# Influence of an Electrical Machine on the Dimension and Packaging of Multi-Machine Systems

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## Keywords

≪Electrical machine≫, ≪Multi-machine system≫, ≪Packaging≫, ≪Standardization≫, ≪Marine≫, ≪Ship≫

## Abstract

The design of multi-machine systems requires the estimated installation space of the e-machines. Developed models calculate the space for different speeds and power concepts. Hereby, the advantages of combining several drives is shown. The paper illustrates the importance of machine parameters and number of units for a multi-machine system. The outlook gives an impression on how the efficiency of the e-machine can be improved by the operation management.

## Introduction

High power density is an important design goal for power train applications [3]. Typically, a combination of an e-machine and a gearbox reduces space requirements. The gear ratio is the main design parameter in single-machine applications and it is used to optimize the systems installation space. RENK's AED concept is an example of electromechanical drive trains for ships, consisting of an asynchronous machine and a transmission gearbox [4]. In the industrial and automotive sector, there are concepts that combine several electric machines onto one gearbox [5], [6]. This leads to more compact and lighter e-machines. Higher reliability [7], standardization and design cost savings are further advantages compared to other concepts [8], [9].

However, it remains the question how multi-machine drives with maximum power density look like. Of specific interest is the empirical model of the machine's installation space. As a contribution to answer this question, this paper focuses on the development of growth models. Based on the design equations and empirical modelling, the installation space of an e-machine for a special speed and shaft power is calculated. The corresponding power curve shows that the nominal shaft power decreases for higher speeds due to electromagnetic limits. This is one reason, why several machines must be combined to reach a system power of some megawatts. These models are combined with a gear model and they are used for multi-motor system concept comparisons. The models illustrate how the number, speed and power of the machines influence the dimensions and packing density.

## Structure of multi-machine drives

The typical structure of a multi-machine drive with a single-stage gearbox is shown in figure 1. Several e-machines drive the central wheel via a pinion. The torque at the output shaft is the sum of all pinions times the gear ratio. The required volume corresponds to a cylinder with the overall diameter $D$ (red) and length $l$ according to:

$$V = \frac{\pi}{4} \cdot D^2 \cdot l \tag{1}$$

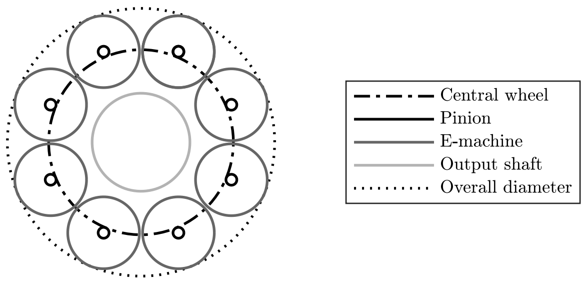


Fig. 1: Front view of a multi-motor system with eight e-machines

Due to the square in equation 1, the diameter dominates over the length. This is the central parameter for the design space. As figure 1 shows, the machines are typically arranged equally spaced in a circuit. For the arrangement of $k$ machines with a flange diameter $d$ in a closed circle, the overall diameter $D$ must be at least [10], [11]:

$$D = d + \frac{d}{sin(\pi/k)} \tag{2}$$

Connecting equations 1 and 2 shows that the space requirement of multi-machine system mainly depends on the flange diameter $d$ of the machine and number of machines $k$.

## Growth model of an electrical machine

The model is based on having the same conditions for the type, voltage and cooling of the e-machines. This paper uses permanent magnet synchronous machines with low voltage up to 690 Volts and a water jacket cooling. The installation space for a specific power and speed is determined via design equation 3. In the literature [12], [13] the shaft power of an e-machine $P_m$ is calculated from the mechanical Esson's utilization factor $C_m$, the stator bore diameter $D_i$, the length $l_i$ and the speed $n$:

$$P_m = C_m \cdot D_i^2 \cdot l_i \cdot n \tag{3}$$

Since the rotor diameter is much larger than the air gap, the bore diameter $D_i$ roughly equals the rotor outer diameter $D_r$, i.e. $D_i = D_r$. For the design of the system, the maximum possible diameter of a machine is the greatest challenge. Consequently, the maximum circumferential speed is used to determine the largest rotor and stator diameter:

$$D_i = \frac{v_{max}}{\pi \cdot n} \tag{4}$$

The diameter $D_i$ is thus indirectly proportional to the machine speed:

$$D_i \sim \frac{1}{n} \tag{5}$$

Equation 4 is the basis of all following diameters – housing, flange and shaft size. Figure 2 illustrates the curve shape for the rotor and the estimated housing. Theses model was validated with reference e-machines. Basically, the e-machine becomes slimmer by increasing speed.

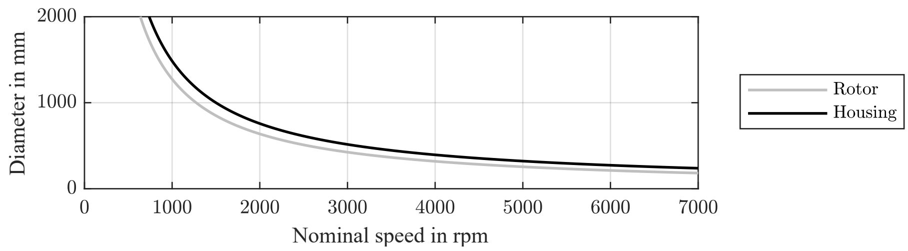


Fig. 2: Speed-dependent diameter curve of the e-machine

The total length of the e-machine is composed of the active iron length, bearing shields and winding heads. Basically thermal and mechanical limits determine the rotor length and the whole machine. Müller and Ponick shows that the relation between length and diameter can be reduced and assumed as [12], [13]:

$$l \sim D_i \tag{6}$$

The resulting housing length is therefore speed-dependent. Manufacturers usually group machines with the same diameter but different lengths into series. The range in length is given in the diagram below.

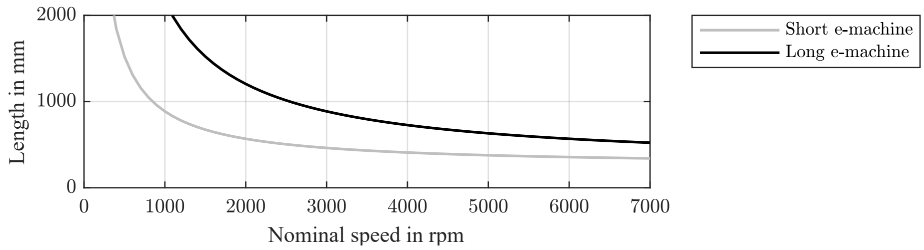


Fig. 3: Speed-dependent max e-machine length

As already shown above, the diameter and length of an e-machine decreases with increasing speed. A high-speed machine is therefore more compact; the correlation is expected to be $V \sim n^{-3}$. If the same electromagnetic conditions are set and the volume of the active part decreases, the maximum possible power declines to the same extent [12], [13]:

$$P \sim D_i^3 \sim n^{-3} \tag{7}$$

The figure 4 gives an overview of the speed-dependant power of a standard e-machine series. The curve underlines the equation 7.

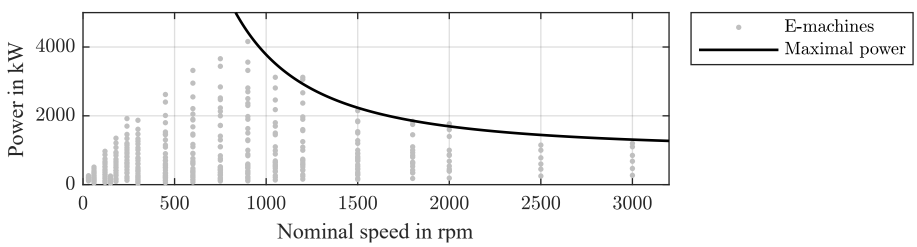


Fig. 4: Course of the maximum power of an e-machine over the speed

## System Behavior

A higher speed of the e-machines leads to lower shaft power. For this reason the number of machines must increase, see Fig. 5. The figure underlines the importance of multi-machine concepts. Several machines must be combined to reach a system power of a few megawatts.

