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Series Hybrid Vehicle System Analysis Using an In-Wheel Motor Design

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***Abstract*— Hybrid vehicles, which employ a technology combining gasoline and electric motors, are a hot item these days for transporters looking for ways to cut their fuel bills. To date, commercial systems implement diesel assisted electrical drives. As such the electrical motor is placed in a series or parallel configuration to assist the combustion engine. In the series configuration, the generator mounts directly to the engine, and most of the engine power is converted into electric energy to drive the traction motors at the axle/wheel ends. This enables the exclusion of the mechanical drive path between the engine and the drive wheels.**

On the contrary, the parallel configuration maintains the conventional mechanical drivetrain architecture and adds the ability to augment engine power with electrical torque. This has the advantage that, if the electrical power malfunctions, conventional engine-powered operation can continue, which allows each system to work independently. Most commercial systems are based on parallel hybrid systems with induction or brushless permanent magnet motors, since they provide for a good balance between costs and fault tolerance.

However, although that this is a very attractive economical solution, it does not allow for a redesign of current trucks for specialised applications. This paper, therefore introduces a drivetrain concept and the design of an in-wheel motor design with extended field weakening capability for use in a specialized series hybrid demonstration vehicle.

***Keywords* — Hybrid, truck, field weakening, brushless, permanent magnet, electrical motor.**

I. INTRODUCTION

Most commercial hybrid systems are based on building parallel hybrid systems, as shown in Fig. 1, with induction or brushless permanent magnet motors. For example, recently DAF unveiled a light-duty diesel-electric hybrid vehicle, as shown in Fig. 1 [1]. The key components of such hybrid vehicles are the lithium ion battery pack coupled to a sophisticated integrated electric motor generator, which complement the 4.5-liter diesel engine. In such systems, power from the diesel engine is used to drive the vehicle directly or to charge the storage device, where hybrid power systems provide maximum fuel savings in applications where frequent braking and acceleration is required, such as local delivery and vocational applications. Further, customers also benefit from lower maintenance costs due to reduced wear on the braking system.

Figure 1. Parallel hybrid system configuration [1].

However, this does not allow for a redesign of current trucks, i.e. for specialised applications. Therefore, a more technologically advanced electric motor design is necessary to increase the power density, hence, reduce the needed space envelope.

Figure 2. Commercial demonstration vehicle.

This has been achieved by using a permanent magnet (PM) direct drive motor inside the wheel attached to a swing arm. This development has enabled a complete redesign of current truck applications, where, for example, the complete loading floor can be lowered to

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the street level, which enables easy access to the cargo, as shown in Fig. 2.

In this respect, the used series hybrid configuration and the in-wheel motor design will be explained in Sections II and III, respectively. Sections IV and V will describe the converter selection and the in-wheel motor design, where Section V will present the conclusions.

II. SERIES HYBRID CONFIGURATION

In the series hybrid vehicles, the conventional engine is mainly used to generate electricity, which then supplies an electric motor that drives the wheels [2]. The truck drive top-level schematic is presented in Fig. 3. This schematic represents the series hybrid configuration, which consists of diesel engine, as a prime mover, PM synchronous generator, active rectifier, storage, brake resistor, two independent PWM inverters and two AC traction motors, which drive the wheels.

In the motor mode mechanical power from the diesel engine, rotated at a speed range of 1100 to 2200rpm, is transferred to the generator, which, in a turn, has PMs on a rotor and generates electrical power with a variable output voltage and frequency. In order to supply the inverters with electrical energy having fixed parameters, as it is required, an active rectifier is installed next to the generator.

This active rectifier uses forced commutation to supply the generator with reactive power and to keep the output DC voltage to a constant level. Further electrical energy conveys through the DC-bus to the inverters, which feed the traction motors. A storage by means of ultra-capacitors is included, however also a battery or, for that manner, any other storage could be utilized.

The control systems of the inverters measures the speed and output torque of the motors and, by regulation of the phase current and frequency, adjust these parameters according to a given torque versus speed characteristic, as will be described in Section III.

Initially, in the commercial system of Fig. 2, the decision is made to eliminate the storage to minimize the investment for the customer, however if a complete electrical drive is required storage could easily be included.

The characteristic of the series hybrid configuration provides that, during braking, kinetic energy of the truck is sequentially converted by the motors and inverters, which act as generators and rectifiers, respectively, in DC electrical energy (as shown in Fig. 4 by the thick brown line). This energy can be delivered to two independent paths: 1) to the brake resistors and 2) to the internal combustion engine. It should be noted that these braking modes are enabled only up to certain velocity level (about 16-19km/h) after that the truck slows down by using the conventional pneumatic brakes mounted inside each wheel.

