Investigation into EV motor Control

1. Introduction

The aim of this piece of work is to simulate and test the field-oriented control (FOC) system of a section of the EV powertrain, specifically the motor and inverter. A motor and inverter have been chosen based on real world specifications and equivalent models calculated in Simulink. The PI control of this system can then be used to tune the response of the motor to a variety of conditions, including dyno testing.

2. Motor

2.1 Motor selection

The motor chosen to carry out this analysis is supplied by EMRAX and is capable of a maximum torque of 230 Nm [1]. This motor was chosen specifically due to its relatively small size and torque output [for full specification, see appendix A].

2.2 Motor modelling

The key parameters required for a functional model are shown below in Table 1 and were used to build a Simulink model of the motor.

Table 1. Motor model parameters

Parameter	Value
Stator phase resistance Rs (Ω)	0.007
Inductance Ld (H)	0.000076
Inductance Lq (H)	0.000079
Flux linkage	0.0355
Pole pairs p	10

3. Inverter

3.1 Inverter selection

The max voltage and current were used to decide on which inverter would fit the system best. The FS650R08A4P2 HybridPACK™ DC6 Module is chosen as it has a collector emitter voltage of 750 V and a peak collector current of 1300 A, comfortably above the motor requirements of 500 V and 350 A at peak conditions [2].

3.2 Inverter modelling

Table 2. shows the values input into the inverter model.

Table 2. Inverter model parameters

Parameter	Value
On resistance Ron (Ω)	0.0008
Forward voltage device Vf (V)	0.4
Forward voltage diode Vfd (V)	0.7

The first of three key parameters required for the successful modelling of the inverter is the on resistance of the device. This is calculated using the gradient of the voltage current graph once conduction has begun. This is shown in red in Fig.1

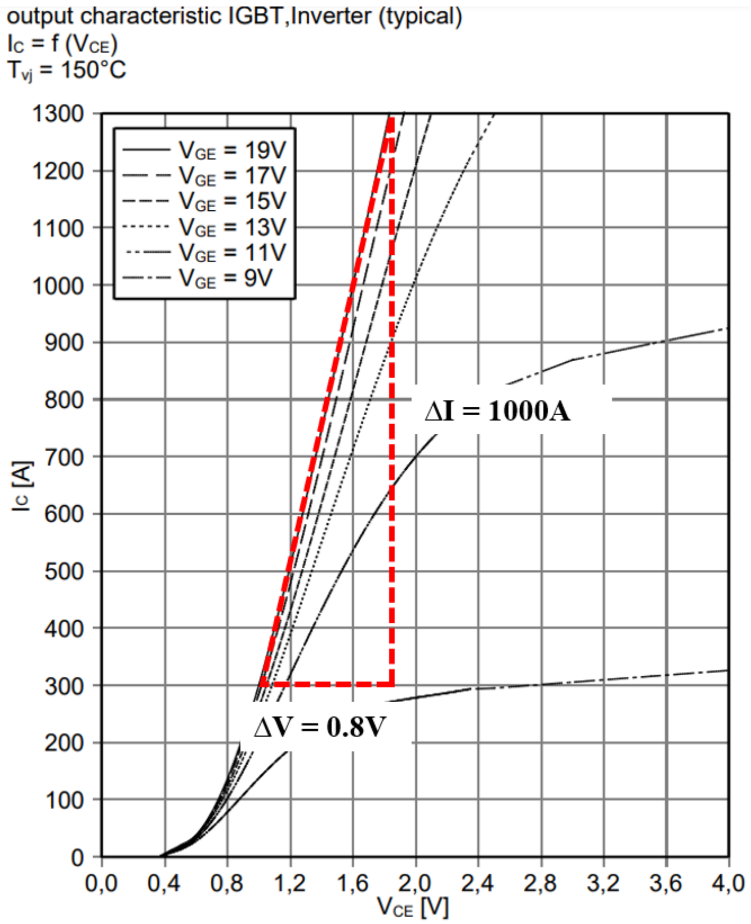


Fig.1 Voltage current gradient from inverter datasheet.

