

Studies on Mechatronics

Fast Driving Concepts for a Walking Excavator

Autumn Term 2015

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Fast Driving Concepts for a Walking Excavator

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Abstract

This *studies on mechatronics* presents the development and comparison of different fast driving concepts for a 12 ton walking excavator with the purpose of increasing its maximum reachable velocity. In order to reach this goal, different on the current market available components have been searched and compared. The best hydraulic and two possible electric solutions are presented in detail. It is shown that with these new concepts, the excavator's maximum velocity can be increased up to four times compared to the current state.

Symbols

Symbols

V_g	pump: displacement / motor: swallowing capacity
n	rotational speed
q_V	volume flow
P	power / performance
T	torque
m	mass
i	gear ratio
d	diameter
r	radius
l	length
v	velocity
T_a	adhesion torque
F_{ta}	adhesion force
g	gravitational acceleration
C_s	adhesion coefficient
z	number of wheels
S_F	safety factor
F_{air}	air resistance force
F_{roll}	rolling resistance force
F_{pit}	pitch resistance force
F_{acc}	acceleration resistance force
ρ_{air}	air density
c_f	flow resistance coefficient
A	projected vehicle front face
f_{roll}	rolling resistance coefficient
α	pitch angle
e_i	mass factor
a	acceleration
U	voltage

Indices

<i>max</i>	maximum
<i>nom</i>	nominal
<i>x</i>	variable
<i>out</i>	output
<i>tot</i>	total

Acronyms and Abbreviations

ETH	Eidgenössische Technische Hochschule
ASL	Autonomous Systems Lab
KTI	Kommission für Technologie und Innovation
PGW	Propylene Glycol
AC	Alternating Current

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Chapter 1

Introduction

Walking excavators belong to one of the most versatile excavator types. This versatility comes with the price of making these mobile construction site machines quite complex due to many joints and degrees of freedom. They are developed for different working tasks that require advanced mobility. Examples are excavating works in hardly accessible areas like mountains and rivers. The object of research of this work is the walking excavator M545 developed by the Swiss excavator supplier Menzi Muck AG [14], which will be described in more details in chapter 2.

The presented work is part of a KTI project of the Autonomous Systems Lab (ASL) [15] of ETH Zurich and Menzi Muck AG. The project goal is to automate walking excavators using control and optimization tools that were developed and tested with legged robots. The shared vision is to enhance the intelligence of these machines such that they can drive or walk on rough terrain autonomously or with little human input.

In the current state, these large-scale construction machines are able to drive at low speeds only and are unable to reach velocities higher than 10 km/h. This circumstance limits their applicability.

The goal of this *studies on mechatronics* is to enable the walking excavator to reach higher velocities than it does at the moment. The application benefits the most by accelerating terrain exploration tours before starting the actual excavating work.

In order to reach this goal, this work is about the development and comparison of different fast driving concepts for the proposed excavator chassis. As a first project step, only components that exist on today's market will be considered to solve this task. Considering complete new component developments is not part of this studies. To find the best possible solutions, the technical data of over 90 components from about 15 different suppliers have been collected and compared. As a result, the best hydraulic and two possible electric solutions will be presented in chapter 3 this report.

Chapter 2

The Walking Excavator

The object of research of this work is Menzi Muck's walking excavator M545 (depicted in figure 2.1). This multi-purpose excavator is equipped with four legs that each have three degrees of freedom and an actuated wheel, which allows it to drive or walk over challenging terrain.



Figure 2.1: Menzi Muck's walking excavator M545; Source: [1]

Before starting with the new driving concepts, the present excavator system will be presented. The analysis of the current system gives the needed information to derive the new fast driving concepts in order to increase the excavator's maximum velocity. First, the dimension of the machine will be shown in chapter 2.1 to get an idea of the scale. Then, the present driving concept will be presented in 2.2. Afterwards additional information about the single components used in this concept will be given in 2.3. Finally, some calculations will be done in chapter 2.4 in order to get the basis for the development of the new concepts. The technical data and specifications of the excavator given in these chapters have been found in [1].

2.1 Dimensions

The M545 excavator type has a total machine weight of 12'300 kg (value without excavating tools). The four wheels have a diameter of 1140 mm and a width of 600 mm. The remaining dimensions can be found in figure 2.2 with the help of table 2.1.

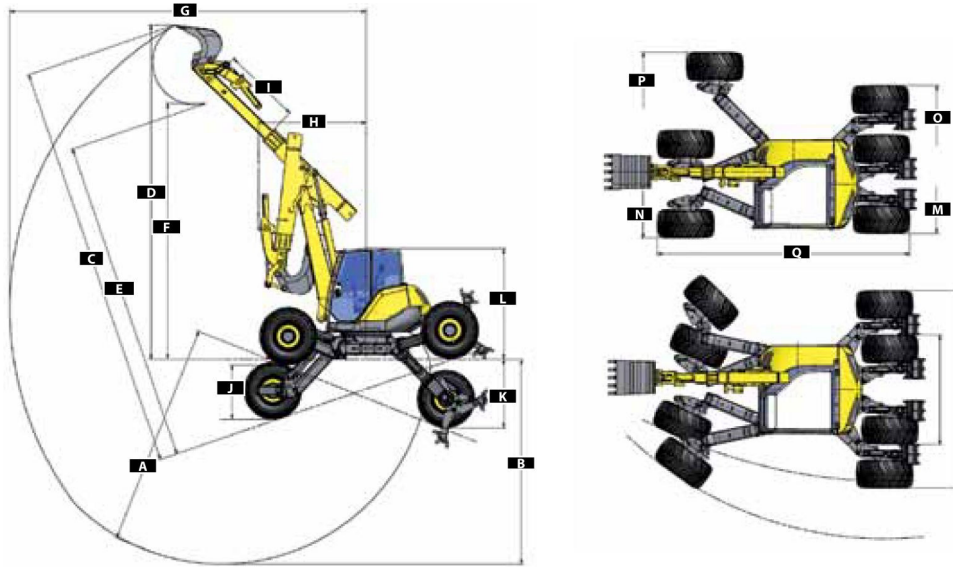


Figure 2.2: Dimensions of walking excavator M545; Source: [1]

Table 2.1: Dimensions of walking excavator M545; Source: [1]

	Dimensions in mm	M545
A	Max. digging depth - with chassis adjustment	5140
B	Max. digging depth - chassis at ground	4730
C	Max. digging height - with chassis adjustment	9370
D	Max. digging height - chassis at ground	7700
E	Max. discharge depth - with chassis adjustment	7430
F	Max. discharge depth - chassis at ground	5890
G	Max. range	8210
H	Min. pivoting radius	2480
I	Telescope length	1800
J	Adjusting range brace support	1250
K	Adjusting range wheels	1650
L	Transport height	2550
M	Min. width backside (transport width)	2380
N	Min. width front side (transport width)	2430
O	Max. width adjustment wheels	4690
P	Max. width adjustment brace support	6140
Q	Chassis length	6190

2.2 Present Driving Concept

In the present version of the excavator, the driving concept is based on a diesel-hydraulic system. This means that the central power source is a diesel engine. It is combined with hydraulic components which drive the excavator's wheels. The structure of this combination will be explained below. Detailed information about the single components will be given afterwards.

