A quantitative comparison between BLDC, PMSM, Brushed DC and Stepping Motor Technologies

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Abstract- **Brushless DC machines (BLDC), Permanent Magnet Synchronous Machines (PMSM), Stepping Motors and Brushed DC machines (BDC) usage is ubiquitous in the power range below 1,5kW. There is a lot of common knowledge on these technologies. Stepping Motors are ideally suited for open loop positioning, BLDC machines are the most obvious candidate for high-speed applications, etc. However, literature lacks comprehensive research comparing these machines over a large range of applications. In this paper, more than 100 motors are considered. Their characteristics are compared and presented in a comprehensive way. These results support the common knowledge concerning the field of application of each technology and new insights follow from this quantitative comparison.**

I. Introduction

Within the power range up to 1500W, machine constructors often doubt between different motor technologies for their drivetrains. In this paper, a range of properties of the machines in Table I are considered and compared to each other in order to back up the choice between motor technologies with concrete numbers. Before comparing these technologies based on data in section III, a summary of the common knowledge and operating principles of these machines is given in section II.

Table I: Machines considered in this study

Motor technology	*Number of machines*	*Number of suppliers*
Brushed DC	23	2
BLDC	21	2
PMSM	26	2
Stepping Motor	34	3

II. Operating Principles

A. Brushed DC machines

In Brushed DC machines the rotor field position is adapted by means of brushes. This results in the simplest machine from a user's perspective as providing a constant DC voltage is enough to drive the motor. When permanent magnets are used to generate the stator field, a compact construction is possible [1]. On the other hand, the brushes used for commutation reduce the robustness [2]. Due to wear of the commutator or the brushes, the lifetime of these motors is limited [3]. This is the major drawback of this technology. Driving a Brushed DC machine in its simplest form is depicted in red in Fig. Figure 2. Position and speed control (depicted in grey in Fig. Figure 2) is possible if some kind of position feedback is available.

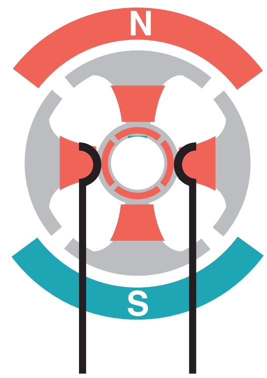

Figure 1: Operating principle of a permanent magnet Brushed DC machine

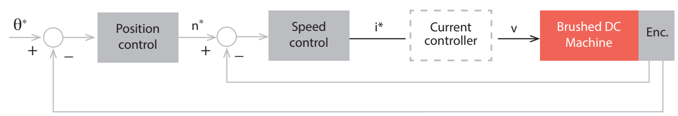

Figure 2: Position control of a Brushed DC Machine

B. Brushless DC machines

For Brushless DC machines (BLDC) the rotor is equipped with permanent magnets but the stator field position should be changed over discrete positions to generate torque as depicted in Fig. 3. Consequently, optimal current wave form as depicted in Fig. 4 takes the form of square waves. Even at high speeds this current waveform is not demanding for current controllers. Together with these current waveforms the absence of brushes means the BLDC motor is the best candidate for high speed applications [4]. Therefore, these motors are mostly used for continuous operation in compressor, pump and ventilation systems [4]–[6].

On the other hand, position feedback is necessary to determine the optimal commutation of the current. However, this feedback can take the form of discrete and rather cheap Hall sensor signals.

Driving a Brushless DC machine (BLDC) in its simplest form is depicted colored in Fig. Figure 6. As indicated a drive and position feedback are minimum requirements to drive a BLDC motor. In commercial drives speed control in the higher speed range is often already possible using the available Hall sensors [7]. For position control and speed control at lower speeds more accurate position feedback is necessary.

