Traction Axial - Flux Motor - Generator for Hybrid Electric Bus Application
MOTOR – GENERÁTOR S AXIÁLNÍM TOKEM PRO HYBRIDNÍ AUTOBUS

TRACTION AXIAL – FLUX MOTOR – GENERATOR FOR HYBRID ELECTRIC BUS APPLICATION

Zkrácená verze Ph.D. Thesis
KLÍČOVÁ SLOVA
Hybridní elektrický pohon, Původní návrh motor-generátoru s axiálním tokem a buzením permanentními magnety, elektromagnetický návrh, tepelný návrh, návrh řízení, účinnost, měření

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1 INTRODUCTION

Hybrid Electric Vehicle (HEV) is one of the more frequently used words of late. What is the driving force behind such a major change of vehicles’ powertrain architecture including not only small cars but line-haul trucks as well?

1.1 WHY HYBRID ELECTRIC VEHICLES?

According to figures shown in [1], transportation accounts for 51% of CO₂ emissions per average American household. The following Fig. 1-1 illustrates on an example of a passenger car, how the CO₂ annual footprint might be reduced by lower fuel consumption (MPG stands for Miles-per-US Gallon), considering average mileage of 15 000 US miles per year with 55% of city driving and 45% of highway driving [1].

![Fig. 1-1 Dependency of CO₂ emissions on fuel consumption [1] according to data from April 2008](image)

Some remarkable achievements presents Clean Cities initiative, when operation of 82000 HEV’s fleet, including Pick-Up & Delivery trucks, buses and refuse disposal trucks, in 87 American metropolitan areas saved in 2007 only, a stunning 16 millions US gallons of fuel [2]. One may relate these savings to the environmental impact.

There are various possible ways of hybridizing a vehicle and making it more fuel efficient and environmentally-friendly in the same time by:

- Reducing idle/low output operation of Internal Combustion Engine (ICE)
- Electrification of engine’s accessory load
- Recapturing waste energy (and using it)
- Reducing the size and power of ICE

Reduction of ICE idling operation is called a mild hybridization, with the engine frequently having the alternator and the starter motor replaced by Integrated Starter-Generator (ISG).

Further room for improvement gives recapturing of waste energy, either mechanical energy through regenerative braking or thermal energy using the Waste-Heat Recovery (WHR) concept [3]. These technologies, of regenerative braking and WHR might be found in various HEV topologies including parallel, combined or series.

1.2 TRACTION MOTOR GENERATOR MG2

A part of the combined hybrid powertrain is the motor-generator MG2. Combined powertrain, as depicted on Fig. 1-2, involves Internal Combustion Engine (ICE) as a dominant source of power with Motor-Generator 1 (MG1) directly coupled to the crankshaft. MG1 fulfils mainly a role of generator keeping state of charge of the battery pack within pre-defined operational range. One may distinguish several different operational modes for MG2 in the hybrid powertrain. MG2 is the only source of power in fully electric mode, when the clutch in between MG1 and MG2 is
disengaged and only MG2 drives the vehicle draining energy out of the battery pack. Fully electric mode of the vehicle seems to be convenient in conditions characterized by drivecycles with intermittent operation, such as in urban areas. Then the ICE may be completely turned-off, unless the vehicle exceeds defined speed and MG2 is unable to maintain desired driveability of the vehicle.

![Fig. 1-2 Layout of the combined hybrid powertrain.](image)

MG2 provides traction power once the clutch is engaged as well. MG2 is capable of fulfilling torque-boost mode, increasing level of available torque at low-speed operation of the powertrain. Instead of wasting kinetic energy of the vehicle by friction brakes or retarder, MG2 is available for recapturing such energy during regenerative braking, when recovered energy is stored in the battery pack.

## 2 MG2 DESIGN SPECIFICATION

MG2 as an electrical drive is designed for two-quadrant operation for positive sense of rotational direction following the engine, and both positive and negative polarities of developed torque. However, electrical drive in hybrid electric vehicle follows specific design requirements, given by nature of power source for the drive, operational conditions or adopted cooling architecture.

### 2.1 DEFINITION OF THE POWER NODE

The torque mode of operation is defined from zero up to base speed of 1300 rpm, where MG2 must develop 734.6 Nm of continuous torque and twice as high maximum torque. The operational zone from base up to maximum speed of 2800rpm is characterized by constant output power. That means, MG2 operates in field weakening mode at rated power of 100kW and twice as much of overload power. Any speed over 2800 rpm is considered as overspeed, when MG2 is not required to develop any power, but only to ensure safe field weakening, so that MG2 will not become uncontrollable.

MG2 is three-phase, inverter-fed machine. The inverter’s DC bus is directly connected to the battery pack terminals, and therefore, is not considered as a stiff voltage source. Battery voltage may swing from 500VDC at minimum state-of-charge (SOC) up to 800VDC at full SOC. To ensure safe operation in field weakening, MG2 design considers the DC bus voltage level corresponding to minimum SOC as a design requirement.
MG2 is water-cooled machine in order to maximize heat rejection capability of the machine. The stator assumes sandwich design with two symmetrical stator corepacks clamped by an aluminium cooling jacket in the middle. A coolant flows circumferentially though a groove in the middle of the jacket. The entire stator core is wound by full-pitch toroidal winding ensuring that the heat rejection path from a coil to the cooling jacket has got effectively low thermal resistance.

Fig. 2-1 shows simplified cross-sectional view of the powertrain in testing configuration.

Fig. 2-1 Cross-sectional view of combined hybrid powertrain – setup for the test cell installation. MG1 occupies the left hand side, whereas MG2 the right hand side housing

Stator of MG2 is mounted by lugs of the water jacket into midhousing, which is cascaded on the MG1’s housing. The mid housing creates in the same time an interface for MG2 and the spline shaft, which transmits torque from the engine, once clutch is engaged. The selected wet clutch is of radial arrangement, when the actual clutch assembly decomposes of several cascaded radial clutches.

The spline shaft rotates in the supporting back plate due to single row ball bearing. However, bearing holding the rotor subassembly of MG2 needs to cope with unbalanced axial forces and tilting forces due to possible misalignments of the machine, making the set of airgaps non-uniform. Therefore, the selected bearing is of double row angular contact arrangement, which is able to cope with axial forces, if appropriately selected. The implication of unbalanced axial forces and tilting on bearing selection process will be discussed further.

3 CONCEPT GENERATION

The outcome of concept selection process is the most feasible topology of an electrical machine for a defined application. A side benefit of the concept selection process is better understanding and prioritization of customer’s needs, reflected into design criterions. Among the other criterions, the top priorities were identified as:

- Short axial length <200mm
- MG2 must fit into SAE0 housing in terms of its diameter
• High power density
• Peak efficiency above 95%
• Ability to operate in field-weakening mode from 1300 up to 2800 rpm with consideration of minimal DC link voltage of 500VDC

Design of electrical machines doesn’t lead to one particular solution, which might be unitarily considered as the greatest. It is rather balanced trade-off in between many variables involved in design of the machine.