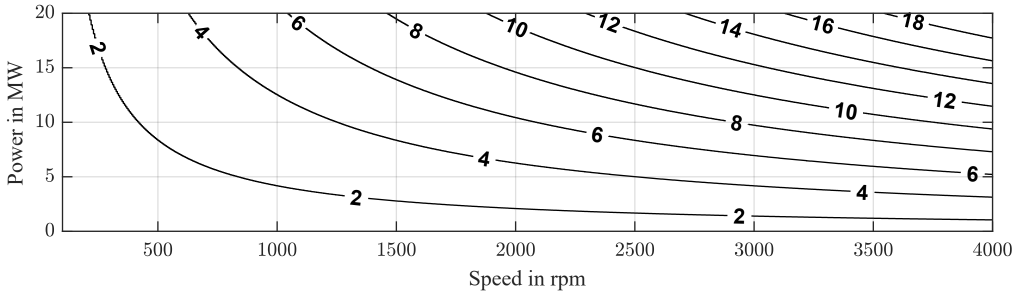


Fig. 5: Required number of standard machines as a function of speed and power

During the design of a multi-motor system there are a few degrees of freedom:

- gear ratio $i$
- number of pinions $z_p$
- number of e-machines $z_e$

These design parameters define the power and speed of the e-machine and its installation space. The gear ratio $i$ of the summation gear determines the e-machine's speed by multiplying the gear ratio $i$ and the speed of the output shaft. The second degree of freedom is the number of pinions $z_p$, which are driving to one central wheel. Additionally, one or two e-machines can be mounted on one pinion. Therefore, the number of installed e-machines $z_e$ is the third degree of freedom.

The figure 6 shows diameters curves for different system concepts for an output shaft power of 5 megawatts at speed of 200 rpm. There is one installed machine per pinion. Due to the interaction of e-machine and gearbox model, two trends can be seen. Firstly, the curve drops steeply for small gear ratios, since the machine's diameter dominates. Secondly, the curve rises for increasing gear ratios, because the central wheel gets bigger and therefore the gearbox dominates. According to the equation 2, the solutions are differentiated between placing the machines in a common pitch circle, solid lines, or not, dashed lines. The curves suggest a minimum with 8 pinions, which is set as reference for the axes. To sum it up, the curves suggest a minimum of the diameter for all numbers of drives.

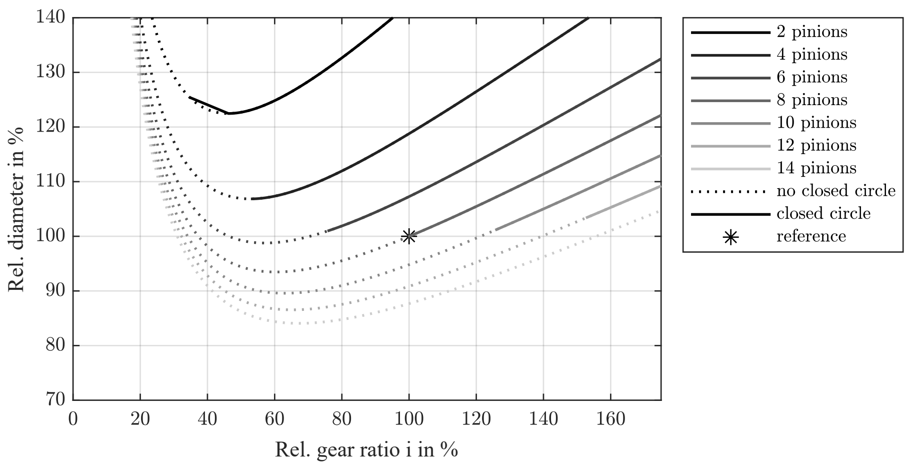


Fig. 6: Comparison of different concepts with one e-machine per pinion

A higher number of e-machines leads to a more compact machine but a higher gear ratio is needed to mount the machines in a common pitch circle. All in all a reduced diameter results when the amount of machines increases. That is why the number of 8 pinions seems to be a optimum solution concerning the diameter.