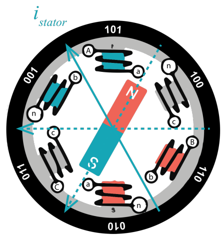

Figure 5: Operating principle of a brushless DC machine

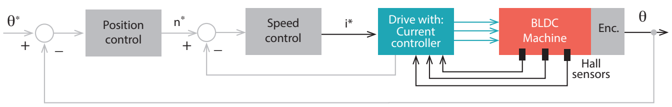

Figure 6: Position control of a BLDC machine

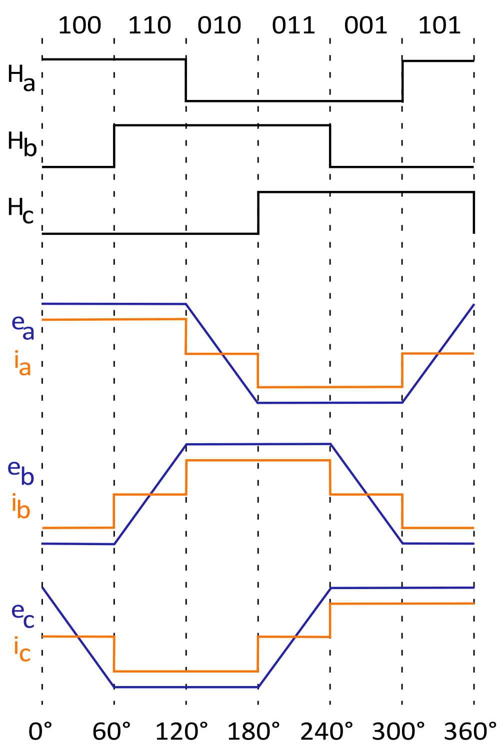

Figure 7: Back-EMF (blue) and optimal current profiles (red) in each phase together with Hall sensor signals (black)

C. *Permanent magnet synchronous Machines*

When the placement of stator magnets in a BLDC is adapted so that the back-EMF takes a sinusoidal form as depicted in Figure 8, a PMSM motor is obtained. Optimal and ripple free torque generation is obtained if the current waveform follows the sinusoidal waveform of the back-EMF. Therefore, accurate continuous position feedback is necessary. The construction and drive methods of these machines result in a good performance, negligible torque ripples [8] and energy-efficiencies up to 97% [9]. However, these brushless AC motors (also often called permanent magnet excited AC motors (PMSM)) have a more complex construction compared to brushless DC machines resulting in a higher price. As accurate position feedback is necessary for torque generation these motors are ideally suited for high-end industrial position or speed controlled applications [10]–[12]. Figure 9 shows the basic configuration of a PMSM system (colored) and the optional speed and position control loops. The latter are easily implementable in the drive as the encoder is already necessary for torque control.

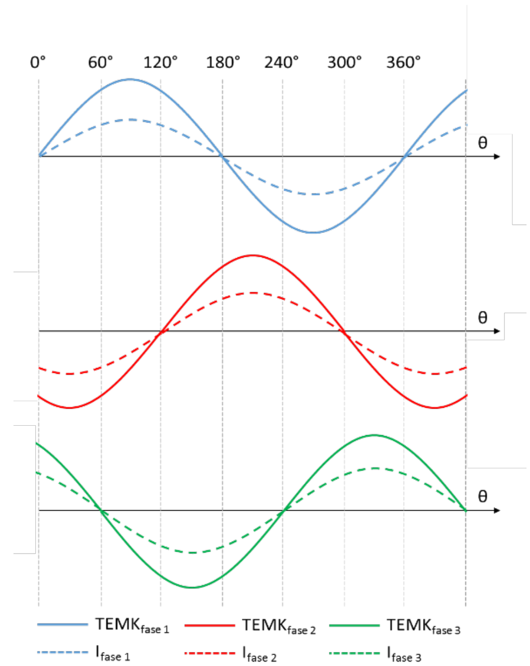

Figure 8: Back-EMF and optimal current profiles for a three phase PMSM

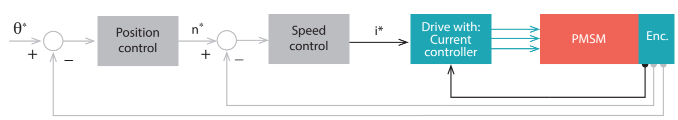

Figure 9: Position control of a PMSM machine

D. *Stepping motors*

The two-phase hybrid stepping motor principle is illustrated in Fig. Figure 10 [13], [14]. The stator is equipped with concentrated windings while the multitoothed rotor is magnetised by means of permanent magnets. The rotor teeth are attracted by the excited stator phase. When a new full-step command pulse is given by the user program to the drive, the excitation of one phase is released while a second phase is excited. Using half- and micro-stepping algorithms, two phases are excited simultaneously in order to increase the number of rotor position steps in a single revolution [15].

By counting the step command pulses, the theoretical rotor position is known and open-loop positioning is achieved. This means no sensor or cascaded control is needed for positioning. Therefore, stepping motors are very appealing for industrial and domestic positioning applications.

However, basic open-loop drive algorithms such as full-, half- and micro-stepping result in torque and speed ripples, noise, vibrations, a poor energy efficiency and no control on step loss [15]–[17].