3.1 INITIAL ASSESSMENT OF CONSIDERED MACHINE TOPOLOGIES

The initial selection of electrical machines for hybrid drives includes variety of different topologies. According to outcomes of literature survey, induction machines alongside with synchronous machines take frequently place in HEV powertrains. Both of these, in sense of operational principle, different families of machines may be laid out in axial or radial plane. Out of radial synchronous machines, surface-mounted-, inset- and embedded-permanent magnet topologies, and switched reluctance machines are considered as competitive for traction purposes. Synchronous permanent magnet axial flux machines are subject of ongoing research, and need to be included due to their advantageous axial length. Fig. 3-1 depicts 3D models of permanent-magnet axial flux machines.

Fig. 3-1 Cross-sectional views of axial flux permanent magnet machines: a) with Iron Poles, and b) PMs embedded in spoke arrangement

The axial flux PM machine with iron poles is derivative of surface-mounted PM machine in terms of magnetic field distribution. The drawback of this topology is in inherently decreased power density since certain proportion of the each winding turn in a slot is not faced to a field of PMs and therefore, do not participate in torque production. The spoke-PM machine should therefore fit into a smaller envelope for given ratings since it is naturally feasible for field weakening, and does not have to employ any additional flux weakening feature.

The initial assessment of features of considered machines shows Pugh Concept Selection matrix on Fig. 3-2. Each individual machine topology is compared against so-called datum that means a machine, which is a baseline for the comparative process. A surface-mounted PM machine has been selected as a datum due its relative matured technology and well understood properties. The actual comparison is carried out in a relative manner. The positive (+) sign indicates improvement
against the datum, whereas negative (-) sign stands for worsening of the assessed parameter. This selection method is relative, based on existing experience with this particular class of machines in terms of their rating.

<table>
<thead>
<tr>
<th>Criteria/Concept</th>
<th>Datum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface-mnt. Synchronous PM</td>
</tr>
<tr>
<td>Axial length</td>
<td>S</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>S</td>
</tr>
<tr>
<td>Efficiency</td>
<td>S</td>
</tr>
<tr>
<td>Power density</td>
<td>S</td>
</tr>
<tr>
<td>Field weakening</td>
<td>S</td>
</tr>
</tbody>
</table>

Fig. 3-2 Pugh concept selection matrix for traction motor generator. (+) indicates improvement, (-) worsening and (S) the same status of a particular parameter in a comparison to the datum.

The Pugh matrix on Fig. 3-2 shows that group of four synchronous machines – radial with inset or embedded permanent magnets, and axial with iron poles and permanent magnets or with spoke magnets only, are proceeded further for more detailed analysis. The Pugh concept selection matrix indicates that permanent-magnet excitation should lead toward more compact size and high efficiency.

### 3.2 EVALUATION OF FEASIBLE CONCEPTS

The initial sizing included candidates marked as „green“ in the pugh matrix for more detailed evaluation. The group of machines proceeding further includes Embedded- and Inset PM radial machines alongside with Axial-flux PM machines with iron poles and with permanent magnets in the spoke arrangement. The initial sizing based on equivalent reluctance circuits for all topologies, estimates size, performance and efficiency according to standard sizing procedures [4] with adequate alterations needed for conversion from radial to axial plane. The following Tab 3-1 summarizes outcomes of basic sizing for above-mentioned machines.

| Tab. 3-1 Initial sizing of concept machine topologies for traction motor generator |
|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Rated power (kW)              | 100                           |                               |                               |                               |
| Base speed (rpm)              | 1300                          |                               |                               |                               |
| Maximum Speed (rpm)           | 2800                          |                               |                               |                               |
| Field Weakening Capability    |                                |                               |                               |                               |
| Peak Efficiency (%)           | 95.8                          | 95.3                          | 96.2                          | 96.1                          |
| Power desity (kW/dm³)         | 16.03                         | 12.62                         | 9.06                          | 10.03                         |
| Outer Diameter Fits into SAE 0| Yes                           | Yes                           | No                            | Yes                           |
| Axial Length below 200 mm     | No                            | No                            | Yes                           | Yes                           |

All considered machine topologies might achieve specification in terms of required torque-vs-speed envelope, including field-weakening. However, axial-flux machines bring advantage in terms of axial length reduction. Both concepts of axial flux machines fit within the desired axial
length of 200mm. However, lower power density and therefore, higher outer diameter disqualifies the configuration with iron poles.

### 3.3 CONCEPT OF SPOKE AXIAL-FLUX PERMANENT MAGNET MACHINE

The major difference against the configuration with iron poles is in the layout and structure of rotor plates. The Spoke concepts represent completely different approach. The rotor structure is created out of strip of electrical steel, which is punched during its winding process so that radially distributed pockets for magnets are created. Such manufacturing process leads to a magnetic circuit of Spoke-PM axial flux machine depicted in terms of distribution of flux lines on Fig. 3-3.

![Fig. 3-3 Distribution of magnetic field within axial-flux machine with iron poles](image)

Spoke-axial flux machine behaves inherently like a traction motor, producing reluctance torque alongside with magnet torque during field weakening operation.

### 4 ELECTROMAGNETIC DESIGN

The following chapter deals with electromagnetic design of the Spoke-Axial Flux Machine, starting by initial design considerations, and leading towards consolidated design following multiphysics approach.

Sizing of MG2 starts by defining Torque-per-Rotor-Volume (TRV) constant, reaching up to $75\, kNm/m^3$ for air-cooled aerospace machines, and from $130\, kNm/m^3$ up to $220\, kNm/m^3$ for large machines with direct water cooling of stator winding [5]. The TRV ratio is directly proportional to linear current density $A$ and magnetic flux density in the airgap $B_g$:

$$TRV = \frac{\pi}{\sqrt{2}} k_w A \cdot B_g \cdot \sin(\alpha)$$  \hspace{1cm} (4-1)

where $k_w$ is winding constant and $\sin(\alpha)$ indicates displacement angle between rotor flux and armature reaction flux waveforms. Assuming $I_d=0$ operation, those waveforms are displaced by 90deg, therefore maximizing torque production.
Specific magnetic loading in terms of airgap flux density reaches typically for embedded-
permanent machines up to $B_g \leq 1T$ [6]. Considering winding factor for toroidal winding with one
slot per pole per phase to be $k_w = 0.95$, the initial linear current density is set up to $A = 50A/mm$.
Selection of aspect ratio in between active outer and inner diameter of the machine has direct
impact on achievable torque density [7]. It has been shown [8] that optimal aspect ratio
maximizing the power density is $\sqrt{3}$.