Using the equation showing in 3.1, the on resistance can be calculated. While this value will change with temperature and gate emitter voltage, this rough estimate is enough accuracy to explore the effects of the FOC:

$$\frac{\Delta V}{\Delta I} = \frac{0.8}{1000} = 0.0008\,\Omega \qquad 3.1$$

In order to find the forward voltages of the device and diode, the voltage current characteristic graphs are used again. The voltage at which conduction begins is what will be used for the forward voltages, shown in Fig.2, and are estimated to be 0.4 V for the device and 0.7 V for the diode.

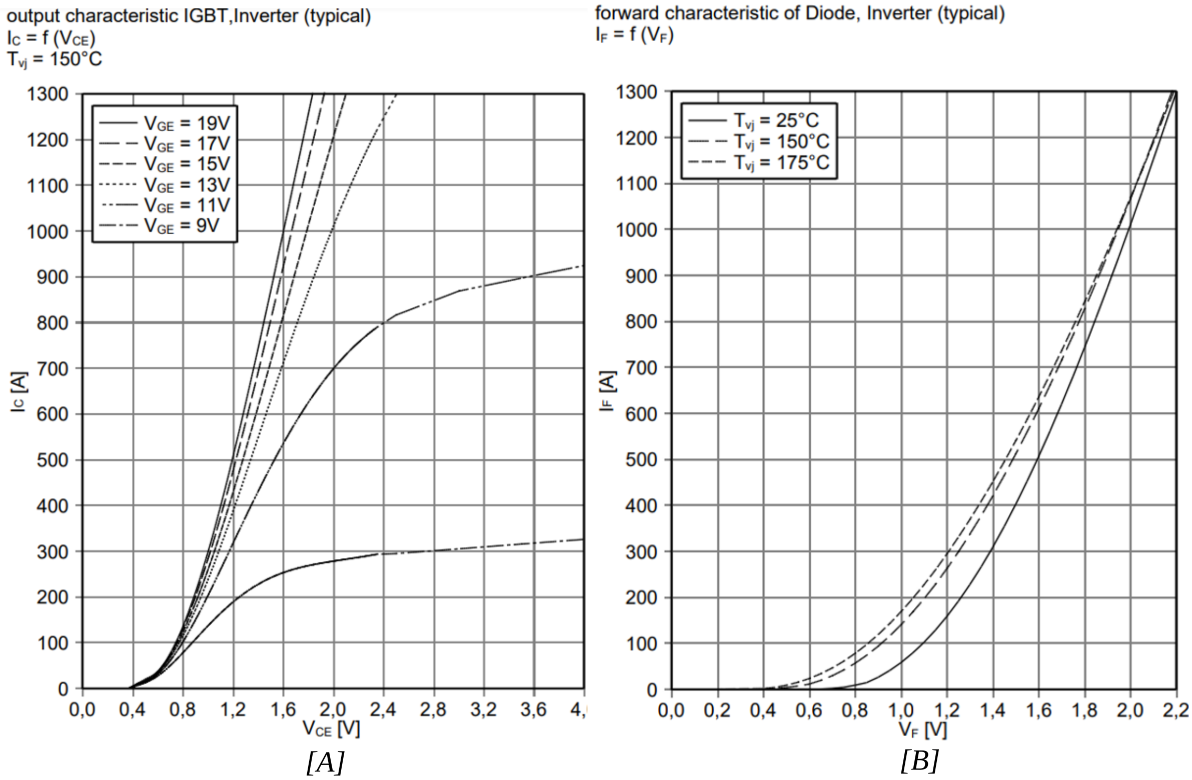


Fig.2 Voltage current gradient from inverter datasheet. *A. for diode B. for device*

4. Model

The FOC model needed to be adjusted based on the motor. The torque to Iq conversion was adjusted to match the motor value of 0.75 Nm/1Aph rms, as well as the number of pole pairs being adjusted to 10 within the FOC unit. The battery voltage was also adjusted to match the maximum motor voltage (500 V), allowing the inverter to supply the full range that the motor may require.