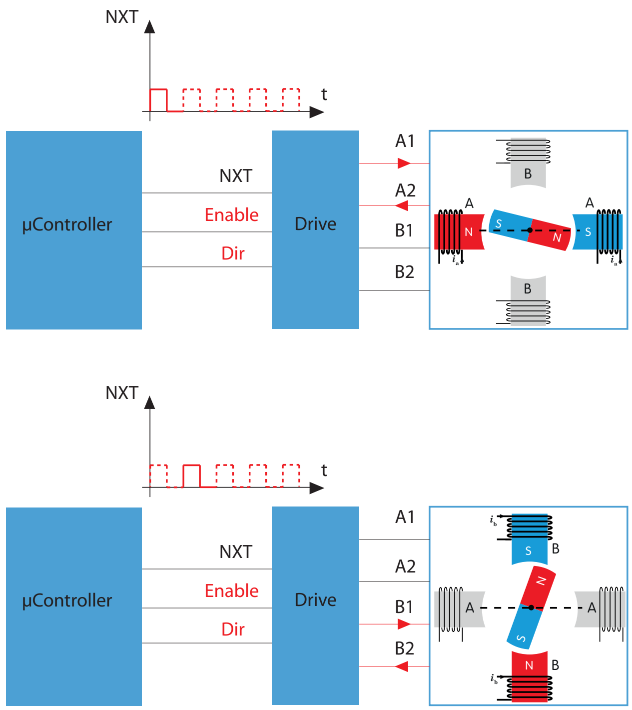

Figure 10: Hybrid stepping motor principle and control hardware

E. *Theoretical conclusion*

Based on the theoretical description of the motor technologies and their operating principles the following, common knowledge guidelines for choosing a motor technology can be summarized:

- A Brushed DC machine is still interesting in some cases due to its very simple torque generation for which no drive is needed. However, its lifetime is limited due to wear.
- BLDC machines are ideally suited for high speed applications.
- PMSM machines give the best performance.
- Stepping motors are ideally suited for open loop positioning.

All four motor technologies allow for position control. However, for some motor technologies this means extra components such as feedback or a drive are needed. Only using the colored minimal configuration depicted in Figure 2, Figure 6, Figure 9 and Figure 10 the following control is possible:

- Open loop drive of a Brushed DC machine.
- Speed control (only accurate at higher speeds) with a BLDC machine.
- Position control (if a cascade control loop is implemented in the drive) with a PMSM machine.
- Simple open loop position control with a stepping motor.

III. Quantitative Comparison

While the previous description of motor technologies and their pros and cons is well known, the novelty in this paper is the comprehensive quantitative comparison between the 100 machines listed in table I. This comparison is done based on the following properties: volume, nominal torque, maximum torque, maximum speed, power, rotor inertia, maximum acceleration and price.

A. *Speed*

When the nominal rotational speed of the electrical motors is compared to the rated power in Fig. Figure 11 the theoretical statement that a BLDC machine is ideally suited for high speed applications is confirmed. Especially smaller BLDC machines with low inertia are able to obtain high rotational speeds. Stepping motors on the other hand seem to be a rather bad option for high speed applications. The maximum speed of Permanent Magnet Machines is limited by the ability of the power convertor to generate a sinusoidal current profile. Finally, the Brushed DC machine maximum speed will be limited by the wear of the brushes at higher speeds.

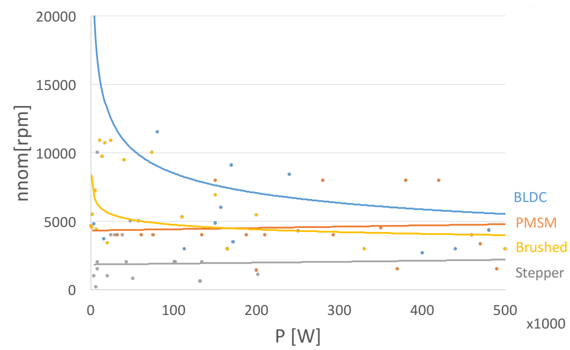

Figure 11: Nominal motor speed compared to rated power

B. *Torque*

Depicting the torque compared to the volume as in Fig. Figure 12 reveals the supreme torque density of stepping motors. Thanks to the optimal commutation PMSM machines are characterized by a higher torque density compared to BLDC and Brushed DC machines. The latter shows the lowest maximum torque compared to volume.