4.1 ELECTROMAGNETIC ANALYSIS OF MG2

According to the flowchart diagram at Fig. 4-1, actual electromagnetic analysis follows the
initial sizing. Magnetic circuit of Spoke-Axial Flux machine may be characterized as non-linear
because of presence of bridges holding permanent magnets in the rotor structure

4.1.1 Equivalent reluctance circuit

A solution of magnetic circuit may take an advantage out of analogy in between magnetic and
electric circuit. A voltage source is represented by source of MMF, current is equivalent to
magnetic flux, and resistance to magnetic reluctance. Following distribution of magnetic fluxlines
within the magnetic circuit according to Fig. 3-3, a network of equivalent MMF sources and
reluctances may be sketched over layout of the magnetic circuit as depicts Fig. 4-2 a) below:
It is sufficient to calculate magnetic field per one-half of a pole since magnetic field is distributed symmetrically against axis of a permanent magnet, as shows Fig. 4-2 b). Therefore, only a half of magnet’s tangential length as well as only half of peripheral airgap length is considered. On the stator side, the equivalent circuit accounts for a half of physical flux tube too.

The actual electromagnetic design also included analysis focusing on optimization of magnet sizing, followed by winding analysis leading toward estimation of induced voltage. Furthermore, equivalent circuit of the machine in dq0 reference frame is a part of the work, as well as estimation of performance and field weakening capability.

4.2 IRON LOSSES

A model of iron losses aims to estimate this particular loss component at various load points in terms of torque and speed. Fig. 4-3 illustrates iron loss map, exactly overlapping an efficiency map.

![Iron loss map](image)

**Fig. 4-3** Iron loss map as an outcome of the iron loss model, exactly overlapping an efficiency map. Violet points represent loadpoints analyzed by FEA.
The intention is to consider true loading of electrical steel in terms of magnetic flux density, including its higher harmonics. For that reason, the magnetic flux density in backiron and stator teeth, at four specific locations, were studied at no-load as well as under variety of torque loads. This allowed mapping up impact of higher harmonics of magnetic field, caused by armature currents, on iron loss, as shows Fig. 4-3. The iron loss map may be stored as two-dimensional look up table, and therefore, is feasible for generating efficiency maps or for system level simulation purposes.

4.3 FINITE – ELEMENT ANALYSIS OF MG2

The numerical modeling of electric machines, in particular Finite Element Analysis, enhanced level of understanding the electric machines [9]. FEA analysis of MG2 focused on estimation of leakage flux, open-circuit voltage including analysis focused on reduction of the total harmonic reduction and assessment of cogging torque. The performance analysis included torque production assessment, as illustrates Fig. 4-4, which assumes stator winding fed by AC current waveform with electrical frequency corresponding to base speed, and locked rotor.

![Fig. 4-4 Torque production of MG2 at base frequency and maximum current of 480Arms](image)

Similar analysis may be performed at maximum speed in order to verify that the machine is able to deliver for predicted current the maximum power. Meanwhile, such analysis provides corresponding current angle as well, helping to verify field weakening performance of the machine.

In terms of inductances, FEA focused on the flux variance method due to nonlinear character of the magnetic circuit. A profile of inductances as a function of current shows Tab. 4-1:

<table>
<thead>
<tr>
<th>Id (p.u.)</th>
<th>-2</th>
<th>-1.5</th>
<th>-1</th>
<th>-0.5</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iq (p.u.)</td>
<td>-2</td>
<td>-1.5</td>
<td>-1</td>
<td>-0.5</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Ld (mH)</td>
<td>0.160</td>
<td>0.160</td>
<td>0.160</td>
<td>0.064</td>
<td>0.157</td>
<td>0.150</td>
<td>0.141</td>
<td>0.131</td>
</tr>
<tr>
<td>Lq (mH)</td>
<td>0.217</td>
<td>0.231</td>
<td>0.253</td>
<td>0.286</td>
<td>0.286</td>
<td>0.253</td>
<td>0.231</td>
<td>0.217</td>
</tr>
</tbody>
</table>

Impact of q-axis inductance saturation needs to be addressed during control design since it may affect optimum split of current components into d- and q- axis for MTPA or field weakening control strategies.
4.4 AXIAL FORCES IN MG2

According to provided Dimensional Variation Analysis, the total nominal airgap variation because of manufacturing and assembly processes is $\pm 0.59\text{mm}$, out of $\pm 0.328\text{mm}$ is contribution caused by pure axial displacements and $\pm 0.262\text{mm}$ is due to angular displacement in bearings. These inputs from mechanical design side identify a case for analysis of axial forces in the machine in the following cases:

- axial forces when both rotor plates are exactly aligned
- a case when rotor plates are axially shifted, but airgaps are still parallel
- angular displacement of rotor versus stator causing unparallel, tilted airgaps
- a combined case of axial shift and angular misalignment.

Any misalignment of airgaps creates misbalance between forces acting on each of the rotor plates. Shorter is the airgap, greater are the axial forces over a rotor plate. This creates a positive feedback loop, so that once the rotor plates are misaligned versus the stator, the effect amplifies.

### 4.4.1 Axial forces at uniform airgaps and axial movement of rotor plates

Attraction force in the airgap may be determined by applying virtual work method as a variation of stored magnetic energy $W_m$ with regards to variation of the airgap length in $z$-direction. A profile of force vs. angle provides therefore necessary inputs for the rotor structural design. A different way of analyzing a profile of axial forces is to perform computation per entire airgap circumference at given radius $r$ with considering a radius increment $\Delta r$. The profile of forces vs diameter was obtained once again for maximum power/maximum speed loadcase. The plot indicates that the rotor plate might be subject of umbrella-type deflection due to the force increases with diameter. In terms of total axial force per a plate, two different load cases were investigated. The total axial forces per a plate at maximum torque/base speed loadcase are estimated to be $21.8\text{kN}$, whereas forces at maximum power/maximum speed loadcase are predicted at $25.8\text{kN}$. Pure axial movement of rotor plates investigates when both rotor plates are still parallel with regards to the stator assembly. The pure axial shift may occur due to tolerancing issues on component side or during assembly process.

Following Fig. 4-5 shows dependency of axial forces on axial move.

![Fig. 4-5 Variation of axial forces for each airgap for pure axial shift of rotor plates](image-url)
As the misalignment progresses, the total force rises for the loadcase maximum power/maximum speed from 25.8kN up 48.6kN, when one of the rotor plates is clamped to the stator core.