5. FOC Tuning

The FOC is tuned with two PI controllers shows below in Fig. 3. By adjusting the proportional gain and the integral gain, the response time, overshoot and oscillations can be controlled in order to achieve a stable response to torque demand. The system of designing a PI controller, however, comes with a dilemma. The faster the controller the controller responds to the input, the more unstable the oscillations become, or the system end ups under damped. These issues are made more complex by the oscillations generated by the switching ripple, which is to be expected.

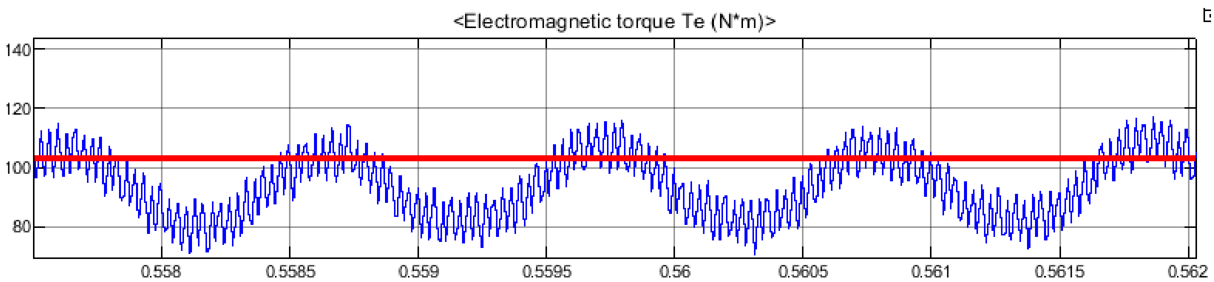
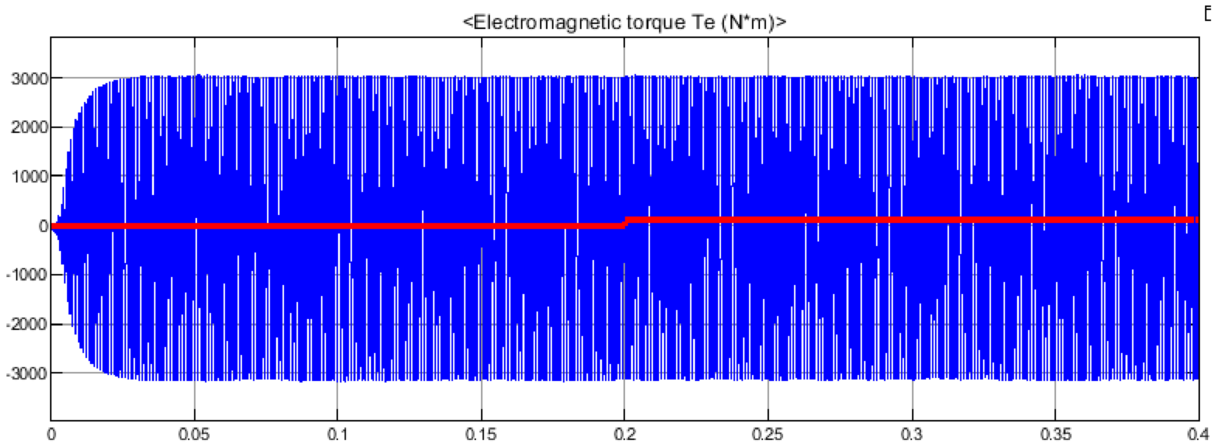