2.2.1 Structure

The excavator's central power source is a 115 kW 4 cylinder turbo diesel engine, placed near the cabin. It drives 4 hydraulic pumps P1 to P4, which for their part drive the 220 l hydraulic oil system content through the hydraulic pipes. Each of these pumps have its own job:

- P1 is responsible for the fan operation.
- P2 drives the work hydraulic system for the excavating work.
- P3 is for the optional powerline. It is recommended for attachments which permanently demand high litre performance.
- P4 is for the drive hydraulic system.

For this work's purpose, just P4 is of interest. This pump is connected in a closed loop to the hydraulic motors. They are placed at each of the four wheels. Together with the planetary gears, which change the ratio from the motors to the wheels, these components form a wheel hub drive. Since each of the four equally sized wheels has such a wheel hub drive, the excavator has a hydrostatic all-wheel drive. This structure is schematically depicted in figure 2.3.

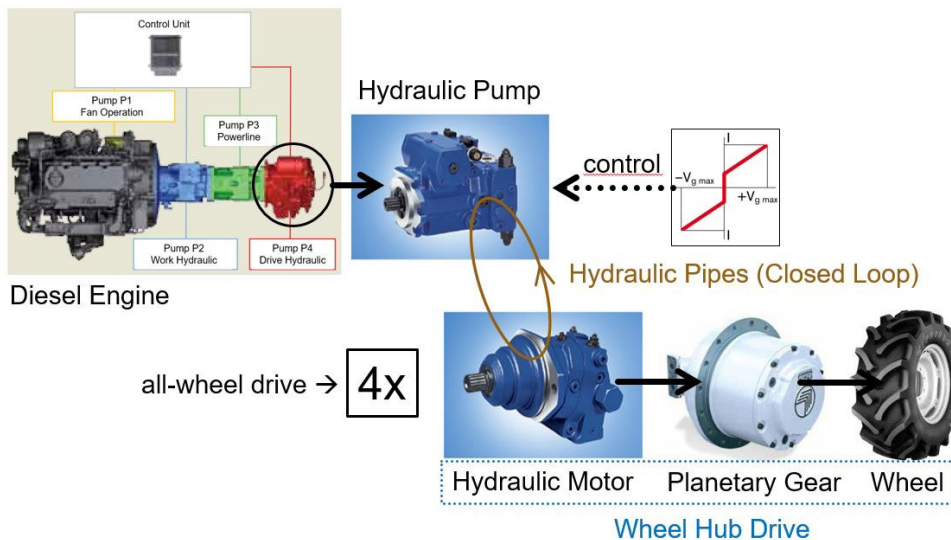


Figure 2.3: Structure of the present driving concept

In general, this kind of propulsion has several advantages. The most important one is that each wheel can be controlled separately, which gives a good basis for control tasks like for example traction control. Furthermore, the “outsourcing” of

the motors to the wheels save a lot of space near the cabin. The reduction of mechanical parts in this area allows the development of optimized chassis concepts. A disadvantage is the increased mass around the wheels, which makes the excavator heavier in total and leads to higher costs since there are more components necessary.

2.2.2 Control

The hydraulic pumps are power controlled. They are connected by a control unit and are steered by the operator's pedals and joysticks. The connection to the hydraulic motors is a closed loop. This means that the hydraulic pump is fed directly by the from the hydraulic motor returning hydraulic liquid (the pump is therefore "clamped" by the suction *and* the pressure side) - in contrary to an open loop, where the pump sucks the hydraulic liquid out of a tank. According to the component catalogues found in [2], the hydraulic drive pump has a proportional control electric. This means that the output flow of the pump is infinitely variable between 0 to 100%, proportional to the supplied electric current. The electric energy is converted to a force acting on the spool of the control valve. This valve spool directs control oil in and out of the stroking cylinder to adjust the pump displacement (which controls the pump's flow) as required. A feedback lever connected to the stroking piston maintains the pump flow for any given current within the control range.

The hydraulic motors placed at the wheels have two-point hydraulic control. This means that the excavator has a two-stage travel drive. This allows the displacement to be set to either the minimum or the maximum swallowing capacity by switching the pilot pressure on or off. Without pilot pressure, the motor is in the maximum swallowing capacity position. In this case it can provide the maximum torque but only the minimum speed. When the pilot pressure is switched on, the motor changes to its second stage which is at the minimum swallowing capacity position. Then it is able to provide the maximum permissible speed but only the minimum torque. The pilot pressure is controlled parallel to the power control of the pump. This means that the motor's rotational speed and the drive pump is actuated synchronously by the operator's accelerator pedal.

This information leads to the conclusion that in this current version of the excavator, the advantage of controlling each wheel separately by the use of wheel hub drives is not fully exploited, as the power of *all four* motors are controlled by the flow of *one single* pump. This makes the current system very inert and limits the individual control capacity of the wheels.

2.3 Components

In this section, detailed information regarding structure and technical data of the before named components will be given. The information about the different operating modes of the hydraulic components have been found in [3].

2.3.1 Hydraulic Pump

Technical Data

The currently used hydraulic pump for the excavator's drive hydraulic is the variable displacement pump *A4VG/32* of the supplier Bosch Rexroth AG [16]. It works for applications in high pressure range up to 450 bar and has a nominal pressure of 400 bar. It has an integrated auxiliary pump for the feeding and control oil supply as well as combined feeding and high pressure relief valves. The nominal size of the in the excavator used type is *90*. The technical data for this size can be found in table 2.2 and have been collected from [2].

Table 2.3: Technical data of the current hydraulic motor (nominal size: 55); Source: [4]

Description	Condition	Variable	Unit	Value
Maximum swallowing capacity		V_{gmax}	cm^3	54.8
Nominal swallowing capacity		V_{gx}	cm^3	35
Nominal rotational speed	@ V_{gmax}	n_{nom}	min^{-1}	4450
Maximum rotational speed	@ $V_g < V_{gx}$	n_{max}	min^{-1}	7000
Absorption capacity	@ n_{nom}	qV_{max}	l/min	244
Torque	$\Delta p = 400bar$	T	Nm	349
Mass		m	kg	26

Operating Mode

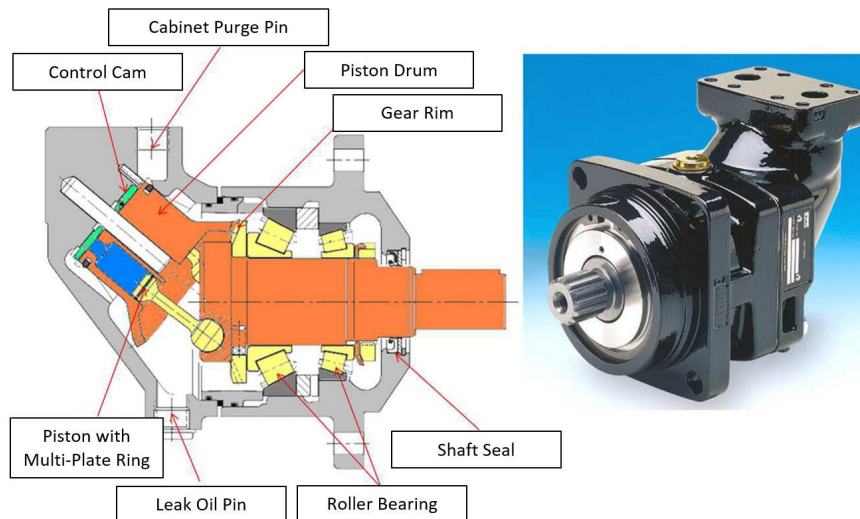


Figure 2.7: Schema of an axial piston - bent axis motor; Source: [3]

In general, axial piston units can work as hydraulic pumps as well as hydraulic motors. This motor is of axial piston – **bent axis** design, which has a similar setup as the swash plate construction. The difference is that the pistons run tilted to the output shaft and the pivoting angle is varied by an axis instead of a plate.