The first braking mode is provided by rheostatic braking, as shown in Fig. 4 by thick blue line. In this mode electrical energy from the DC-bus is transferred through brake chopper to the brake resistors, where it is dissipated in a form of thermal losses. The second braking mode incorporates the use of the engine kinetic energy, shown in Fig. 4 by the thick green line, when the exhaust is closed and the diesel engine is revved up by motor torque of the generator. These two braking modes could be used separately or simultaneously, where the dissipative energy is electronically regulated, although that the driver can always interfere by further pushing the brake pedal to activate the pneumatic brake.

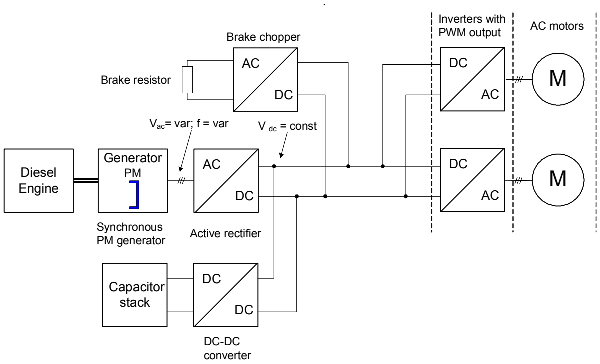

Figure 3. Series hybrid drivetrain with storage.

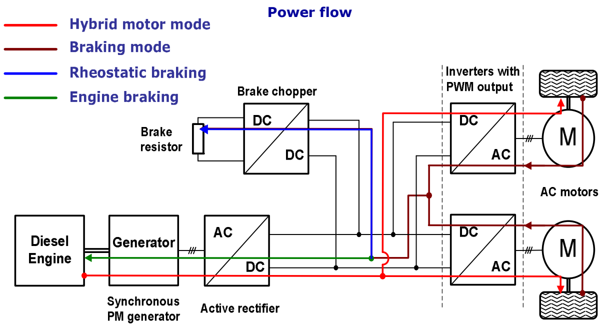

Figure 4. Series hybrid drivetrain without storage.

III. VEHICLE REQUIREMENTS

Commercially, high torque motors, which are necessary for this application, are limited in their speed envelope. Therefore, specially designed motors are currently used in the demonstration vehicle. However, these in-wheel motors are also limited in their output power, which has lead to the vehicle not being able to attain the maximal torque and velocity. Further, this motor utilises an oil-cooling, which is very environmentally unfriendly, hence it is requested to increase the power envelope and utilize water cooling. This is a very challenging task, since the space envelope is limited (power requirement is approximately 2.3MW/m^3) and an extended field weakening capability of almost five times base speed is necessary, as shown in Fig. 5. In order to enable the practical implementation of the design a commercial drive is selected, which, although augmenting practical implementation, requires innovative motor designs, since the switching frequency of these devices is limited to the previously specified 300Hz.

For fuel economy purposes, the combustion engine speed range is approximately within the range of 1100 to 2200rpm, which translates into a 50% variation of the frequency and voltage from the generator (the design is outside the scope of this paper). This cannot be dealt with by the commercial drives and hence an active rectifier is implemented which directly connects to the DC-link.

In this demonstration vehicle a gearbox is implemented to reduce the required torque and increase the speed of the motor for the same output power. Albeit that this reduces the system efficiency, it also minimizes the needed motor space envelope. However, probably more importantly, the commercial gearbox has an integrated pneumatic brake, which is a requirement to enable road worthiness in the Netherlands.

The inclusion of the gearbox results in the torque and output power versus speed characteristics, as shown in Fig. 5. The continuous operation mode is the nominal characteristic and the peak torque and power are required for one minute operation from the nominal output power. The motor is sized for the base speed field-weakening (FW) point, which is near the knee of the curves. This base speed FW point is given by: 1000rpm, 80kW, 750Nm.

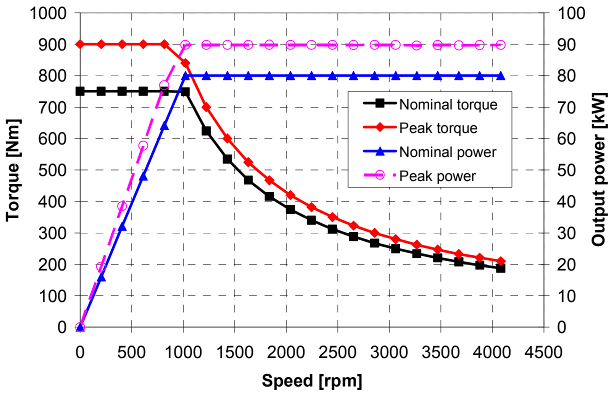

Figure 5. Output power and torque versus speed characteristics.