Fig.3 FOC response to a constant torque demand of 103 Nm

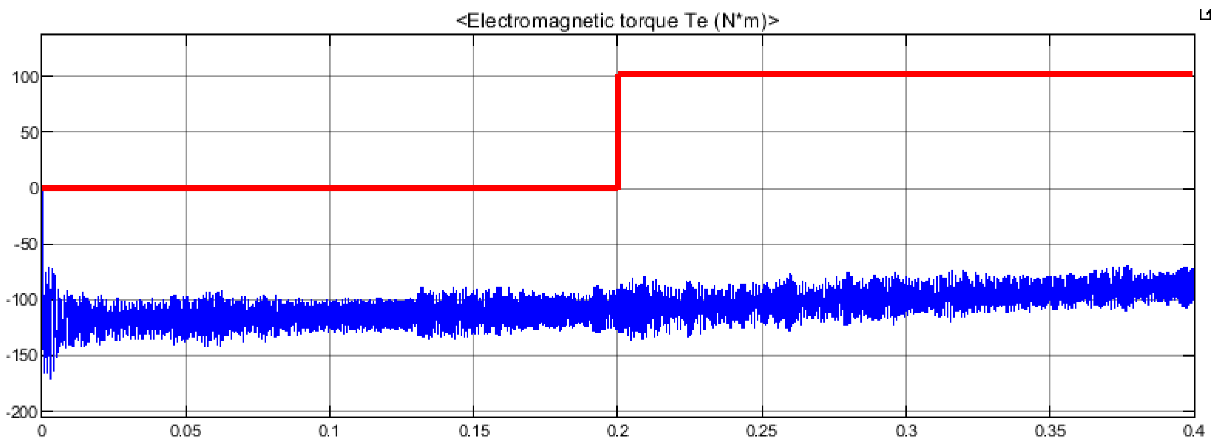
The aim of the PI optimisation was then to improve the response time of the motor to a torque demand without causing unstable or unacceptably large oscillations.

Observe and explain impacts of params on control performance

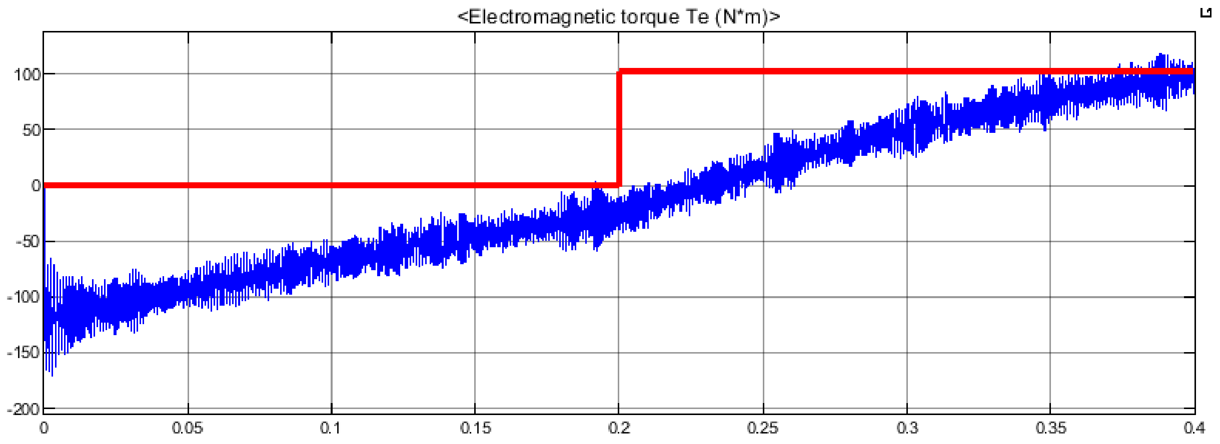
The motor speed was set to 5500 rpm and a step change in torque requirement of 103 Nm was used to simulate normal operating conditions of the motor. Initially, the system showed large oscillations far outside the range of the working torque (up to 3000 Nm) seen in Fig.4A. By reducing the proportional gain, the oscillations can be dramatically reduced, seen in Fig.4B where the reduction from 0.001 to 0.000001 removes most of the high amplitude error. The torques average error is not reduced as the integral term is too low, however. By increasing the value first to 0.01 then to 0.1, the average error can be reduced, and the motor toque is shown to roughly follow the torque demand showing that the system is near a potential solution (Fig.4C/D). After more fine tuning and longer runs to test stability, the optimised PI control can be seen in Fig.4E.