The piston drum is driven directly over a gear ring by the shaft. Out of that, the pistons run free of lateral forces in the cylinders and can be sealed much easier and generate less friction. These factors, together with the kinematic connection of shaft and piston drum, lead to the fact that the bent axis motor can reach high rotational speeds.

The piston seal can be done by a lamella piston ring, which enables a lesser internal leakage and an insensibility to fast temperature changes. Therefore, at pressures up to 480 bar, very high output powers are possible. Another advantage is that mechanical connection to other components is eased by the tilted design of the motor.

It is possible to build the motor with a variable pivoting angle. But in comparison to the swash plate construction, the mass of the complete piston drum has to be moved, which reduces the adjust dynamic and increases the adjust forces.

2.3.3 Planetary Gear

Technical Data

The gear comes out of the 700C gear series of the international supplier Bonfiglioli [17]. The current in the excavator used gear is the *707 C3 B* type. Bonfiglioli offers this gear type with ratios from 55 to 120. In the excavator's wheel hub drives, gears with a ratio of 109.2 are integrated.

Technical data and figures can be found in table 2.4 and figure 2.9, respectively.

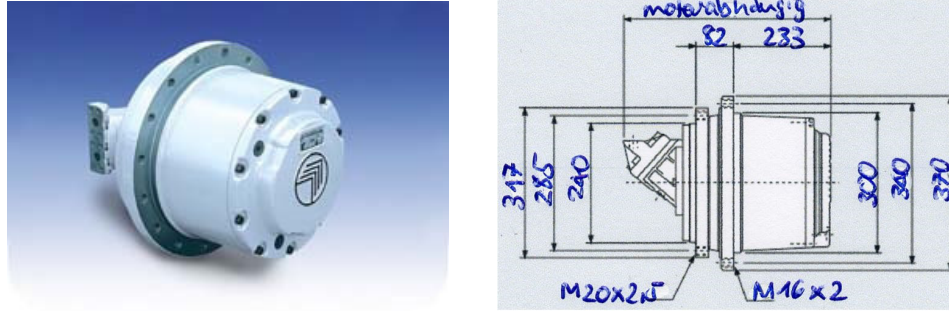


Figure 2.8: Image and drawing of the current planetary gear; Source: [5]

Table 2.4: Technical data of the current planetary gear (type: *707 C3 B*); Source: [5]

Description	Variable	Unit	Value
Ratio	i	—	109.2
Maximum input speed	n_{max}	min^{-1}	3500
Maximum output torque	T_{max}	Nm	26'000
Mass	m	kg	135

Operating Mode

The planetary gear belongs to the gear types with uniform, constant translation. The power transmission from input to output shaft occurs form-closed, which has the advantage that no slip occurs within the gear. It is a special form of a pinion gear. The basic construction consists of a set of gear wheels, which are (from the inside out) the sun gear, the by the planet arms carried planet gears and a ring gear with internal gearing. This structure is depicted in figure 2.9.

The planet arms connect the center of the sun gear and the planet gears and rotate to carry the planet gears around the sun gear. Different gear ratios can be achieved by holding one of these gear components fixed and by driving another one. Most often, the ring gear is fixed and the sun gear is driven. By varying the size and configurations of these components, different gear ratios can be achieved in order to change the translation from input to output shaft.

The main advantage is that this gear type has a very compact design. Additionally, the planetary gear can transmit high torques compared to other gear types. Together with the fact that it allows a good combination with axial piston motors, it is the perfect candidate for wheel hub drives.

The in this subsection given information are from [18].

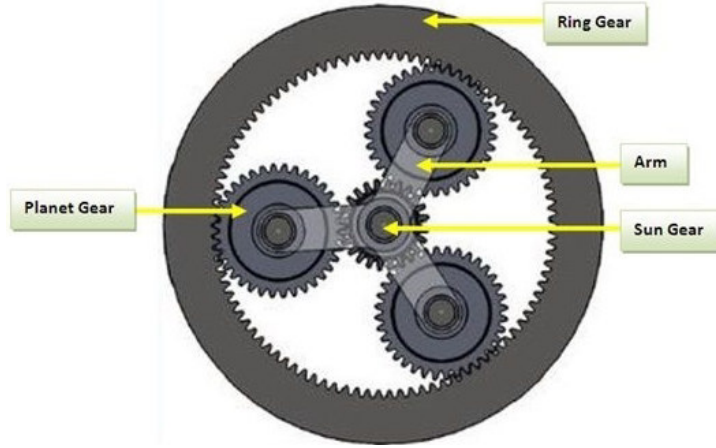


Figure 2.9: Schema of a planetary gear; Source: [6]

2.4 Calculations

Now that the technical data of the components are known, we can do the calculations of the important values which are needed to find new components in order to increase the excavator's maximum velocity. We will start with the maximum velocity the current excavator is able to reach.

2.4.1 Maximum Velocity

The maximum velocity can be calculated with the formula

$$v_{max} = \frac{n_{max}}{i_{gear}} \cdot \frac{1min}{60s} \cdot \pi \cdot d_{wheel} \cdot 3.6 \frac{km/h}{m/s} \quad (2.1)$$

where n_{max} is the maximum rotational speed of the gear or the motor, i_{gear} the gear ratio and d_{wheel} the wheel diameter, which together with π forms the wheel circumference. The remaining factors are just given to receive the velocity in km/h . This formula is evaluated for three different rotational speeds: one time for the maximum input speed of the gear and one time for the nominal and maximum rotational speed of the motor, respectively. The results can be seen in figure 2.10. We can learn the following things out of these calculations: first, the current excavator is able to reach a maximum velocity of about $10km/h$. This is also the velocity the Menzi Muck AG claims the excavator can reach. Furthermore, we learn that the limiting element of the maximum velocity is the maximum rotational speed of the gear.

The investigations conducted within the scope of this work have shown that there are no suitable gears available today that can endure significantly higher rotational speeds than 3500 rpm. This limit comes out of mechanical and design reasons of these gear types.