4.4.2 Tilting of rotor plates

Calculation of tilting forces illustrates Fig. 4-6 considers discretization of the rotor plate surface by a grid defined angularly by one degree electrical and radially by one millimeter. Each of such incremental areas $S_{r,\theta}$ contributes adequately to the total force per rotor plate.

![Fig. 4-6 Linearized map of axial forces for tilted rotor plates](image)

Subtracting axial force according to Fig. 4-6 developed by incremental area $S_{r,\theta}$ on the side of the rotor plate with longer airgap from axial force developed at area displaced by 180deg mechanical $S_{r,\theta+\pi}$, but defined by the same set of radiiuses, will indicate difference in force per two counter-located areas, and hence also a tilting moment, critical for bearing selection.

5 THERMAL DESIGN

Assessment of thermal behavior of the water-cooled electric motor-generator for a hybrid electric vehicle does not reduce to estimation of steady-state winding temperature, but rather focuses on prediction of temperature of the machine in transient operational mode.

5.1 DESIGN AND MODELING OF WATER-COOLED MACHINES

The design and modeling of the cooling system assumes the only effective heat rejection path through the stator cooling jacket. Since the rotor structure is laminated with magnets protected from spacial harmonics of magnetic field by rotor laminations, it is assumed that the only heat sources are on the stator side in terms of copper and iron loss. Therefore, the modeling effort focuses on the stator subassembly only.
5.2 HEAT REJECTION CAPABILITY OF THE COOLING JACKET

The aluminium jacket is shaped like a torus and has a narrow duct in the middle where the coolant flows. The duct has got a ‘width gradient’ along its length due to presence of grooves. These grooves force flow of the coolant to become turbulent and therefore, improve heat transfer. Since the axial thickness $l_a$ of the duct formed in the cooling jacket is far smaller than its radial thickness $l_r$, $l_r \gg l_a$, the hydraulic diameter [10] $L$ of the duct is defined to be equal to twice the radial thickness $l_r$. The inlet and outlet pipes are on the same side of the jacket and therefore, a temperature gradient is created between the outlet coolant $T_{out}$ and inlet coolant $T_{in}$ pipes due to the coolant flow and heat absorption. The gradient $T_{out} - T_{in}$ is given by:

$$T_{out} - T_{in} = \frac{P_{loss}}{q_m \cdot c_s}$$

(5-1)

where, $q_m$ is mass flow rate, $P_{loss}$ is the power loss to be dissipated from the stator and $c_s$ is the specific thermal capacity of the coolant. Equ. (5-2) gives the average coolant temperature $T_{av}$ with temperature of the aluminium duct surface $T_{Al}$ obtained from CFD:

$$T_{av} = T_{Al} + \frac{T_{in} - T_{out}}{\ln \left( \frac{T_{in} - T_{Al}}{T_{out} - T_{Al}} \right)}$$

(5-2)

The assumption of turbulent flow in the duct needs to be supported by calculation of Prandtl number $Pr$, which should lie in the interval $0.7 < Pr < 2500$:

$$Pr = \frac{\mu}{\alpha \cdot \rho}$$

(5-3)

Reynolds number $Re$ needs to exceed 10,000 for flow to be qualified as turbulent:

$$Re = \frac{q_m \cdot L}{\mu \cdot S_{cj}}$$

(5-4)

where $S_{cj}$ is cross-sectional area of the aluminium jacket duct. Once the assumption of turbulent flow in the cooling duct is validated, Dittus-Boelter correlation [10] is applied to determine a value of Nusselt number $Nu$:

$$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4}$$

(5-5)

Heat transfer coefficient $h$ is obtained from a $Nu$, $L$ and thermal conductivity of the coolant $\lambda$:

$$h = \frac{\lambda \cdot Nu}{L}$$

(5-6)

A set of Equ. (5-1) – (5-6) provides closed-form solution for estimation of heat transfer coefficient for a given flow rate of the coolant, and its variable physical parameters. The mathematical model of the cooling jacket was validated by CFD simulation work [11], which was taken over from design of Motor-Generator MG1 with exactly the same design of the cooling system. Heat transfer coefficient at inner surface of the cooling jacket for the flow rate of 10 l/min is presented in Fig. 5-1.
The actual accuracy of analytical calculations versus results obtained by CFD is within 10% error margin for a range of flow rates from 5 up to 20 l/min.

5.3 EQUIVALENT LUMPED-PARAMETER THERMAL CIRCUIT

Heat dissipation out of Spoke Axial-Flux machine occurs vastly through the aluminium heat sink due to totally enclosed housing of the machine disabling any air flow from ambient, and thus convection heat transfer. An equivalent 3D transient thermal model consisting of 17 nodes has been developed. Assuming distribution of heat flux paths, the equivalent thermal circuit in linearized circumferential view is shown on Fig. 5-2. In order to increase accuracy of the thermal model, the stator core is radially divided into three tangential segments.

The equivalent circuit is expanded in a plane defined by toroidal shape of a coil.

5.4 PREDICTION OF WINDING TEMPERATURE RISE

Coupling of the equivalent transient thermal circuit with heat transfer calculations for the heat sinks helps in understanding of the winding temperature for variety of load cases. The profile of winding temperature on Fig. 5-3 assumes fixed load of nominal torque at base speed of 1300rpm.
A rate of slope of the functional dependency of winding temperature on flow rate helps to optimize coolant flow rate through the heat sink. It is apparent that once the coolant flow rate exceeds 15 l/min, the effect of incremental increase of flow rate by 1 l/min reduces the winding temperature only by 0.13 K/l, unlike by 0.64 K/l for range of flow rates below 10 l/min.

However, the machine is designed to sustain the overload as well. Following Fig. 5-4 depicts time-on (scaled against thermal time constant $\tau$ as a ratio $t_{on}/\tau$) as a function of duty cycle $D$, defined as ratio of time-on $t_{on}$ versus period of the overload cycle $T$. Each particular curve is parameter of overload factor $k$, defined as ratio of actual power loss versus power loss at base point.

As an example, following the purple curve on Fig. 5-4 defining the overload factor $k \approx 1.3$, the machine under duty cycle $D \approx 0.4$ may stay at this load point for duration of $0.4\tau$, that means 113.24s before the load needs to be reduced at a level of power loss at the base point, or below.
EFFICIENCY AND CONTROL OF MG2

From a hybrid powertrain standpoint of view, the electric drive may be considered as a “black box” consuming electrical power and delivering mechanical power on a shaft in the motoring mode, or vice versa in the generating model.