The length of the overall system with one e-machine per pinion is the sum of e-machine length and the gear unit width. Figure 7 shows the technically maximum lengths. Due to the relation $V \sim D^2 \cdot l$, the length plays a subordinate role in the installation space consideration. In additional, multi-motor applications usually use higher gear ratios and the relative difference in length between different speeds gets very small.

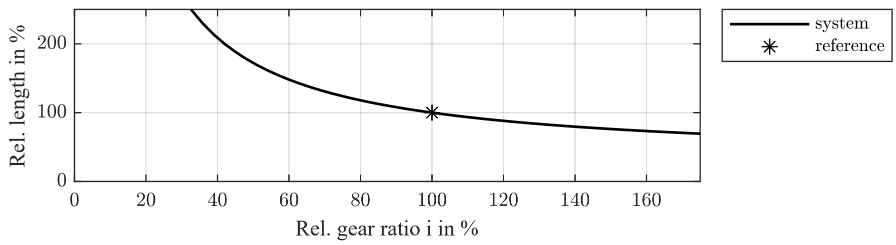


Fig. 7: Length of the total system

Another possibility to reduce the system diameter is to mount two e-machines per pinion. In this way, the torque requirement of one e-machine is put to half. According to equation 4, the torque or P/n-ratio essentially determines the diameter. Depending on the physical limits, the diameter $D_i$ can be reduced and power $P$ is delivered by two smaller e-machines. The speed $n$ is not changed. For equal electro-magnetic and thermal boundary conditions the Essons's utilization factor $C_m$ is identical for one or two e-machines per pinion. The following equation shows, that it results a smaller diameter of round about 70 percent.

$$D_i = \sqrt{\frac{P_m}{n \cdot C_m \cdot 2 \cdot l_i}} \simeq \sqrt{\frac{1}{2}} \tag{8}$$

A smaller diameter of the machines makes the system more compact, see equation 1. Figure 8 illustrate the relative diameter advantage compared to the reference system with 8 pinions and 8 machines. For the same machine speed, the diameter can be reduced by nearly 10 percent. In addition, the figure shows a new minimum (circle) for a concept with 8 sprockets and 16 e-machines.

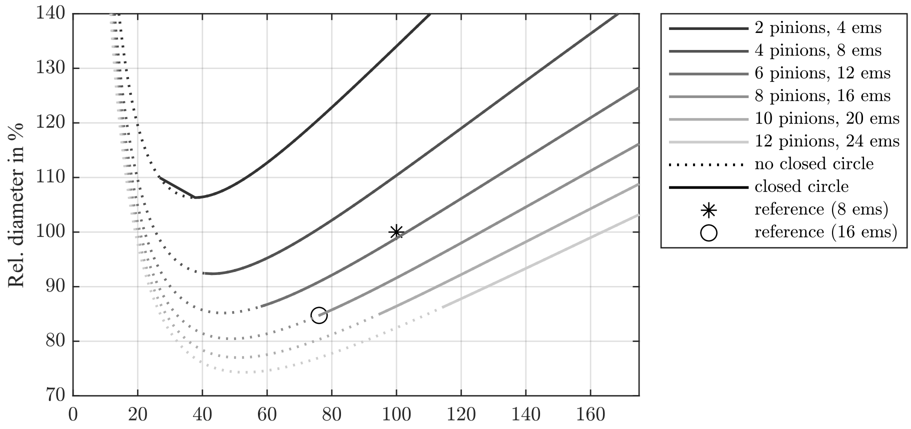


Fig. 8: Systems lengths for concepts with two e-machines per pinion

The diameter for the new minimum can be reduced to about 85 percent of the reference concept. This new minimum confirms that 8 pinions driven by two e-machine per pinion are useful. Further, this concept uses less gear ratio, round about 75 percent of the reference.