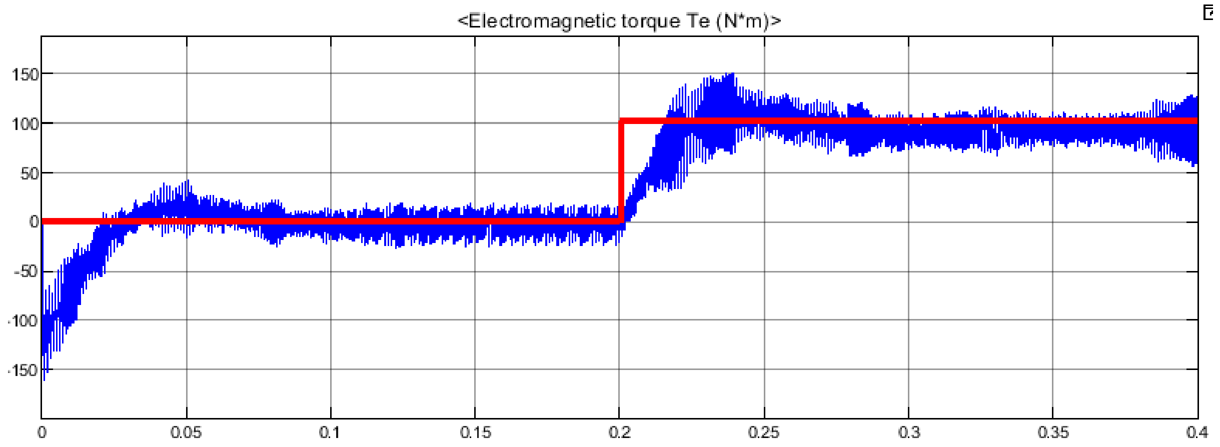
[A]



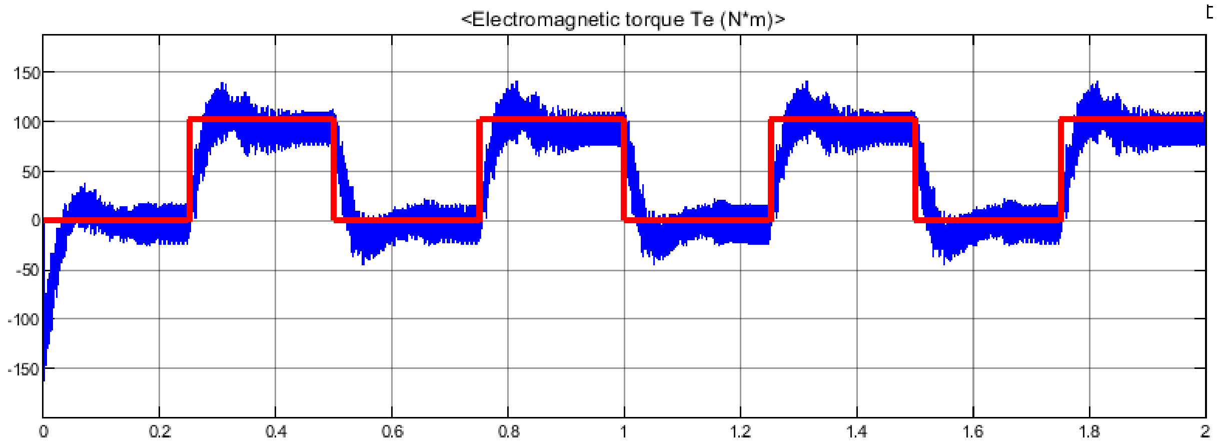
[B]



[C]



[D]



[E]

Fig.4 FOC response to input torque demand. A. *Kp = 1x10*$^{-3}$ *Ki = 0.001* ***B****. Kp = 1x10*$^{-6}$ *Ki = 0.001* ***C.*** *Kp = 1x10*$^{-6}$ *Ki = 0.01* ***D.*** *Kp = 1x10*$^{-6}$ *Ki = 0.1* ***E****. Kp = 1x10*$^{-9}$ *Ki = 0.07*