6.1 ELECTRICAL MACHINE LOSS MODEL

The machine’s power loss may decompose into:
- Copper loss
- Stator iron loss due to magnet field and armature current reaction
- Stray losses in the stator core as an effect of PWM-caused current ripple
- Eddy current loss in the heat sink due to current in stator winding (PHS)
- Eddy current loss in permanent magnets (PPM)
- Eddy current loss in the rotor outer stainless steel retaining ring (PRR)
- Bearing loss (PMB) and Windage loss (PW)

The equivalent circuit of synchronous PM machine in dq0 reference frame leads toward following expression of controllable power loss $P_{\text{loss,EM}}$ within the machine:

$$P_{\text{loss,EM}} = P_{\text{Cu}} + P_{\text{Fe}} = \frac{3}{2}(R_a \cdot (I_d^2 + I_q^2) + R_c \cdot (I_{dc}^2 + I_{qc}^2))$$  \hspace{1cm} (6-1)

The actual torque production of the machine is due to $I_{q0}$ and $I_{d0}$ components of total q-axis $I_q$ and d-axis $I_d$ current respectively, so that machine’s torque production may be described as:

$$T_{EM} = \frac{3}{2} p_p \cdot i_{q0} (\Psi_{PM} + I_{d0} \cdot (L_d - L_q))$$  \hspace{1cm} (6-2)

Uncontrollable power losses have been determined as a part of Finite-Element Analysis effort, and included into the overall loss model of the drive. Dependency of each individual component of uncontrollable losses on speed shows Fig. 6-1.

6.2 POWER ELECTRONICS LOSS MODEL

An integral part of MG2 drive loss model is representation of power electronics in terms of their losses. Conduction losses $P_c$ are determined out of Volt-Ampere characteristic of a device in on-state providing threshold voltage $V_i$ and dynamic on-state resistance of silicon $R_d$ at a specific load current so that:

$$P_c = V_i \cdot I_{sw} + R_d \cdot I_{csw}$$  \hspace{1cm} (6-3)

Switching losses $P_{sw}$ generally depends on switching frequency $f_{sw}$ and dissipated energy during turning-on $W_{on}$ and –off process $W_{off}$:

$$P_{sw} = f_{sw}(W_{on} + W_{off})$$  \hspace{1cm} (6-4)

A convenient way of obtaining switching losses is through switching energy as a function of current $W_{sw} = f(I)$ from a datasheet of the device by a quadratic approximation so that switching loss is function of time-variant current:

$$W_{sw}[I_a(t)] = E_{max} \cdot k^2 \cdot \sin^2\left(\frac{2\pi}{T \cdot t}\right)$$  \hspace{1cm} (6-5)
where $E_{\text{max}}$ is datasheet value of the switching energy at maximum current, $T$ is period of the current waveform and $k$ is current utilization factor as a ratio between actual phase current and maximum current of the switching device.

The model for estimation of power electronics losses principally follows the block diagram on Fig. 6-2 below.

The Modulation index $M_i$ according to Fig. 6-2 is defined as a ratio of fundamental component magnitude of the line-to-neutral inverter output voltage $V_{lm}$ to the fundamental component magnitude of the six step mode voltage $2 \cdot V_{DC} / \pi$

$$M_i = \frac{V_{lm}}{2 \cdot \frac{V_{DC}}{\pi}} \quad (6-6)$$

Although power factor $\cos \phi$ is not directly involved in calculation of power loss of power electronics devices, it influences quantity of power loss due to assumed Discontinuous Pulse-Width Modulation scheme [12]. The switching frequency assumed for these particular calculations is $f_{sw} = 10kHz$.

### 6.3 CONTROL STRATEGIES FOR SPOKE AXIAL FLUX MACHINE

It is required to assess impact of each particular control strategy on performance and efficiency of the electrical drive involving MG2.

![Fig. 6-1 Profiles of uncontrollable power losses versus speed.](image)

![Fig. 6-2 Block diagram for power electronics loss calculation](image)
6.3.1 Maximum Torque-per-Ampere Control Strategy

Frequently employed option in terms of current control strategies for inverse-salient PM machines is Maximum Torque-per-Ampere (MTPA) Control Strategy. An analytical way of calculating reference $i_d^*$ current introduces Equ. (6-7) [13].

$$i_{d,MTPA}^* = \frac{\Psi_{PM}}{2(L_d - L_q)} - \sqrt{\frac{\Psi_{PM}^2}{4(L_d - L_q)^2} + (i_{q,MTPA}^*)^2}$$

(6-7)

The reference $i_q^*$ current may be then obtained from Equ. (4-24). However, availability of MTPA is constrained by maximum input voltage. Considering voltage equations of permanent magnet synchronous machines:

$$\left(\frac{V_{DC}}{\sqrt{3}}\right)^2 = (\omega_e \cdot L_q \cdot i_q) + (\omega_e \cdot L_d \cdot i_d + \omega_e \cdot \Psi_{PM})^2$$

(6-8)

Equation (6-8) represents an ellipse from mathematical standpoint of view. Such ellipse is eccentric concerning the origin, with its centre point lying at negative portion of the x-axis. The ellipse represents voltage envelope for MTPA control strategy. Considering the MTPA reference current trajectory on Fig. 6-3, the intersection of the trajectory with voltage ellipse determines the boundary for MTPA at a given speed, as illustrates Fig. 6-3.

![Fig. 6-3 Reference $i_q$ and $i_d$ currents for MG2 under MTPA taking into account nonlinear machine parameters and limitation due to maximum input voltage](image)

Any requested load point, which would require combination of reference currents beyond the voltage ellipse, means transition into voltage-constrained field weakening.

6.3.2 Maximum Efficiency Control Strategy

The aim of Maximum efficiency control strategy is to minimize both copper and iron losses, as MTPA focuses on copper loss only. Maximum Efficiency control strategy may be derived, with consideration of Equation (6-1) out of loss minimization conditions:
\[
\frac{\partial P_{\text{loss, EM}}}{\partial i_d} = 0 \quad (6-9)
\]

followed by
\[
\frac{\partial T_{\text{EM}}}{\partial i_d} = 0 \quad (6-10)
\]

The analytical solution is obtained by combining these loss minimization conditions, and in terms of d- and q-axis reference currents might be found in [14].

6.3.3 Field Weakening Control Strategy

The main purpose for introducing of field weakening control strategy is to satisfy voltage conditions described by Equation (6-8). It is necessary to inject additional negative \( i_d \) current in order to reduce EMF by reactive voltage drop projecting into \( v_q \) voltage. Neither MTPA, nor ME control strategies are therefore valid.

6.4 EFFICIENCY MAPS FOR MG2 AND ITS DRIVE

A way of representing efficiency of the electric machine, power electronics, or combined one for entire drive, is through efficiency maps [15]. An efficiency map may be also incorporated into overall vehicle power flow model, enabling thus modeling of electrical machine on a system level.