The use of two e-machines per pinion makes the system about twice as long, see figure 9. This is essentially because the length of the e-machine is much greater than the width of the gearbox.

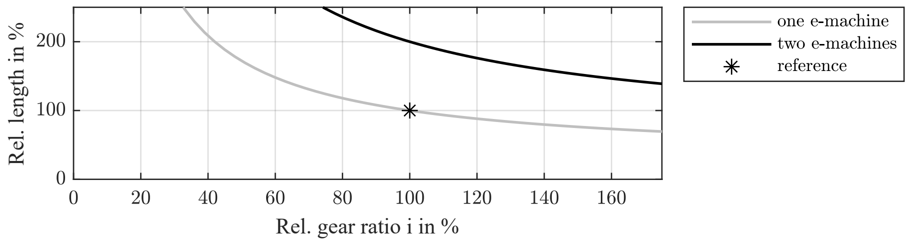


Fig. 9: Length of the total system

In ships with a narrow hull, the width of the drive system is limited and therefore concepts with two e-machines per pinion are particularly interesting. In these cases, the length is less critical. The system model shows a diameter reduction of approximately 10 percent but a volume increase of approximately 62 percent must be accepted.

## Outlook

In addition to the installation space and weight advantages, the operating strategies can improve the efficiency of e-machines in multi-machine drivetrains. Figure shows three different operating strategies for speed-dependent power curve ($P \sim v^3$) of ships. One possibility is, that all e-machines run actively with identical load. Another solution is to operate the plant with the minimum number of e-machines. The system can be use the minimum required number of e-machines. Thirdly, an operating strategy is shown where efficiency has been improved.

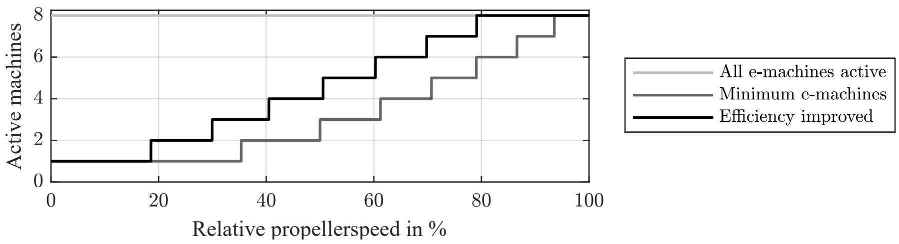


Fig. 10: Different operating strategies of the e-machines

The comparison of the three operating strategies shows the potential for improvement in efficiency of the e-machines, figure 11. Basically, the efficiencies differ considerably in the lower speed range. The efficiency when operating all e-machines is lower in relation to the other operating strategies. Switching off the e-machines brings some advantages, see orange and blue curves. By adjusting the switching points, the efficiency can additionally be tuned a little bit.

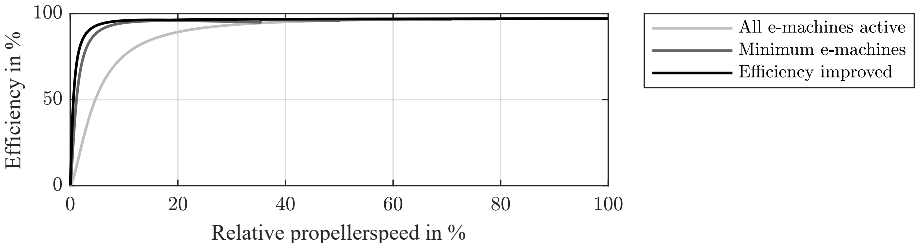


Fig. 11: Comparison of the e-machines' efficiency with different management strategies

## Conclusion

The models demonstrate that multi-machine systems provide advantages in the megawatt range. Moreover, using multi-machine drives improve packaging and power density depending on the number of e-machines and the gear ratio. As the outlook shows, the models can also be used to investigate and improve the system efficiency.

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