6.Test Plan

6.1 Test high frequency torque response

In order to test the stability of the design, a single step is not enough. By using a square wave, the performance of the design with repetitive harsh changes in torque demand can be measured and, by changing the frequency of these changes, the response time can be put to the test (Fig.5). The test should be run at 103Nm torque demand at 5500 RPM (59.3kW) to simulate accelerating to normal operating torque and back down again. Monitoring motor torque, speed and current draw to get an idea of how the rapid changes affect the design can provide additional insight into the performance limitations of the system. It is expected based on simulation that the motor should begin to struggle to meet demands at roughly 10 Hz.

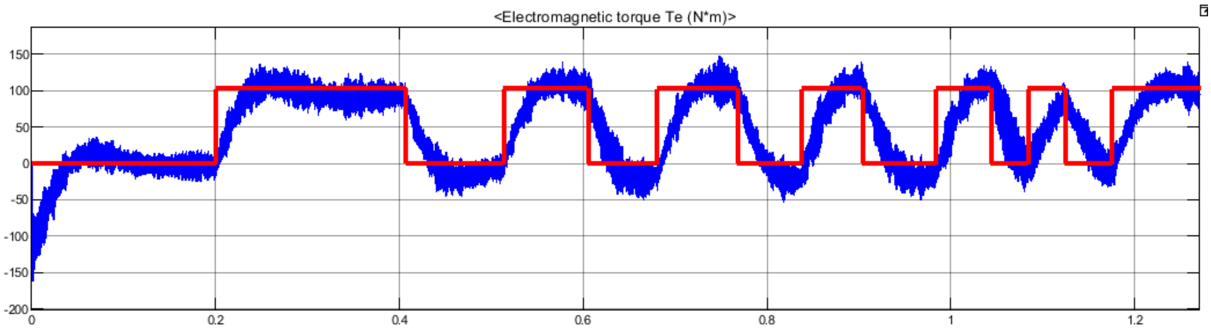


Fig.5 FOC response to varying frequency input torque demand

The datasheet specifies that a maximum RPM of 6500 is achievable with field weakening. In this case a test is run at 6500 RPM with a continuous torque of 103 Nm (70.1kW). The FOC should achieve similar performance in response time and stability as with the normal operation speed of 5500, achieving stability in 0.1s. Fig.6 shows the result of this in simulation.

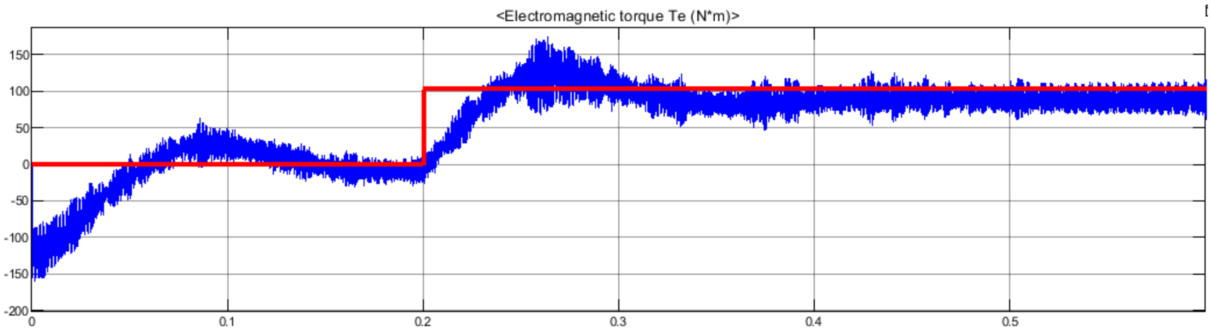


Fig.6 FOC response to step torque change at rated maximum motor speed

As the battery loses charge, its voltage can droop. A simulation of a battery voltage test should be run in order to prove that the system can cope with this change within operational limits. The battery voltage was chosen to drop from 500 V down to 475 V. The test should measure the torque and power output in order to make sure it does not deviate from the expected 59.3 kW specified by the 5500 RPM and 103 Nm inputs.