6.4.1 Electrical Machine Efficiency Map

The primary aim of this section is to assess impact of control strategy on efficiency of the machine. Since it is expected that ME will provide greater efficiency that MTPA, the efficiency map of electrical machine under MTPA is subtracted from the map under ME strategy, as depicts Fig. 6-4 below:

![Improvement in electrical machine efficiency under ME over MTPA control strategy](image)

Fig. 6-4 Improvement in electrical machine efficiency under ME over MTPA control strategy

The peak efficiency improvement by employing ME control strategy instead of MTPA is up to 2.5%. A similar efficiency map may be generated for the entire electric drive.
7 TESTING OF MG2

The design and analysis iterations leading toward proposed and constructed MG2 design requires validation by test results. Proposed structure of tests focuses on demonstration of performance, efficiency, cooling capability and support of modeling work.

7.1 TEST BED SETUP AND INSTRUMENTATION

Testing as described in this work, took its place in Tech Centre of Cummins Generator Technologies, Stamford, UK. Following Fig. 7-1 illustrates MG2 in its housing as a part of test bed setup, ready for testing.

![MG2 as a part of the test bed setup](image)

The actual test setup includes a DC motor drive able of operation in four quadrants of torque-vs-speed map, driving or braking MG2 depending on required operational mode. The DC motor also includes reference speed measurement. The driveline then continues by strain-gauge torque transducer, followed by flexible coupling and actual MG2 located in its housing.

7.2 WINDING RESISTANCE

The Tinsley 5895 Micro Ohm meter was used for measurement of the winding resistance. Actual measurement considers line-to-line resistance, which is then divided by two in order to obtain resistance per a phase. The measured value at 8.8degC ambient temperature is \( R_{a,m} = 9.172 \text{m} \Omega \). The analytical spreadsheet predicts \( R_{a,p,corr} = 9.357 \text{m} \Omega \) at 8.8degC winding temperature.

7.3 PHASE INDUCTANCES

MG2 is characterized as inverse-salient machine, thus having profile of inductances dependent on relative position of the rotor to the stator. Considering MG2 is 18-pole machine, a rotor locking mechanism with 40deg mechanical span and with discretization by 0.5 deg mechanical was
developed. This allows fixing the rotor position and thus, overcome cogging torque prior to the measurement. Two different methods, by LRC meter, and by resonant LRC circuit were implemented, both providing close results.

7.3.1 Surge Test by RLC Resonant Circuit

The experiment setup consists of a capacitor \( C \) connected in parallel to the terminals of the winding as illustrates Fig. 7-2. The capacitor may be isolated from the winding by opening the switch \( S2 \). Having this situation as initial condition, a DC voltage source is connected via a switch \( S1 \) to the terminals of the capacitor.

\[\text{Fig. 7-2 Circuit diagram for LRC resonant circuit}\]

Considering \( S1 \) closed and \( S2 \) opened, the DC voltage source charges up the capacitor to the required value. Once \( S1 \) is opened and \( S2 \) closed, the capacitor discharges to the winding creating oscillatory waveform, with angular frequency corresponding to Thomson’s equation.

7.3.2 Test Using LRC-Meter

The test using LRC meter was specifically performed at testing frequency of the internal AC source at 195Hz, matching up the base electric frequency of the machine. Both methods of Surge test by LRC circuit and Hioki LRC meter measured inductance with defined discretization in terms of rotor position by 0.5deg in 40deg span, thus inductance profiles vs rotor angle were obtained as illustrates Fig. 7-3 below.

\[\text{Fig. 7-3 Profile of phase inductance vs. rotor angle obtained by Hioki LRC tester and LRC resonant circuit}\]

Tab. 7-1 below records values in terms of \( L_d \) and \( L_q \) for both testing methods and FEA analysis for comparison.
Tab. 7-1 Comparison of measured values of inductances with FEA-based prediction

<table>
<thead>
<tr>
<th>Phase</th>
<th>Predicted</th>
<th>Tested</th>
<th>Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductances</td>
<td>FEA</td>
<td>RLC</td>
<td>Hioki</td>
</tr>
<tr>
<td>Ld (mH)</td>
<td>160</td>
<td>162</td>
<td>156</td>
</tr>
<tr>
<td>Lq (mH)</td>
<td>286</td>
<td>244</td>
<td>220</td>
</tr>
</tbody>
</table>

As measured values of $L_d$ differs from FEA prediction by as little as $4 \mu H$, in terms of $L_q$ measurements shows results lower by up to $66 \mu H$.

7.4 BACK-EMF TEST

Measurement of Back-EMF was performed by digital power analyzer allowing sampling of the actual voltage waveform and thus, further data postprocessing.

7.4.1 Measurement of EMF

The EMF waveform, as presented on Fig. 7-4, was obtained at base speed of 1300 rpm and at 18.7degC ambient temperature. The no-load FEA considered exactly the same speed and temperature conditions as during testing in order to mimic the exact coercitive force $H_c$ and remanent flux density $B_r$ of the magnets.

![MG2 Back-EMF at 18.7degC](image)

Fig. 7-4 Phase EMF waveform at 1300rpm

The FEA-predicted waveform includes all aspects of manufacturing causing extra leakage flux on the rotor side.

7.4.2 Harmonic Distortion of EMF Waveform

The waveform presented in Fig. 7-4 contains in fact raw data. It is necessary to apply Fourier analysis and discover the actual magnitude of the carrier waveform, and its higher harmonic counterparts. Tab. 7-2 below compares harmonic content of EMF waveform measured and obtained by FEA at 1300 rpm.

Tab. 7-2 Comparison in between predicted vs. measured harmonics of phase EMF

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>1st</th>
<th>3rd</th>
<th>5th</th>
<th>7th</th>
<th>9th</th>
<th>11th</th>
<th>13th</th>
<th>15th</th>
<th>17th</th>
<th>19th</th>
<th>21th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Voltage - Measured (V)</td>
<td>188.03</td>
<td>24.7</td>
<td>2.57</td>
<td>1.22</td>
<td>3.89</td>
<td>0.21</td>
<td>0.68</td>
<td>0.59</td>
<td>0.14</td>
<td>0.14</td>
<td>0.04</td>
</tr>
<tr>
<td>Peak Voltage - Predicted (V)</td>
<td>189.29</td>
<td>17.34</td>
<td>2.86</td>
<td>0.25</td>
<td>0.86</td>
<td>0.13</td>
<td>0.21</td>
<td>0.51</td>
<td>0.2</td>
<td>0.18</td>
<td>0.48</td>
</tr>
<tr>
<td>Absolute Error ($\Delta V$)</td>
<td>1.26</td>
<td>7.36</td>
<td>0.29</td>
<td>0.91</td>
<td>3.03</td>
<td>0.08</td>
<td>0.47</td>
<td>0.08</td>
<td>0.06</td>
<td>0.04</td>
<td>0.44</td>
</tr>
</tbody>
</table>
The first harmonic shows close match with absolute error of only 1.26\(V\). Critical for quality of torque production is the fifth harmonic reaching 2.57\(V\), which was accurately predicted.