IV. CONVERTER SELECTION

In this application, the use of a commercial converter is preferred due to costs and reliability considerations. In these modern commercial drive electronics the regular 50Hz three phase current is fed to a half bridge rectifier, the DC-link voltage and then converts this to sinusoidal currents to the motor phases, e.g. using DTC (Direct Torque Control) from ABB, PWM-CSI (Current Source Inverter) from Rockwell, TCSF (Torque Control Speed Feedback) from Danfoss, etc.

However, all these drives have a 300 Hz limitation, which results in a maximum number of poles for the motor. Considering that the output power of the electrical machine is proportional to the air gap diameter squared [3], the maximized air gap diameter, at a limited outer diameter, can be achieved by a large number of pole-pairs. Since the maximum rotor speed is 4500rpm, the maximum inverter output frequency is 300Hz, and hence, the maximum number of pole pairs is four. This, relatively small pole-pair number leads to increased back-iron lengths and consequently decreases the airgap diameter.

Further, it needs noting that, for a given outer diameter, the armature reaction flux is inversely proportional to the number of pole-pairs. Hence, in case of a large electrical loading the armature reaction flux saturates the back iron parts at rated load condition. Therefore, the back-iron length should be increased in order to eliminate steel saturation.

Another motor constraint defined by the drive is the terminal voltage of the motor. In this demonstration vehicle, it was decided that the maximum DC-bus voltage is 690V and since the inverters use the sine-triangle PWM, the maximum motor phase voltage is defined as [4]:

$$V_{1\max} \leq \frac{1}{2\cdot\sqrt{2}}\cdot V_{DC} = \frac{1}{2\cdot\sqrt{2}}\cdot 690 = 244V_{rms}. \qquad (1)$$

Additionally, the drive apparent power, S, also provides constraints on the motor design, i.e. minimum possible power factor and maximum armature current. The maximum armature current of the motor should not be higher than the maximum continuous current of the drive. For instance, at 1000rpm the output power of the motor should be 80kW with a maximum apparent power of 120kVA. Therefore, the minimum power factor is defined as follows:

$$\cos\phi_{\min} \geq \frac{P_{out}}{S} = \frac{80}{120} = 0.67. \qquad (2)$$

It needs noting that the abovementioned design constraints have a very large impact on the possible motor type and configuration, where the next Section will summarize the motor design.

V. ELECTRICAL IN-WHEEL MOTOR DESIGN

The motor configuration considered in this paper is a brushless AC permanent magnet motor with concentrated winding, as shown in Fig. 6. These concentrated windings are short-pitched, which results in the back-emf waveform of concentrated winding being close to a sine, even if airgap flux density distribution is far from sinusoidal. However, it needs noting that it is crucial that the correct ratio of the number of rotor poles and stator teeth is selected [5], [6]. The main advantage of the concentrated windings is their ease of manufacturing and assembly, where the main disadvantage is the relatively high torque ripple and high magnet losses, owing to the airgap flux harmonic distortion.

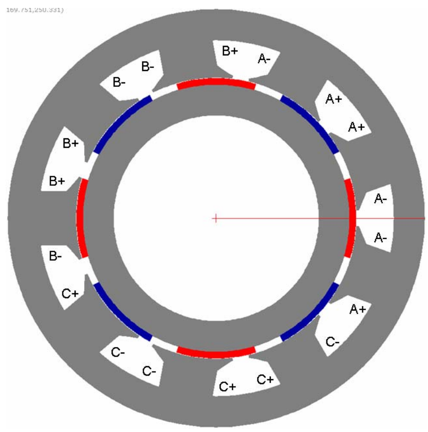

Figure 6. Cross-section of the SPM internal rotor motor with concentrated windings.

Considering the extended FW capability, many authors [7-8] prefer the inset or even interior rotor design, however the requirement of a large FW operation range with a high specific power provides saturation within the machine, which eliminates the attractiveness of such topologies. However, the selection of the most appropriate motor configuration remains a highly challenging task, which could not be done without detailed electromagnetic and thermal investigations. These analyses resulted in the motor design as summarized in Table I with the torque-speed characteristic of Fig. 7.