Out of this information, we can conclude that in order to increase the excavator's maximum velocity, it has no influence when the present motor is replaced by one with a higher rotational speed. The only other possibility is to decrease the gear ratio. By doing this, the output torque at the excavator's wheels will decrease as well, since this value depends on the gear ratio and the motor torque in the following linear way:

$$T_{out} = i_{gear} \cdot T_{motor} \quad (2.2)$$

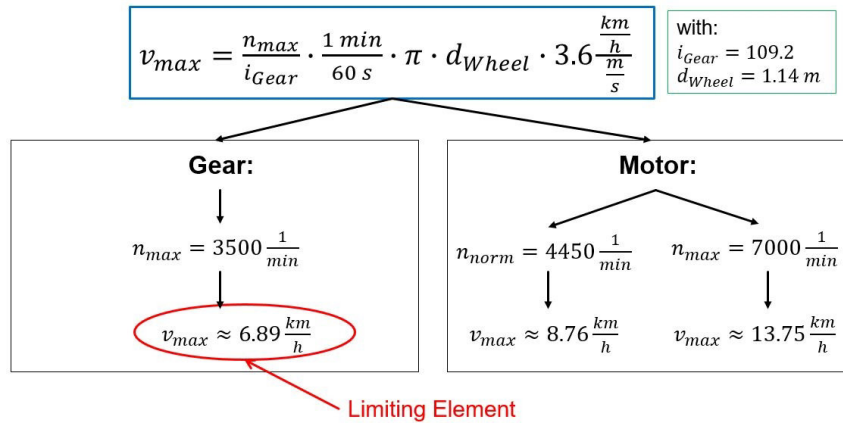


Figure 2.10: Overview and results of the maximum velocity calculation

When this maximum value is too low, it is possible that the drivability of the excavator is limited (this means for example that it will not be able to climb hills with high inclinations).

So as a next step, we are interested in the minimum output torque we need to reach with the components of the new driving concepts in order to ensure the excavator's drivability.

2.4.2 Minimum Output Torque

This value can be estimated by the help of a formula which has been found in a catalogue of the specialized Italian wheel gear supplier Reggiana Riduttori [19] [20]:

$$T_a = F_{ta} \cdot r_{wheel} = \frac{m \cdot g \cdot C_s}{z} \cdot r_{wheel} \cdot S_F \quad (2.3)$$

The maximum torque that has to be transmitted by the wheel gear is the one which is obtained when the limit of adhesion between tire and ground is reached. This torque is calculated by multiplying the radius r_{wheel} under load of the wheel gear by the maximum tangential force that it can transmit to the ground by adhesion F_a . This force is calculated by the total weight of the vehicle m times the gravitational acceleration g times an average vehicle adhesion coefficient C_s divided by the number of driving wheels z .

The adhesion coefficient C_s has been chosen to be 0.6. This value has been found in corresponding tables in [20] and seems to be reasonable as a first guess. z has been chosen as 2, because in minimum, two wheels will have contact with the ground and we want to ensure the excavator's driving ability in every possible configuration. Finally, an additional safety factor S_F is multiplied which has been set to 1.3.

By plugging in these values into the formula, the searched minimum output torque can be found as about $26'000 \text{ Nm}$. This value is just a rough estimation with the purpose to get an idea of which torque dimensions we are speaking of. To get more exact values, requirements regarding the excavator's driving skills (for example the maximum inclination it should be able to climb) have to be fixed, and based on that, more detailed calculations have to be done. However, the resulting value seems to be reasonable since it is the same torque the present gear is able to transmit.

With the derived results, it can be concluded that in order to increase the excavator's maximum velocity, the components of the current state have to be replaced by a gear with a **lower ratio** combined with a motor that can provide a **higher torque**.

2.4.3 Motor Power Estimation

In order to narrow down the choices of on the market available motors, the power of the new wheel hub motor will be estimated in this section. We do that with the following formula [21]:

$$P_{drive} = F_{drive} \cdot v = (F_{air} + F_{roll} + F_{pit} + F_{acc}) \cdot v \quad (2.4)$$

where P_{drive} is the required power to reach the velocity v . This formula consists of the to achievable velocity v times the following four resistance forces:

$$F_{air} = \frac{\rho_{air}}{2} \cdot c_f \cdot A \cdot v^2 \quad (2.5)$$

$$F_{roll} = m \cdot g \cdot f_{roll} \cdot \cos(\alpha) \quad (2.6)$$

$$F_{pit} = m \cdot g \cdot \sin(\alpha) \quad (2.7)$$

$$F_{acc} = e_i \cdot m \cdot a \quad (2.8)$$

These equations consist of the following parameters:

- F_{air} is the air resistance force in $[N]$
- ρ_{air} is the air density, which is assumed to be $1.2km/m^3$ (air at $20^\circ C$)
- c_f is the dimensionless flow resistance coefficient. It is assumed to be 0.51 (corresponds to the value of a truck, according to [22])
- A is the projected vehicle front face with the conservative assumption of being $10m^2$ (corresponds to the value of a train, according to [23])
- F_{roll} is the rolling resistance force in $[N]$, caused through elastic tire deformation
- $m = 12'300kg$ is the total vehicle mass
- $g = 9.81m/s^2$ is the gravitational acceleration
- f_{roll} is the dimensionless rolling resistance coefficient. It is assumed to be 0.6 (corresponds to a car tire on a pothole road, according to [24])
- α is the pitch angle
- F_{pit} is the pitch resistance force in $[N]$
- F_{acc} is the acceleration resistance force in $[N]$
- e_i is the dimensionless mass factor (> 1) that respects the moments of inertia of the accelerated, rotating mass in the drive train
- a is the vehicle acceleration in m/s^2

For the calculation of the **maximum** velocity, it is assumed that there is no acceleration anymore ($a = 0$) and that the vehicle drives in a flat area without any inclination ($\alpha = 0$). Out of that, the forces F_{pit} and F_{acc} can be neglected, which leads to the following simplified equation in order to calculate the required power:

$$P_{drive} = v^3 \left(\frac{\rho_{air}}{2} \cdot c_w \cdot A \right) + v(m \cdot g \cdot f_{roll}) \quad (2.9)$$

By plugging in the assumed values, we evaluate this formula for different discrete velocity values. The results can be found in table 2.5. By dividing the received values by four (number of driven wheels), we get a good guess of the power a potential motor should have.

Table 2.5: Results of the power calculation for different discrete velocity values

Velocity in <i>km/h</i>	30	35	40	45	50	55	60
Total power in <i>kW</i>	62.1	73.2	84.4	96.5	108.8	121.5	134.8
Power per wheel in <i>kW</i>	15.5	18.3	21.2	24.1	27.2	30.4	33.7

Chapter 3

Fast Driving Concepts

In the last chapter, basic information has been derived in order to develop new fast driving concepts for the excavator. The idea of these new concepts is to replace the current by new components that are available on the market. Hydraulic as well as electric components have been assessed to achieve the goal of increasing the excavator's maximum velocity. In the first two chapters 3.1 and 3.2, the best hydraulic components plus two possible electric approaches will be presented. Afterwards, the dimension check of the components will be shown briefly in chapter 3.3. To sum up, the different concepts will be compared in chapter 3.4.

The description of all the checked and compared components within this work would go beyond the scope of this documentation. All considered suppliers which are not named in this chapter are listed in appendix A.

