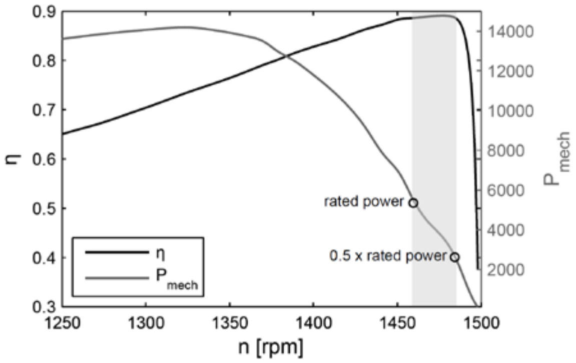


Figure 6: Efficiency and mechanical power of a 5.5kW induction machine.

3.3 Loss distribution of induction machines

The data basis of the following investigation is obtained from manufacturer data sheets [5]. The induction machines are classified with efficiency class IE2. Four machines with ratings between 2.2 kW and 7.5 kW are considered. The nominal input voltage is 400 V. The load is kept constant at 2.2 kW.

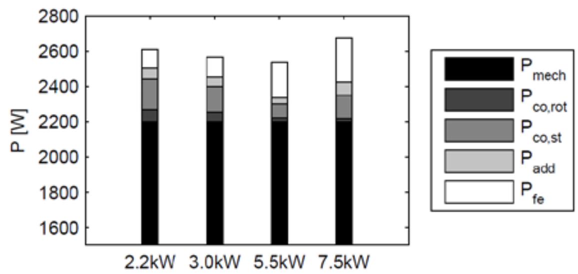


Figure 7: Power distribution of different rated induction machines at constant load P=2.2kW.

Figure 7 depicts the comparison of the power distribution of different rated machines at constant load of 2.2kW. The losses are calculated based on data from manufacturer data sheets. As expected the iron losses increase with an increasing rated power due to the higher amount of stator iron. The rotor copper losses decrease with a higher rated power due to a decreasing slip. By the smaller winding resistance for larger machines the stator copper losses also decrease. Bearing and friction losses are included in the mechanical power and are not separated in this analysis. The power factor of the induction machine decreases by an increasing rated power. Table 1 shows the power factor and the efficiency of the investigated induction machines at 2.2kW load and at rated operation of each machine. It is shown that the efficiency of the 3.0kW and 5.5kW machine for the applied partial load exceeds the efficiency of the small machine in rated operation. The 7.5kW machine is loaded with only 30% of its rated load. In this operation point the efficiency decreases to 82.2% and the operation gets inefficient. The presented investigations affirm results from [6].

Table 1: Efficiency and power factor of different Induction machines.

P_{rated} [kW]	$\eta_{100\%}$	$\cos\varphi_{100}$	$\eta_{2.2kW}$	$\cos\varphi_{2.2kW}$
2.2	84.3 %	0.81	---	---
3.0	85.5 %	0.82	85.7 %	0.75
5.5	87.7 %	0.80	86.8 %	0.62
7.5	88.7 %	0.83	82.2 %	0.40

4 LEAD WIRE LOSSES

4.1 Calculation of lead wire losses

To get a holistic overview over the efficiency of induction machines lead wire losses, which will increase with a lower power factor, has to be considered. Lead wire losses are ohmic losses on the lead wires. They are defined as:

$$P_{Loss} = \frac{3 \cdot l \cdot I^2}{\sigma \cdot q}, \quad (5)$$

with the length of the lead wire l, the lead wire current I, the electrical conductivity σ and the cross-section of a strand q. Assuming a constant active power which is submitted over the wire the current magnitude will depend on the power factor of the consumer:

$$I = \frac{P_{cons.}}{\sqrt{3} \cdot U \cdot \cos\varphi_{cons.}}. \quad (6)$$

Applying equation 6 to equation 5 leads to:

$$P_{Loss} \sim \frac{1}{\cos^2 \varphi_{cons.}}. \quad (7)$$

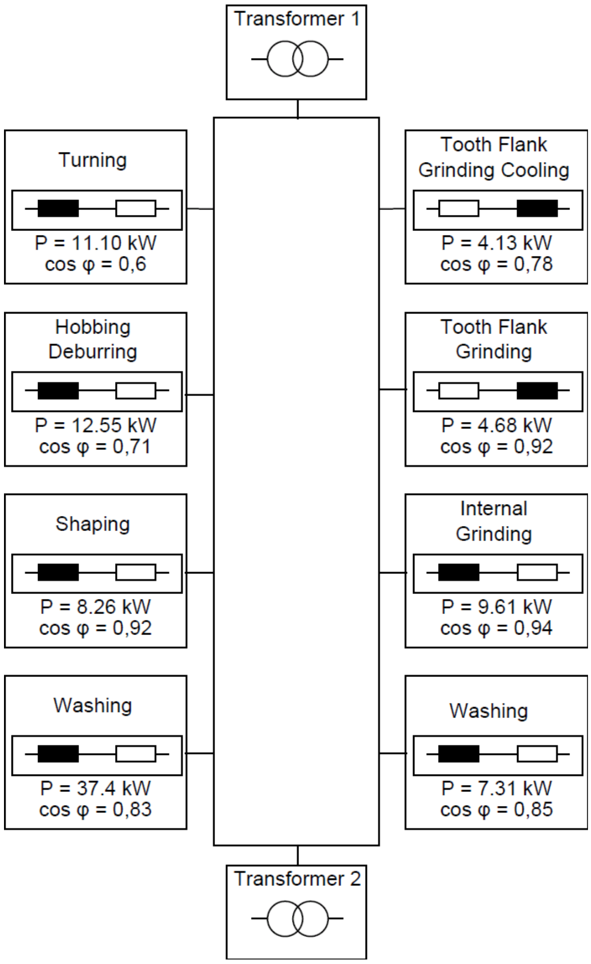


Figure 8: Schematical power grid of the production line.

4.2 Calculated lead wire losses of the measured production line

The lead wire configuration of the investigated production line is not known in detail. Nevertheless, to consider lead wire losses a ring system as it is schematically depicted in Figure 8 is assumed. The lead wire cross-sections are determined so that the maximum allowable voltage drop is abided. The length of the lead wire is fixed to 10m for the line between a machine tool to the ring system and to 20m of each section of the ring grid. Two feeding transformers are considered as they are classically used in ring systems. Data basis for the calculation is the measured power consumption of the machine tools.

The calculated lead wire losses by equation 5 are 552W in normal operation and 243W in standby mode. Taking as basis an average utilisation ratio of 52% for normal operation and 29% in standby mode, the annual energy consumption of lead wires is 3132 kWh.

4.3 Improvement of the Turning machine

The power factor of the turning machine is with a value of 0.6 low compared to the other machine tools. From Figure 2 it is known that the turning machine has two large auxiliary drives, the hydraulic auxiliary system and a compressor. The compressor has a power consumption of 2.2 kW with a power factor of 0.6. As it was shown in section 3 the low power is founded by an operation in partial load range. A replacement of the induction machine with an induction machine rated at 2.2kW will lead to a higher power factor of the compressor of 0.81 (see Table 2). The adapted compressor improves the resultant power factor of the complete turning machine to 0.67. The input power increases due to the lower efficiency of the compressor to 11.13kW. Due to the higher power factor, the complete lead wire losses are reduced by 41 W to 511W. A comparison of both machines shows that the turning machine with an adapted compressor operating at rated conditions has by 34 W higher losses, despite the better power factor.

5 CONCLUSION

This paper discusses the effect of oversized machine tools auxiliary drives to energy efficiency aspects. It is shown that the efficiency of typically used standard induction machines increases with an increasing rated power. The use of an oversized induction machine can be more efficient than the use of an adapted machine. It is shown that for a constant load of 2.2kW an induction machine rated at 5.5kW produces minor losses than an induction machine of 2.2kW. But it has to be considered that the efficiency advantage vanishes, the more the machine is operated at no load condition. As an example a 7.5kW machine is loaded with only 30% of its rated load and its efficiency decrease to 82.2 % compared to 84.3% of the 2.2kW machine in rated operation.

For a holistic view on the energy efficiency, lead wire losses are considered. By the lower power factor of induction machines which operates in partial load range, lead wire losses will increase. Lead wire losses are estimated for the given production line. They amount to less than 1% of the consumed active power of the machine tools. An adaption of a compressor of a turning machine to improve the power factor of the complete machine decreases the lead wire losses, but due to higher machine losses the resulting consumed active power increases compared to an oversized compressor.

This paper shows that oversized induction machines can be more efficient than adapted machines, despite a lower power factor and therefore higher lead wire losses.

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