### 7.4.3 Magnet Flux Linkage

Considering Equ. 4.25, the FEA predicted flux linkage constant to be \(\psi_{PM,FEA} = 0.1535\text{Wb}\). The measurement results as presented in Tab. 7-2 show very close match in terms of EMF carrier magnitude, giving thus \(\psi_{PM,m} = 0.1537\text{Wb}\).

### 7.5 TORQUE PRODUCTION TEST

The main objective of this test is to validate torque production of MG2 at nominal current and base speed. Furthermore, this test allows determining proportion of reluctance and magnet torque knowing the flux linkage constant and \(i_q\) current.

The actual test is based on variation of current angle \(\beta\), thus proportion between \(i_d\) and \(i_q\) current whilst keeping the total current constant. The proportion of d-axis current increases with the current angle since the machine is operated under MTPA current control strategy. This projects into required input voltage, which decreases with the current angle. Profiles of torque production and voltage profile is depicted on Fig. 7-5.

![MG2 Torque Characteristics - Measured](image)

**Fig. 7-5** Reluctance torque test at nominal current and base speed. The magnet torque is proportion of the total torque production due to permanent magnet flux, unlike electromagnetic torque includes both magnet and reluctance torque

The measurement has shown peak production of 744Nm at the nominal current applied to the machine.

### 7.6 MEASUREMENT OF EFFICIENCY

Probably the most critical measurement from hybrid drive stand point of view is focused on validation of efficiency models. Actual post-processing of testing was directly performed throughout digital power analyzer. Results of efficiency measurement summarize Tab. 7-3 below.
### Tab. 7-3 Comparison of predicted and measured MG2 efficiency

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>700</th>
<th>1300</th>
<th>2000</th>
<th>2800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Torque (Nm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>η, predicted (%)</td>
<td>95.35</td>
<td>95.76</td>
<td>95.44</td>
<td>94.92</td>
</tr>
<tr>
<td>η, measured (%)</td>
<td>91.14</td>
<td>92.88</td>
<td>92.82</td>
<td>92.32</td>
</tr>
<tr>
<td>Error (%)</td>
<td>-4.62</td>
<td>-3.10</td>
<td>-2.82</td>
<td>-2.82</td>
</tr>
<tr>
<td>Winding temperature (degC)</td>
<td>-215.379</td>
<td>-355.222</td>
<td>-498.087</td>
<td>-631.2</td>
</tr>
<tr>
<td>η, predicted (%)</td>
<td>95.35</td>
<td>95.76</td>
<td>95.44</td>
<td>94.92</td>
</tr>
<tr>
<td>η, measured (%)</td>
<td>91.14</td>
<td>92.88</td>
<td>92.82</td>
<td>92.32</td>
</tr>
<tr>
<td>Error (%)</td>
<td>-4.62</td>
<td>-3.10</td>
<td>-2.82</td>
<td>-2.82</td>
</tr>
</tbody>
</table>

The input torque was varied across four fixed reference speed at 700, 1300, 2000 and 2800rpm allowing consistent map up of efficiency across wide speed range. The maximum available torque was limited by capabilities of power electronics.

### 7.7 HEAT RUNS ON MG2

The main objective of this test is to discover steady-state temperature rise of the winding for nominal torque within speed range up to 1300rpm and at nominal power above the base speed. The test results are compared to the prediction using the transient 3D thermal model so that the thermal model considers as an input parameter the exactly same coolant temperature as occurred during the actual testing. Tab. 7-4 below summarizes load points under testing, including measured and predicted temperature rise of the winding.

### Tab. 7-4 Predicted and measured temperature rise at selected loadpoints of MG2

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>700</th>
<th>1300</th>
<th>2000</th>
<th>2800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Torque (Nm)</td>
<td>-772.016</td>
<td>-772.629</td>
<td>-524.508</td>
<td>-359.580</td>
</tr>
<tr>
<td>Coolant Inlet Temp. (degC)</td>
<td>49.1</td>
<td>50.3</td>
<td>52.0</td>
<td>62.3</td>
</tr>
<tr>
<td>R at Coolant temp. (mΩ)</td>
<td>10.648</td>
<td>10.694</td>
<td>10.760</td>
<td>11.159</td>
</tr>
<tr>
<td>Temp. rise, measured (degC)</td>
<td>61.628</td>
<td>65.075</td>
<td>41.434</td>
<td>51.450</td>
</tr>
<tr>
<td>Temp. rise, predicted (degC)</td>
<td>57.570</td>
<td>67.431</td>
<td>47.416</td>
<td>50.831</td>
</tr>
<tr>
<td>Error (%)</td>
<td>6.585</td>
<td>3.620</td>
<td>14.437</td>
<td>1.203</td>
</tr>
</tbody>
</table>

Error in temperature prediction oscillates from 1.2% up to 14.4% in various load points. Further improvement of the thermal model relies, besides increased fidelity of loss model, also on further CFD work estimating temperature conditions in surrounding components of the hybrid powertrain.
8 FUTURE IMPROVEMENTS

Since the main objective first design iteration of MG2 was mainly a proof concept study, it is necessary to revisit achievements and lessons learned out of the prototype of the machine. The main drawbacks of the first generation prototype turned into following redesign goals:

- Easier system integration in terms eliminating safety clearance behind the rotor plate, and reduction of three-phase short circuit current below peak current
- Design for Manufacturing/Assembly reducing bespoke machining tasks and thus, overall time and cost required by manufacturing process
- Reduction of cost, especially throughout lower consumption of expensive rough materials
- Maintaining or enhancing of performance in terms of torque density

8.1 PROPOSALS FOR 2ND GENERATION OF MG2

Many ideas for design improvements came across during development of MG2 prototype and particularly, during manufacturing and assembly process of the machine. Those ideas crystallized into three different concepts, which are introduced as redesign proposals.

8.1.1 MG2 with casted Aluminum Backplate

The idea of aluminum backplate aims to reduce both rotor inertia and leakage flux by effectively eliminating the back-side bridge of the rotor plate. The laminated rotor structure would be manufactured free of this bridge, having a locking feature stamped out in the middle of the iron pole between magnet slots. Fig. 8-1 below introduces actual concept of MG2 with aluminum backplate.