3.1 Hydraulic Components

3.1.1 Motor

Technical Data

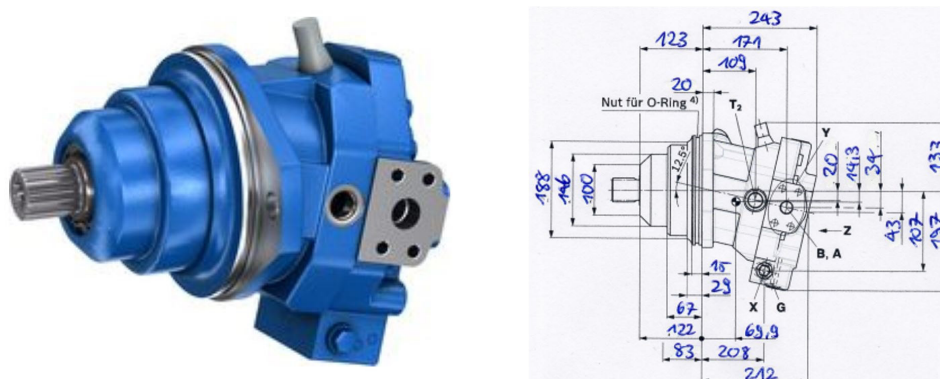


Figure 3.1: Image and drawing of the new hydraulic motor; Source: [7]

As the best hydraulic motor, again a variable displacement motor from Bosch Rexroth has been found. It is of bigger size and a different type series than the current one. The type description is *A6VE/71* with nominal size 170. It has a nominal and maximum pressure of 450 and 500 bar, respectively, which is 50 bar higher than before.

Out of the technical data presented in table 3.1, one can see that the maximum torque this motor is able to deliver is 1230 Nm. This is about 3.5 times more than the old one. The maximum rotational speed is lower than before, which is no problem as the limiting element concerning this criteria is the gear anyway. This motor type has a much higher swallowing and absorption capacity, which leads to the conclusion that it probably has to be combined to a bigger hydraulic pump than the current one.

A disadvantage is that it is about 2.4 times heavier than the old one. A dimension check will be seen in section 3.3.

Table 3.1: Technical data of the new hydraulic motor (nominal size: 170); Source: [7]

Description	Condition	Variable	Unit	Value
Maximum swallowing capacity		V_{gmax}	cm^3	171.8
Nominal swallowing capacity		V_{gx}	cm^3	65
Nominal rotational speed	@ V_{gmax}	n_{nom}	min^{-1}	3100
Maximum rotational speed	@ $V_g < V_{gx}$	n_{max}	min^{-1}	4900
Absorption capacity	@ n_{nom}	q_{Vmax}	l/min	533
Torque	$\Delta p = 400bar$	T	Nm	1230
Mass		m	kg	62

Operating Mode

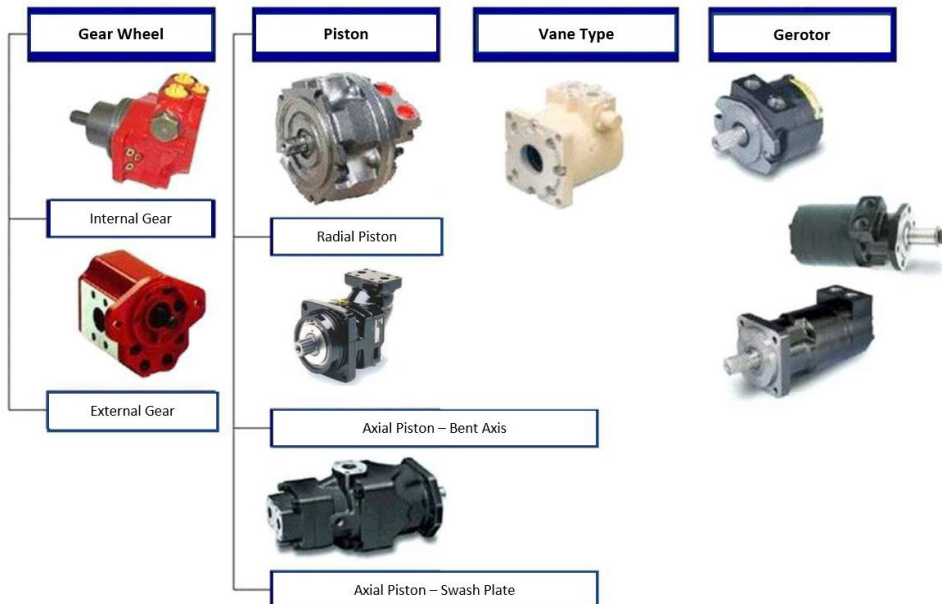


Figure 3.2: Overview different hydraulic motor types; Source: [3]

Different hydraulic motor operating modes have been checked and compared to each other in order to find the best one for the excavator. An overview of the different types is given in figure 3.2. The classification criteria is the construction. Hydraulic motors can basically be divided into gear wheel, piston, vane type and gerotor

motors, where gear wheels can additionally be divided into internal and external construction and piston motors into axial and radial piston design.

As a result, the axial piston – bent axis design – the same design the current motor is built of – has been found to be the best choice. The bent axis construction type allows to reach high rotational speeds out of his mechanical building (see section 2.3.2). Furthermore, it has a good proportion of rotational speed and torque, good operating characteristics in a wide rpm-range and a low dirt sensitivity, which is important as we want to use the component to drive an excavator.

Vane types and gerotors can be neglected, as they are classified as low-speed motors in the lower and middle pressure range. Out of that they are not adequate for a use in a large-scale construction machine.

Radial piston motors could have been a good alternative. The difference to the construction of axial piston designs is that the pistons stand radial to the rotation axis. Out of that, they can be built with large swallowing capacity which leads to the advantage that these motor types can provide very high torques. On the other hand their maximum rotational speeds are significantly lower than that of the current gear. Therefore, they are not very useful to drive the excavator.

External gear wheels can provide a quite high rotational speed but only low torques. That is why they have to be neglected as well.

Internal gear wheel designs have been found to be promising to fulfil the given requirements. They have a high smoothness and can provide high rotational speeds as well as high torques. However, no components built in this design have been found on the market, which can provide the right combination of speed and torque and could additionally pass the dimension check.

That is why the current design has been found the best for this application.

3.1.2 Gear

Technical Data

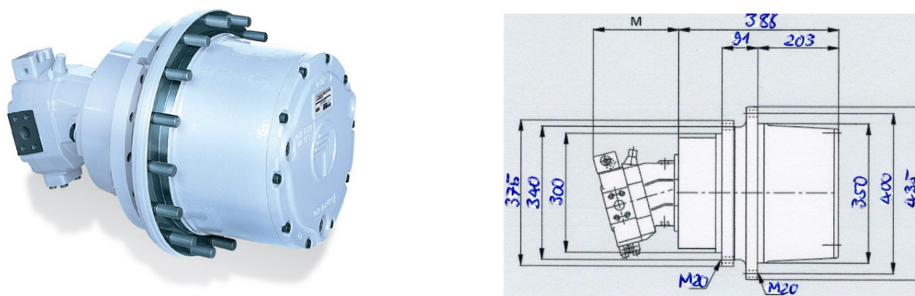


Figure 3.3: Image and drawing of the new hydraulic gear; Source: [8]

As a new gear, the wheel drive *610W2/3* offered by Bonfiglioli is recommended. The gear can be well combined with axial pistons motors to form a wheel hub drive. It can be ordered with a ratio of 20.5, which is about 5 times lower than that of the old one. As an additional feature, Bonfiglioli offers this gear type with a Low-High-Speed switching function. With this function, the gear ratio can be changed to a higher one (exact value depends on the execution) by a hydraulic operated multidisc clutch. This clutch is also used for braking. By the use of this function, the output torque can be significantly increased while driving in this low speed mode. Additional information can be found in [8].