TABLE I
BASIC MOTOR GEOMETRY AND WINDING DATA

Description	Symbol	Unit	Value
Number of pole pairs	p	-	4
Number of slots	Z	-	9
Number of slot per pole per phase	q	-	3/8
Stator outer diameter	D_{OD}	mm	501.3
Stator bore diameter	D_1	mm	338
Axial length	l_1	mm	100
Air gap height	δ	mm	1
Magnet height	h_m	mm	7.5
Magnet span angle	α_m	el.deg.	132
Magnet remanence	B_r	T	1.175
Magnet recoil permeability	μ_r	-	1.05
Number of turns per branch	w_1	-	78
Net slot fill factor	k_f	-	0.65

TABLE II
BASIC RESULTS OF THE THERMAL AND HYDRAULIC ANALYSES

Description	Symbol	Unit	Value
Ambient temperature	T_0	ºC	40
Average winding temperature	T_{Cuav}	ºC	153
Stator back iron temperature	T_{sby}	ºC	77

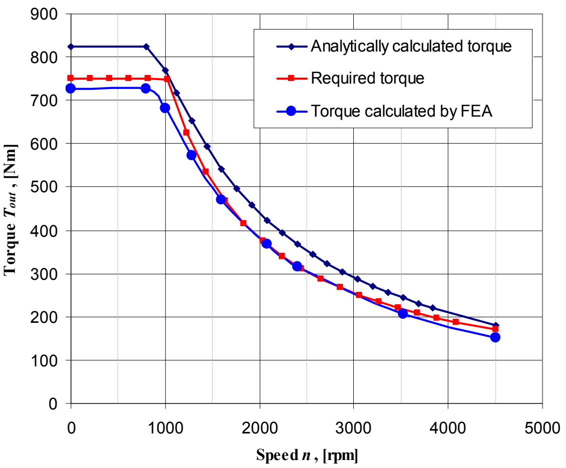

Figure 7. Torque-speed motor characteristic.

The differences between analytical and FEA [9] results are the effect of saturation in the steel, especially of stator and rotor back irons. A thermal analysis was undertaken using the Motor-CAD software [10]. The water-cooling is placed on the outer surface of the stator lamination. The hydraulic analysis is done by means of an analytical method, where the main results are summarized in Table II. The motor, as shown in Fig. 8, is currently under construction to be measured on the demonstration vehicle.

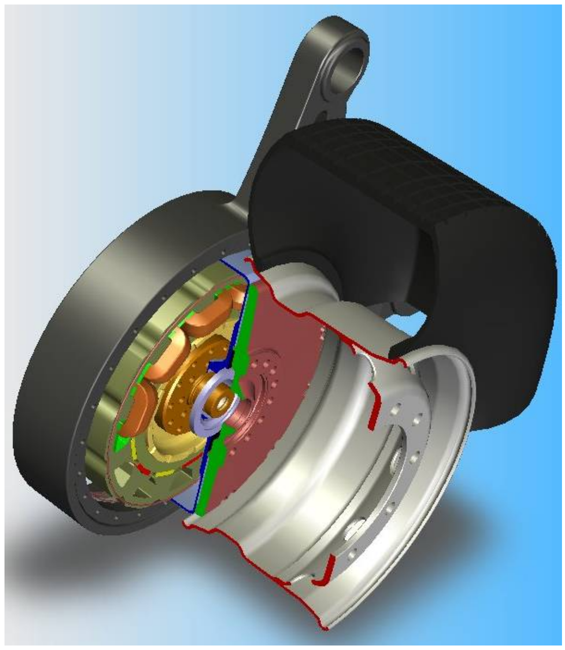

Figure 8. In-wheel motor with swing-arm and tire schematically illustrated (gearbox is not visible).

VI. CONCLUSION

A comprehensive description of the series hybrid configuration has been given, which is advantageous for special vehicles that benefit from removing the rear axle, where from the specific requirements for the electrical system have been derived. The selected inverter was a commercial drive, which has the limitation of a maximum output frequency of 300Hz. This severely complicates the motor design due to the limited volume envelope within the wheel of the demonstration vehicle.

However, a suitable four pole-pair surface permanent magnet motor with the concentrated armature winding has been designed. Albeit that the motor performance does not fully satisfy the specifications, this design is considered to be sufficient especially taking into account the restriction in the output frequency of the commercial inverters. As such, it is well known that the motor back-iron sizes and other dimensions of the core are dependent on the air gap flux per each pole, which is inversely proportional to the number of rotor poles.

In addition, the limitation imposed by the number of pole-pairs, the electrical loading of the designed motor has restricted the maximum output power. However, it is obvious that the output power can be extended by a higher armature current or, that the same, by increasing of the electrical loading. Although Section V discussed that the motor temperatures are near to the maximum limits, hence, increasing the electrical loading is not desirable, although that this could be overcome by a more efficient cooling system.

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