![Fig. 8-1 Cross-section through a rotor plate with casted aluminum backplate](image)

The amount of leakage flux dropped down by 45%, which resulted in further analysis focused on structural stability of the concept. Unfortunately, the concept of casted aluminum backplate does not provide sufficient structural strength to the rotor sub-assembly.

8.1.2 Inner Rotor MG2

Magnetic field of MG2 rotor plate may divert principally into both axial directions. The machine is made of two separate stator cores with sunflower winding and one rotor plate in the exactly same electromagnetic configuration, as for the double rotor MG2, located in between them. An advantage of such arrangement is in considerable reduction of leakage flux, resulting in 19% saving of magnet mass.
However, this topology makes the cooling arrangement more complicated due to the need for two separate cooling jackets, one for each stator core.

### 8.1.3 Tapered-Magnet MG2

In this concept, the rotor iron pole located in between magnets is composed out of electrical steel patches of constant cross-section cascaded from inner up to outer diameter of the rotor. Magnets are of a tapered shape, fitting into slots created by stack up of lamination patches. A small lip, instead of a whole bridge, locates magnet axially in the rotor structure. The rotor composition out of permanent magnets and columns of steel patches is mechanically strengthened by a backplate.

![Cross sectional views of Tapered-Magnet MG2 with emphasis on the rotor structure](image)

### 8.2 BENCHMARKING OF OPTIONS FOR MG2 REDESIGN

Since proposal of MG2 with casted backplate was scrapped for principal issues related to its mechanical design, Inner Rotor MG2 and Tapered-magnet MG2 were nominated for actual benchmarking with first design iteration of MG2, as shows Tab. 8-1.

<table>
<thead>
<tr>
<th>Tab. 8-1</th>
<th>Comparison in between MG2 topologies concerning design and performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in OD (mm)</td>
<td>Current MG2</td>
</tr>
<tr>
<td>Datum</td>
<td>+20</td>
</tr>
<tr>
<td>Change in Axial Length (mm)</td>
<td>Datum</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>228</td>
</tr>
<tr>
<td>Rotor Inertia (kg.m²)</td>
<td>6.25</td>
</tr>
<tr>
<td>13,SC (p.u.)</td>
<td>2.86</td>
</tr>
</tbody>
</table>

Important criterion is three-phase short circuit current $I_{3,SC}$, which must fit below 2 per-unit current limit, or in other words, the maximum converter current.
9 CONCLUSION

The Spoke Axial Flux Motor-Generator represents a novel electrical machine designed for a specific application of a traction drive as a component of hybrid electric powertrain. The actual design combines several features, which led toward intellectual protection of this machine.

The MG2 design followed the “Multiphysics” approach combining electromagnetic, thermal, mechanical, and controls design in a closed iterative loop. This ensured balance in between electromagnetic performance, cooling, static and dynamic structural stability and controllability of the machine. Analytical calculations were extensively supported by FEA and CFD in order to obtain a higher degree of confidence in actual design. Since modeling of the motor-generator included also three phase inverter supplying the machine, overall functionality, efficiency and performance of the electric drive as a subsystem of hybrid electric vehicle, it was well understood prior the testing of the unit.

The actual topology adopted from the electromagnetic standpoint of view flux focusing technique is able to achieve high magnetic loading in the airgap. Meanwhile, the magnet arrangement features inverse-saliency as a preferred option for traction motor drives with Synchronous Permanent Magnet Machines. Once the machine enters field weakening in constant output power mode, the negative d-axis current, required for suppressing of the base harmonic of EMF, helps to produce extra reluctance torque enhancing performance of the machine.

The thermal design in fact enabled operation of the machine under specified electromagnetic loading. Adopted water/glycol cooling through aluminum heat sink sandwiched in between stator cores allowed the machine to operate with relatively low thermal gradient from winding side to the coolant circulating in the cooling jacket. The analytical tool developed for thermal design and analysis predicted temperature of the winding even in transient mode at various load points, coolant flow rate and inlet temperature.

The control design dealt with assessment of different control strategies feasible for the discussed machine topology. In particular, the optimization potential in terms of drive efficiency is assessed. Understanding of efficiency is a critical element in the design of a hybrid drive, thus a set of simulation tools have been developed for that reason.

The manufacturing and assembly of MG2 introduced revolutionary design of axial-flux permanent magnet machines by adopting strip-wound structure embedding permanent magnets in the rotor core. This concept has proven itself to be functional though it was faced with many difficulties to during the development phase of the machine. However, the manufacturing and assembly process in the first design iteration of the machine is not straightforward enough for lean manufacturing approach. The rotor design might be optimized further due to knowledge gained from the first prototype built. Therefore, a set of follow-up design concepts has been proposed.

Several prototypes of Spoke-MG2 have been built in order to pass through extensive testing. It has been shown that the machine met performance target as predicted in the design stage. This thesis summarizes the thought process leading toward selection of a concept, design and analysis, followed by manufacturing and testing of a unique Axial-Flux Synchronous Permanent Magnet Machine. This design is remarkable because it has pushed forward boundaries in terms of actual machine topology and its construction, it has achieved torque density, targeted actual power rating and provided a downsized envelope. Moreover, integrated design and analysis package was developed, which may be applied for its generic nature to another machine design projects as well.
LITERATURE


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**ABSTRACT**

This thesis deals with a design of a novel Axial-Flux Permanent Magnet Motor-Generator for a hybrid electric bus application. Thus, the design specification represents a set of requirements, which leads toward a concept of a unique topology meeting performance, efficiency and dimensional targets.

The particular topology of the Axial Flux Permanent Magnet Motor-Generator discussed in this work is an outcome of deep literature survey, followed by the concept selection stage with the layout of the machine as an outcome of these processes.

The design approach behind this so-called Spoke Axial Flux Machine follows an idea of “multiphysics” iterations, including electromagnetic, thermal, mechanical, and controls design. Such a process behind the eventually proposed design ensured a right balance in between all of these engineering disciplines. A set of bespoke design and analysis tools was developed for that reason, and was backed up by extensive use of Finite-Element Analysis and Computational Fluid Dynamics. Therefore, the actual machine design gained higher level of confidence and fidelity.

Modelling of the machine and its drive provided understanding of performance and efficiency of the whole subsystem at various operational conditions. Moreover, it has illustrated an optimization potential for the controls design, so that efficiency of the machine and power electronics might be maximized.

Several prototypes of this machine have been built and passed though extensive testing both on the subsystem and system level. Actual test results are discussed, and compared to analytical predictions in terms of the machine’s parameters.

As a lesson learned from the first prototype of this machine, a set of redesign proposals aiming for simplification of manufacturing and assembly processes, are introduced.

This work records steps behind all phases of development of the Axial Flux Machine from a basic idea as an outcome of concept selection stage, up to testing and wrap-up of experience gained from the first generation of the machine.