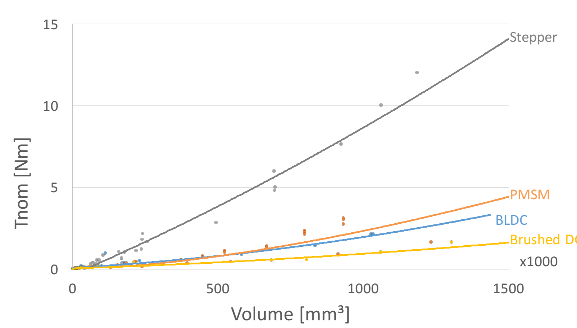

Figure 12: Nominal motor torque compared to motor volume

C. *Power Density*

If volume is an issue, fig. Figure 13 shows the optimal machine in terms of power density is a PMSM closely followed by stepper motors thanks to their high torque capabilities.

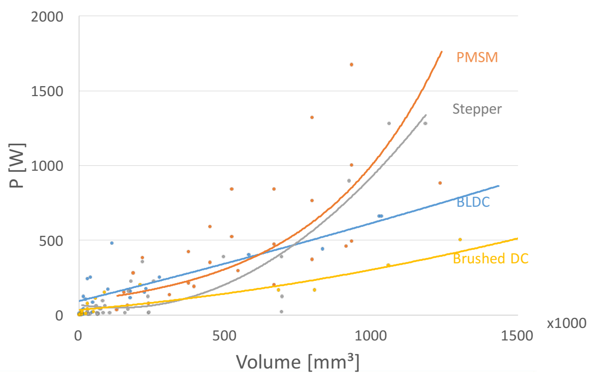

Figure 13: Motor power compared to motor volume

D. *Acceleration and overload capacity*

For dynamic applications the maximum acceleration is of interest. Therefore, the maximum motor torque is divided by the rotor inertia and plotted against the rated power in Fig. Figure 14. The load inertia should be included as well but this greatly depends on the application and therefore Fig. Figure 14 only mentions the maximum motor acceleration. This graph illustrates the high dynamic performance of BLDC machines in the power range below 500W. However, at higher rated powers the PMSM becomes equally interesting in terms of dynamics. Overall the stepping motors is not that interesting for dynamic applications.

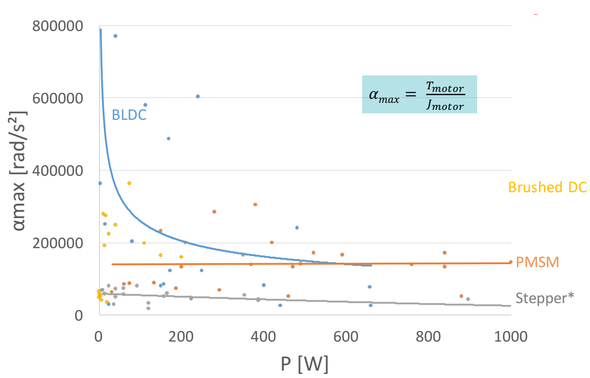

Figure 14: Maximum acceleration compared to motor power

Brushed DC, PMSM and BLDC datasheets mention a nominal torque T_{nom} (Fig. Figure 12) and maximum torque T_{max} applicable for a short period of time. The ratio between these two can be seen as the overload capacity. This capacity, given in Figure 15, can be useful in high dynamic applications as extra temporarily available torque can be beneficial for quick acceleration. Surprisingly the Brushed DC machine is the best suited motor when it comes to overload capacity. Depending on the rated power the BLDC scores slightly better than the PMSM (below 750W) or the other way round (higher then 750W).

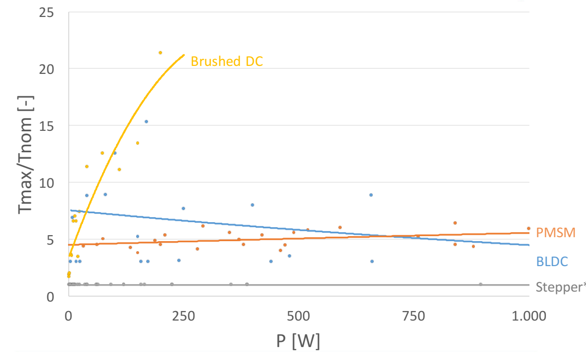

Figure 15: Overload capacity compared to motor power

E. *Price*

Finally, the price can be a very strong argument to choose for a certain motor technology. Therefore the price of the minimal motor configuration (colored in Figure 2, Figure 6, Figure 9 and Figure 10), given on the internet or in publicly available datasheets, is plotted against the nominal speed (Figure 16), the motor torque (Figure 17) and the motor power (Figure 18). This means the prices mentioned in Figs. 16 to 18 enable position control with PMSM (if a cascaded control loop is implemented and tuned) , stepping motors, speed control with a BLDC (if a speed control loop is implemented and tuned) and open loop operation with a Brushed DC machine. The graphs reveal the cheap character of a stepping motor drive combination while a PMSM-encoder-drive combination is in all cases the most expensive solution.