The gear is able to stand maximum output torques up to 40'000 Nm which is enough

to ensure the drivability of the excavator.

A disadvantage is again the mass of the component. With 200 kg it is about 1.5 times heavier than the current gear.

A summary of these technical data are given in table 3.2.

Table 3.2: Technical data of the new planetary gear (type: *610W2/3*); Source: [8]

Description	Variable	Unit	Value
Ratio	i	–	20.5
Maximum input speed	n_{max}	min^{-1}	3000
Maximum output torque	T_{max}	Nm	40'000
Mass	m	kg	200

Operating Mode

The new gear is again of planetary gear design. This gear type has been found to be the only possibility for a wheel hub drive, as it has compact design, is able to transmit high torques and has a high load capacity. Other gear types, like for example types based on frictionally engaged power transmission cannot nearly transmit the claimed torques and performances and are too unhandy to integrate them into the wheel of a vehicle.

3.2 Electric Components

To give alternatives to the hydraulic components, electric components that exist on the market have been searched as well. In contrary to the hydraulic counterparts, electric wheel hub drives are not very common for large-scale machines yet. That is why only suitable components have been found which are still prototypes and not in serial production yet.

In this section, two approaches will be presented which are promising to meet the given requirements. The intended parts have been developed as custom products for other machine types. Out of that, some further adaptations have to be made in order to integrate these parts into the walking excavator.

During this project, we have already been in contact with the two below presented suppliers. The contact data of the responsible people can be found in appendix B.

3.2.1 The Bonfiglioli Approach

As a first proposal, Bonfiglioli offers a combined set of gear and electric motor as electric wheel hub drive. The *609W* planetary wheel drive can be coupled to a high power density electric motor. The solution is completely mechatronic and designed for a high voltage hybrid powertrain system. It was originally developed for the use on self-propelled crop sprayers. The components have compact dimensions which are comparable to the hydraulic counterparts. The technical data of both components are listed in table 3.3.

The proposed gear has a ratio of 44.16 and the very high value of 7600 rpm as maximum input rotational speed. It is able to stand a maximum output torque of 23'000 Nm which is as a first step sufficiently close to the needed value.

The 44.6 kW electric motor can reach a high rotational speed but can deliver a comparatively low maximum torque. It is based on the BPD motor technology, developed by Bonfiglioli itself, which promises increased power density. Detailed

information can be found in [25]. This technology combines non-conventional stator windings (hairpin) with a variable reluctance rotor geometry. In contrary to the conventional round-wire windings, this hairpin technology uses precision-formed rectangular wires in order to achieve higher slot-fill factors. Furthermore, the design allows a shorter end-windings height compared to round-wire stators. This combination reduces the winding resistance, causes less heat generation and improves the torque, power density and efficiency of the motor (Bonfiglioli promises a maximum efficiency of 95.6 %). The motor has to be cooled by PGW (propylene glycol – water) 50/50 or oil.

Electric motors have to be combined with frequency converters which convert alternating current (AC) of one frequency to alternating current of another frequency for the direct feed-in of the motor. As a suitable component to manage this task for the proposed motor type, the AC motor controller of the company Sevcon [26] in execution of type *Gen4* (size 10) has been recommended by Bonfiglioli. Detailed information as well as drawings of the components can be found in appendix C.

As an orientation price per unit for the combination of gear and motor, 19'000 Euro and a delivery time of about 18 weeks have been named by the supplier.



Figure 3.4: Image of the combined gear and electric motor supplied by Bonfiglioli; Source: [9]

Table 3.3: Technical data of Bonfiglioli's electric components; Source: [9]

Description	Variable	Unit	Value
BPD electric motor			
Nominal rotational speed	n_{nom}	min^{-1}	4800
Maximum rotational speed	n_{max}	min^{-1}	8000
Maximum rated power	P	kW	44.6
BUS DC Voltage	U	V	700
Maximum Torque	T_{max}	Nm	400
Compact gearbox 609W			
Ratio	i	–	44.16
Maximum input speed	n_{max}	min^{-1}	7600
Maximum output torque	T_{max}	Nm	23'000

3.2.2 The Rigitrac Approach

As a second proposal, components developed for a tractor of the Swiss company Rigitrac AG [27] have been found. The development was part of a cooperation between the TU Dresden [28], the German company EAAT GmbH Chemnitz [29] and Rigitrac AG. This work contained the development of an all-electric single-

wheel drive, which can be fully integrated into the wheel rim of the 8'000 kg heavy tractor *Rigitrac EWD 120* depicted in figure 3.5.



Figure 3.5: Picture of the Rigitrac EWD 120 (Source: [10]) and scheme of the corresponding electric wheel hub drive (Source: [11])

Similar to the walking excavator, the power source of this tractor is a 90 kW diesel engine. This one is connected to an 85 kW electric generator. This generator is connected to frequency converters, which are for their part connected to the four electric wheel hub drives. The schematic of this diesel electric structure can be seen in figure 3.6. There are additional cutting sites for the braking resistance and for the energy supply of removable attachments.

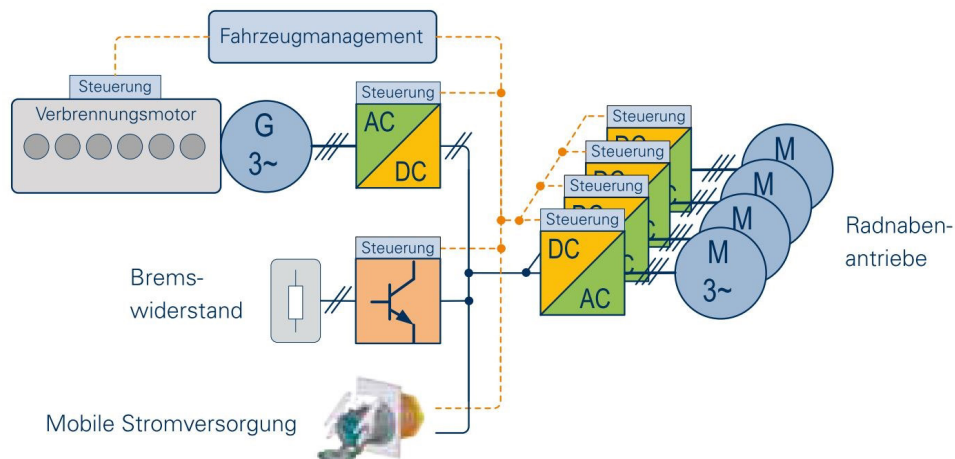


Figure 3.6: Structure of the diesel electric propulsion system of the Rigitrac EWD 120 (in German); Source: [11]

The velocity of the tractor is continuously adjustable between 0 – 65 km/h, where each wheel can be controlled separately. The electric braking resistance promises non-wearing braking.

The technical data of the components can be found in table 3.4.