More generic testing of the powertrain can be used to gather a wider dataset. Tests such as current/voltage surges, battery voltage failures and tests that push the limits of the components themselves can be used to predict performance in more extreme situations.

7. References

[1] EMRAX. 2022. 228 (109kW | 230Nm) - EMRAX. [online] Available at: <https://emrax.com/e-motors/emrax-228/> [Accessed 13 January 2022].

[2] Infineon.com. 2022. [online] Available at: <https://www.infineon.com/dgdl/Infineon-FS650R08A4P2-DataSheet-v03_00-EN.pdf?fileId=5546d46272e49d2a017351f435eb5977> [Accessed 13 January 2022].

8. Appendix

A – EMRAX 228 Technical Datasheet

Type Technical data	EMRAX 228 High Voltage			EMRAX 228 Medium Voltage			EMRAX 228 Low Voltage		
Air cooled = AC Liquid cooled = LC Combined cooled = Air + Liquid cooled = CC	AC	LC	CC	AC	LC	CC	AC	LC	CC
Ingress protection	IP21	IP65	IP21	IP21	IP65	IP21	IP21	IP65	IP21
Cooling medium specification (Air Flow = AF; Inlet Water/glycol Flow = WF; Ambient Air = AA) If inlet WF temperature and/or AA temperature are lower, then continuous power is higher.	AF=20m/s AA=25°C	WF=8l/min at 50°C; AA=25°C	WF=8l/min at 50°C; AA=25°C	AF=20m/s AA=25°C	WF=8l/min at 50°C; AA=25°C	WF=8l/min at 50°C; AA=25°C	AF=20m/s AA=25°C	WF=8l/min at 50°C; AA=25°C	WF=8l/min at 50°C; AA=25°C
Weight [kg]	12,0	12,4	12,3	12,0	12,4	12,3	12,0	12,4	12,3
Diameter ø / width [mm]	228 / 86								
Maximal battery voltage [Vdc] and max load RPM	680 Vdc (5500 RPM)			500 Vdc (5500 RPM)			160 Vdc (5500 RPM)		
Peak motor power at max load RPM (few min at cold start / few seconds at hot start) [kW]	109								
Continuous motor power (at 5500 RPM)	50	53	62	50	53	62	50	53	62
Maximal rotation speed [RPM]	5500 (6500 for a few seconds with magnetic field weakening)								
Maximal motor current (for 2 min if cooled as described in Manual) [Arms]	240			340			900		
Continuous motor current [Arms]	115			160			450		
Maximal motor torque (for a few seconds) [Nm]	230								
Continuous motor torque [Nm]	96	102	120	96	102	120	96	102	120
Torque / motor current [Nm/1Aph rms]	1,1			0,75			0,27		
Maximal temperature of the copper windings in the stator and max. temperature of the magnets [°C]	120								
Motor efficiency [%]	92-98%								
Internal phase resistance at 25 °C [mΩ]	16,7			7,0			1,1		
Input phase wire cross-section [mm²]	11,4			17,0			42,5		
Wire connection	star								
Induction in Ld/Lq [µH] of 1 phase	177/183			76/79			10,3/10,6		
Controller / motor signal	sine wave								
AC voltage between two phases [Vrms/1RPM]	0,0730			0,0478			0,0176		
Specific idle speed (no load) [RPM/1Vdc]	9,8			14			40		
Specific load speed (max load) [RPM/1Vdc]	8			11			34		
Magnetic field weakening (for higher RPM at the same power and lower torque) [%]	up to 100								
Magnetic flux – axial [Vs]	0,0542			0,0355			0,0131		
Temperature sensor on the stator windings	kty 81/210								
Number of pole pairs	10								
Rotor inertia LC motor [kg*m²]	0,0383								
Bearings (front:back) - FAG	6206:3206 (for axial-radial forces; for pull-push mode, α=25°)								