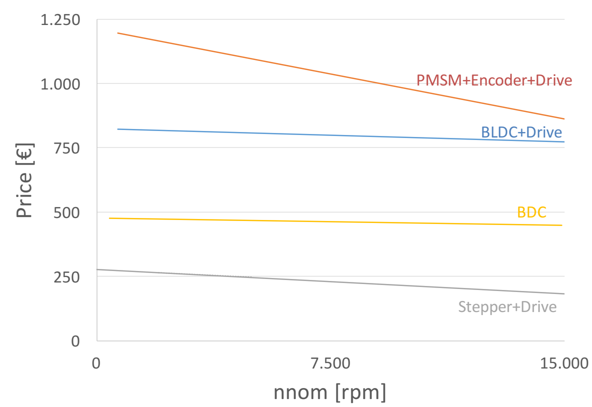

Figure 16: Unit price compared to motor speed

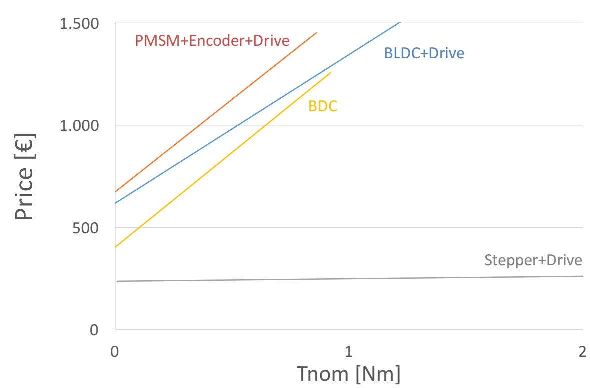

Figure 17: Unit price compared to motor torque

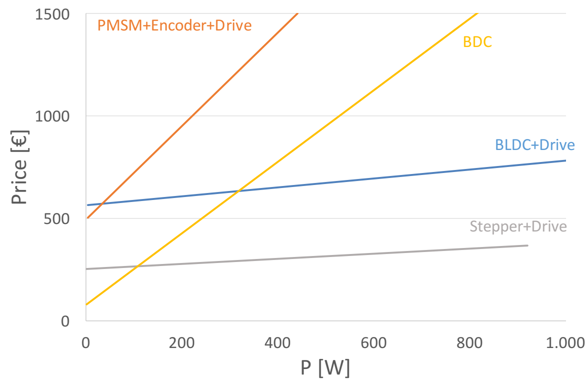

Figure 18: Unit price compared to motor power

F. Concluding comparison

The results of Figs. Figure 11Figure 18 are summarized in table II. A few conclusions can be drawn from this comparison. First of all, a BLDC machine is best suited for high speeds. For high torques on the other hand a stepping motor is the best option. When it comes to power density a PMSM is best suited while maximum accelerations will be obtained with BLDC machines. The overload capacity is best for Brushed DC machines while stepping motors are the most economical solution.

Table II: Performance on different criteria (1: best, 4: worst)

Criterion	*Brushed DC*	*BLDC*	*PMSM*	*Stepping Motor*
Nominal speed	2-3	1	2-3	4
Nominal torque	4	3	2	1
Power Density	4	3	1	2
Maximum Acceleration	-	1	2	4
Overload capacity	1	2-3	2-3	4
Price	2	3	4	1

IV. Conclusions

A quantitative comparison between motor technologies can add useful information to the common knowledge on choosing an optimal motor technology.

It is a common misassumption that a Brushed DC machine is the cheapest option. However, this machine is still interesting due to its high overload capacity.

BLDC machines are especially interesting for high speed applications and applications where a continuous rotation is needed. Using them to position would be cost inefficient but eventually justifiable based on its high dynamic performance.

PMSM machines are known to be the most expensive option but as the minimal configuration already requires position feedback they are ideally suited for accurate positioning.

Stepping motors seem to score extremely well on maximum torque. They are interesting for open loop positioning. However, using them to drive continuous loads such as a fan or pump is not a good option given the limited maximum speed. The latter can only be justified by its low price.

V. References

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