Table 3.4: Technical data of Rigitrac's electric components; Source: [13]

Description	Variable	Unit	Value
Synchronous motor			
Nominal rotational speed	n_{nom}	min^{-1}	157
Maximum rotational speed	n_{max}	min^{-1}	1000
Nominal rated power	P_{nom}	kW	33
Maximum rated power	P_{max}	kW	44
BUS DC Voltage	U	V	650
Nominal Torque	T_{nom}	Nm	2300
Maximum Torque	T_{max}	Nm	3500
Single-stage planetary gear			
Ratio	i	—	4
Maximum input speed	n_{max}	min^{-1}	n.a.
Maximum output torque	T_{max}	Nm	n.a.

The electric motor is a permanently excited synchronous motor in external rotor construction (schematically depicted in figure 3.7), which is Can-Bus controlled and liquid-cooled. Synchronous machines belong to the category of induction machines, which means that the electric fields generated by the stator are rotating. In contrast to asynchronous machines, the field rotation and the mechanic turns of the rotor are synchronous. A rotational field is generated in the stator by a frequency converter. The rotor follows this field in a similar way as a magnet.

The advantages of this construction type are the high power density (regarding maximum torque at given constructed space) and the convenient efficiency in a wide rpm range. The information to the synchronous motor has been found in [30].

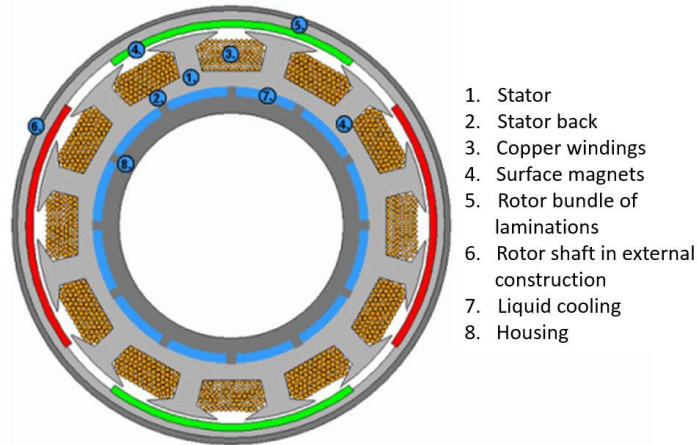


Figure 3.7: Scheme of a permanently excited synchronous motor; Source: [12]

The gear is a single-stage planetary gear with the very low ratio of 4. It is in the execution of a standard gear, which means that the planet carrier is fixed. The data of the maximum input speed and the maximum output torque are not yet available, but in clarification with the supplier EAAT GmbH.

The motor as well as the gear are custom products and not in serial production. The frequency converters which are necessary for the electric system can be bought from EAAT GmbH as well.

torques are needed. On the other hand, electric motors can be overloaded by delivering more current for a short time when peak torque is needed. Under normal conditions, the electric system works in the area of the highest efficiency. Electric wheel motors also provide the opportunity to generate power by energy recuperation when braking or travelling downhill. Other benefits include greater serviceability due to the mechanical simplicity and improved reliability.

Another point to mention is the motor control. With both system types the individual wheel control is possible. With which system this control can be done more easily and efficiently is to be clarified and out of scope of this work.

Chapter 4

Results and Conclusion

In table 4.1, the most important technical data of the current components and the components of the three presented fast driving concepts have been collected. In order to get the results, we do the exact same velocity and torque calculations that we did in chapter 2.4 for the current components.

The results of the evaluations for the different rotational speeds of the gears and the motors as well as the maximum output torque can be found in the lower columns of table 4.1.

Table 4.1: Overview technical data of the current and the different fast driving concepts with calculation results

CONCEPTS		NOW	HYDR.	ELEC.1	ELEC.2
MOTOR		A6VE 55	A6VE 170	BPD	PE SM
Nom. rotational speed	min^{-1}	4450	3100	4800	157
Max. rotational speed	min^{-1}	7000	4900	8000	1000
Max. torque	Nm	349	1230	400	3500
GEAR		707 C	610W2/3	609W	SS PG
Ratio	–	109.2	20.5	44.16	4
Max. input speed	min^{-1}	3500	3000	7600	n.a.
Max. transm. torque	Nm	26'000	40'000	23'000	n.a.
CALCULATIONS					
Max. output torque	Nm	38'111	25'215	17'664	14'000
Max. velocity gear	km/h	7	31	37	n.a.
Nom. velocity motor	km/h	9	33	23	8
Max. velocity motor	km/h	14	51	39	54

We can see that maximum velocities between 39 and 54 km/h can be reached with the new components. This is about four times of what the current excavator is able to reach. Again, the gear limits the velocity to 31 and 37 km/h , respectively. The transgression of this velocities is possible, but doing it for a longer time will lead to an increased wear of the gears and could in worst case lead to a breakdown of the components.

By having a look at the maximum output torques, we can see that with the hydraulic components, the targeted value of 26'000 Nm can be reached quite well. Additionally, there is the option to change to the low-speed-mode in which the gear has a higher ratio. This will lead to a further increase of the by output torque.

The values for both electric approaches are clearly below the minimum value. This

leads to the conclusion that some further adaptations have to be made in order to reach a higher output torque. Otherwise, the drivability of the excavator won't be guaranteed. Options to do so are on one hand building gears with a higher ratio, which would lead to a maximum velocity decrease, and on the other hand increasing the motor's maximum torque. These adjustments should be possible as the components are still in the prototype phase, but have to be discussed with the suppliers. In contrast, the hydraulic parts are already in serial production and can be bought directly from the market.

Chapter 5

Future Work

As a next step of this project, further discussions with the suppliers regarding the sales and delivery terms of the components have to be done. Furthermore, it has to be clarified how and with which effort the electric components can be adjusted so that a higher output torque can be achieved. In order to do that, one has to specify the requirements for the excavator's drivability (for example which inclination it has to be able to climb). With this information, further and more detailed calculations regarding the maximum output torque of the excavator's wheels can be done.

Another important point is the power supply to the wheel hub drives. For realizing the hydraulic fast driving concept, bigger hydraulic motors have to be used, which have higher absorption capacities. Therefore, there is likely the need for a bigger hydraulic pump which can deliver a higher volume flow. Bosch Rexroth offers hydraulic pumps of axial-piston swash plate design in different sizes which are promising to fulfil this requirement (see [31]). Additionally, one can think about introducing several pumps of the same nominal size instead of one with a bigger size. This could lead to advantages in the individual wheel control, but will require more construction space and will probably be more expensive. These ideas should be discussed with the experts of Bosch Rexroth. Another idea is to use the already existing powerline pump in order to support the drive hydraulic pump for high speed driving. The feasibility of this proposal should be discussed with Menzi Muck.

For the realization of the electric approaches, an additional electric generator has to be integrated into the excavator. The required power of this generator has to be determined with the use of the data of the electric motors. The Rigitrac EWD 120, for example, uses an 85 kW generator. One has to consider the fact that this component will need additional constructed space.

Another open question is if the current diesel engine is able to handle these additional efforts or if the engine has to be replaced by a new, more powerful one.

As soon as these open questions have been answered, a prototype can be built in order to run test drives.

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Appendix A

Supplier List

All the components which have been considered within the scope of this work are listed in the following tables.

A.1 Gears

Table A.1: List of gear suppliers

Supplier	Homepage	Components
Bonfiglioli	www.bonfiglioli.de	600 & 700 series
Brevini	www.brevini.de	RSF, RFL & RFD
Bosch Rexroth Group	www.boschrexroth.com	HYDROTRAC CFT
Reggiana Riduttori	www.reggianaridutt.it	RRM, RRWD & RRTD
ATP GmbH	www.atp-antriebstechnik.at	PGR / PGW
ASG GmbH	www.allweier.com	PGR 500 & PGR 1500

A.2 Hydraulic Motors

Table A.2: List of hydraulic motor suppliers

Supplier	Homepage	Components
Bosch Rexroth Group	www.boschrexroth.com	Axial piston motors A6VE/63 & 71
Bosch Rexroth Group	www.boschrexroth.com	Radial piston motors MCR
paul forrer	www.paul-forrer.ch	Radial wheel hub drives BB & BBC
Hydromot	www.hydromot.lu	Hydraulic motors CPMS
Linde Hydraulics	www.linde-hydraulics.com	Variable displacement motors HMV-02
Danfoss	www.powersolutions.danfoss.com	Piston motors OMS, OMT & OMV

A.3 Electric Motors

Table A.3: List of electric motor suppliers

Supplier	Homepage	Components
Bonfiglioli	www.bonfiglioli.de	BPD electric motor
Leroy Somer	www.leroysoomerservice.de	Synchronous motors with permanent magnet (LSRPM)
Pfeiffer Elektro- motoren GmbH	www.electromotoren.at	Norm and standard motors
Etel	www.etel.ch	TMB torque motors
Moog	www.moog.com	DB matrix series
Heinzmann GmbH & Co. AG	www.heinzmann.com	Electric wheel hub drives PMSG

Appendix B

Supplier Contact Data

B.1 Bonfiglioli

Bonfiglioli Deutschland GmbH
i.A. Jörg Riffel
Vertriebsingenieur Mobile Solutions
BU Mobile & Wind Solutions
Address: Sperberweg 12, 41468 Neuss, Deutschland
Tel.: +49 7251 36753 80
Fax.: +49 7251 36753 78
E-Mail: j.riffel@bonfiglioli.de
Webpage: www.bonfiglioli.de

B.2 EAAT GmbH

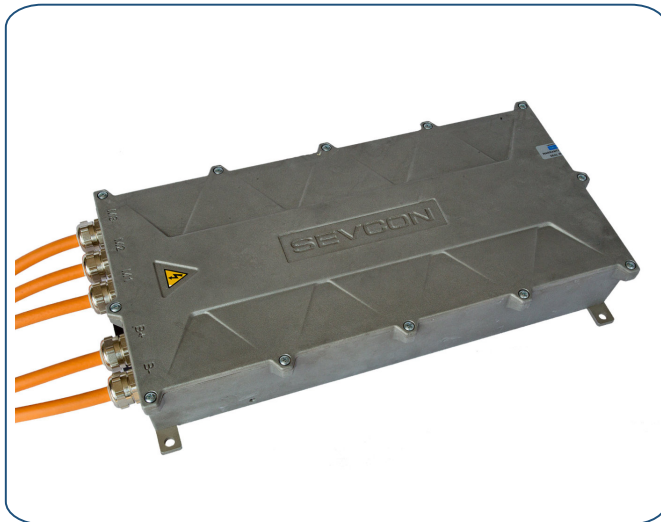
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Appendix C

Datasheets

SEVCON®

Partner with Performance



Gen4

AC MOTOR CONTROLLER

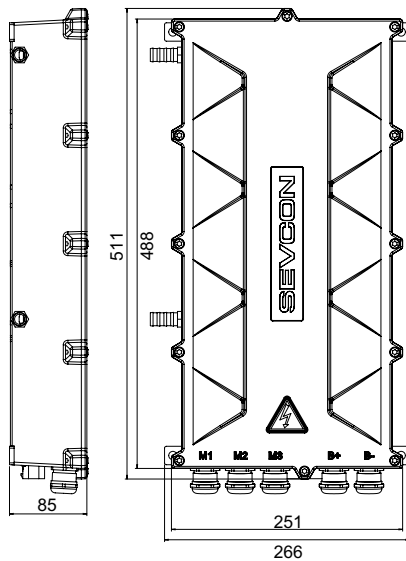
An AC motor controller designed to meet the high performance requirements of on-road and off-road Electric (EV) and Hybrid Electric Vehicles (HEV).

A compact, rugged and cost effective design, the Gen4 is well suited for EV OEMs, EV conversions and EV drive train system integrators.

Its high voltage range, up to 800VDC, is well matched to the needs of the automotive and commercial transport markets. The same hardware platform handles both AC Induction and Permanent Magnet AC motor technologies.

FEATURES

- AC Permanent Magnet synchronous motor
- AC Induction motor
- Up to 800V DC peak supply voltage
- Up to 300kW peak power output
- Up to 150kW continuous power output
- Advanced flux vector control
- Integrated logic circuit
- Includes an additional dedicated safety supervisory processor
- 12V or 24V nominal supply
- Designed for ISO26262 ASIL C compliance
- Safety interlock pulsed enable signal



Gen4

KEY PARAMETERS

- Operating voltage range at full current 50V to 800V
- Output motor phase current:
 - 400A rms (2 min)
 - 200A rms (Continuous)
- Water/Glycol coolant. Oil cooling available - contact Sevcon
- Safety:
 - Electrical safety to ISO 6494, IEC 60664 and UL840
 - Functional safety to ISO26262
 - Pulsed safety enable input
 - Pulsed status output
- Environmental:
 - -40°C to +85°C operation
 - IP6k9k and IP67 protection
 - ISO 16750
- 12V or 24V nominal supply
- Weight: 10.9kg

MULTIPLE MOTOR FEEDBACK OPTIONS

Gen4 Size 10 provides a number of motor feedback possibilities from a range of hardware inputs and software control, allowing a great deal of flexibility.

- Absolute UVW encoder input
- Absolute Sin/Cos encoder input
- Incremental AB encoder input
- Resolver input
- Programmable 5V to 10V encoder power supply

INTEGRATED I/O

Gen4 Size 10 includes a fully-integrated set of inputs and outputs (I/O) designed to handle a wide range of vehicle requirements. This eliminated the need for additional external I/O modules or vehicle controllers and connectors.

- All I/O protected to 40V
- 4 analogue inputs 0-10V
- 4 digital inputs
- 3 power supplies 0-10V 100mA
- 3 digital outputs PWM max 2A

OTHER FEATURES

- A CANopen bus allows easy interconnection of controllers and devices such as displays and driver controls.
- The CANbus allows the user to wire the vehicle to best suit vehicle layout since inputs and outputs can be connected to any of the controllers on the vehicle and the desired status is passed over the CAN network to the relevant motor controller.
- The Gen4 Size 10 controller can dynamically change the allowed battery current by exchanging CAN messages with a compatible Battery Management System.
- Configurable as vehicle control master or motor slave.

CONFIGURATION TOOLS

Sevcon offers a range of configuration tools for the Gen4 Size 10 controller, with options for Windows based PC or calibrator handset unit. These tools provide a simple yet powerful means of accessing the CANopen bus for diagnostics or parameter adjustment. The handset unit features password protected access levels and a customized logo start-up screen.



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