Design Procedure for Low Cost, Low Mass, Direct Drive, In-Wheel Motor Drivetrains for Electric and Hybrid Vehicles

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***Abstract*-Direct drive, in-wheel motors are ideal for electric and hybrid vehicles because the packaging of the drivetrain is so simple, because drivetrain losses are eliminated, and because individual wheel control improves handling and safety. In applications where cost is not a constraint, e.g. solar car racing, direct drive, in-wheel motors are the norm. In-wheel motors are also regularly demonstrated in concept vehicles. However, in-wheel motors are not used for production vehicles because of their high cost and high-unsprung mass. This paper describes a project that addresses these issues through the use of a novel, multiple-airgap, axial-flux, switched-reluctance motor with optimized packaging and low cost electronics. The emphasis of the paper is on how to design the system as a whole.**

I. INTRODUCTION

This paper describes the outcomes from the first stage of a larger project funded by the Automotive Cooperative Research Centre (AutoCRC) Visionary Project [1] and the authors' institutions. This first stage is the design of the drive system components. The second stage, which is just beginning, is the construction of the drivetrain. The third stage is fitting the drivetrain to a prototype vehicle. In this paper emphasis is given to the design procedure rather than the outcome for each individual unit of the drivetrain, though each unit is described and some details are provided where relevant to discussing the design procedure.

Direct drive, in-wheel (DDIW) motors are recognized as ideal for vehicles, from an efficiency, packaging, handling (other than unsprung mass), and safety perspective. So too are their drawbacks of cost and mass; e.g. [2]. In cost-insensitive applications, e.g. solar car racing, DDIW are the norm, e.g. [3]. In these applications, the drawback of mass can be eliminated at the expense of increased cost by using 'exotic' motor types, e.g. ironless, Halbach magnet array, axial-flux motors [4]. Concept vehicles have featured DDIW motors, e.g. [5]. Tellingly production vehicles, even when the vehicle manufacturer has DDIW technology, have used a single electric motor driving a differential typically through a fixed speed reduction gear, e.g. [6]. Therefore developing a low cost and low mass DDIW motor is challenging and hence its inclusion in the AutoCRC's Visionary Project suite.

The project is not yet complete and therefore success cannot be guaranteed, however the project has progressed well and preliminary data can be given along with a description of how the design is formulated in terms of an optimization problem. It is hoped that articulating our design formulation will be beneficial to others working on wheel motors.

The authors *speculate* that previous DDIW motors are either/both too expensive or too heavy because of two factors:

1. Inappropriate choice of technology
2. A focus on components instead of the system

The choice of technology is discussed in light of the specification in the following sections.

Instead of focusing on a particular aspect of the drivetrain, e.g. the motor, a holistic approach is taken to the whole drive system in this project. This allows an overall optimum to be found for the complete system for a given weighting and/or limits of system cost and wheel mass. The starting point of such an optimization is the specification, which defines limits and weightings for design parameters and/or derived quantities.

Having defined the optimization parameters and limits, the individual components (motor, wheel, power electronics, system electronics, and battery pack) can each be designed and each component is addressed below. Although designed separately on the basis of the optimization parameters the individual items are interlinked by the motor component:

1. The wheel has to house the motor and therefore the motor and wheel are mechanically linked
2. The power electronics control the motor and the ratings and detailed operation of the controller are defined by the motor
3. The system electronics coordinate all the units and the limits of its control are defined by the motor
4. The ratings of the battery pack depend on motor performance

The start of the design processes is the specification.

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II. SPECIFICATION

The specifications are in Table 1; the values given are targets since the specification necessarily existed before the component designs. It is expected that some specifications will be exceeded and others not, but overall the specification will be approximated.

TABLE I
TARGET SPECIFICATIONS

Description	Symbol	Target
Vehicle mass	m_v	1,200 kg
Vehicle rolling resistance	C_{rr}	0.012
Vehicle maximum speed	v_m	39 m/s (140 km/h, 87 mph, on flat)
Vehicle acceleration time	t_a	16 s
Vehicle average acceleration and deceleration (under regen)	a_a	1.5625 m/s^2 (0 to 25 m/s, 90 km/h, or 55.9 mph in t_a)
Vehicle frontal area	A_v	1.5 m^2
Vehicle drag coefficient	C_d	0.3
Rolling radius	r	0.3184 m (P205/50R17 85N)
Number of driven wheels	n	2 (rear)
Cooling Coefficient	h	50 W/(m^2 K)(both motor and electronics to be cooled by air flow from vehicle movement)
Power electronics efficiency at continuous rating	η_p	0.9
Motor efficiency at continuous rating	η_m	0.9
Max. motor mass	m_m	25 kg
Maximum gradient	θ_m	0.2 rad (1 in 5 or 11.5 deg)
Coefficient of friction in wet	μ_w	0.5
Maximum wheel braking torque under a fault	τ_m	-78 Nm (1/3 of the wheel locking torque in the wet)
Minimum DC link voltage	V_n	234 V
Motor power factor at continuous rating	K_{pf}	0.7 (to allow embedded PM motor)
Motor material cost factor at peak rating	K_{mc}	0.1 US\$/Nm (from past experience and [7] prices x 2)
Power device cost factor at peak rating	K_{pc}	0.016 US\$/VA (from past experience and [8])
Motor active mass factor at peak power	K_{mm}	17 Nm/kg

Passenger vehicle tire sizes are given by Pwww/hhRdd; where P denotes passenger tire, www is the width of the tire in mm, hh is the height of the side wall as a percentage of www, R denotes radial tire, and dd is the inside diameter in inches. Small, high-finish vehicles typically have P165/60R16 tires and the tire size of P205/50R17, in the specification, was chosen to be larger than standard wheels to give space for the motor. There are legal limits to alternate vehicle wheels [9] and P205/50R17 is close to the limit allowed for a vehicle normally fitted with P165/60R16. Care must also be taken to choose sizes for which low rolling resistance tires are available.

The vehicle straight-line motion is described by

$$F_d = \frac{1}{2}\,\rho\, C_d\, A_v\, v^2 + m_v\, g\,(C_{rr}\cos\theta + \sin\theta) \quad (1)$$

$$F_t - F_d = m_v\, a \quad (2)$$

where F_d is the drag force on the vehicle at speed v through air of density ρ with acceleration due to gravity g on an incline of θ and F_t is the traction force applied by the motors to the vehicle, which results in acceleration a. The vehicle motion can be translated into a single motor's load point by

$$\omega = \frac{v}{r} \quad (3)$$

$$\tau = \frac{F_t\, r}{n} \quad (4)$$

where ω is the motor speed and τ the torque. From (3) and (4) the motor power, power-electronics power, and battery power can be found

$$P_m = \omega\,\tau \quad (5)$$

$$P_p = \frac{P_m}{\eta_m} \quad (6)$$

$$P_b = \frac{n\,P_p}{\eta_p} \quad (7)$$

At the maximum speed there is no acceleration (by definition), therefore the continuous ratings from (1) to (7) at $a = 0$ and $v = v_m$ are:

- Motor speed: 122 rad/s
- Motor torque: 88 Nm
- Motor power: 10,763 W
- Power electronics power: 11,959 W
- Battery pack power: 26,575 W

The peak motor torque has an upper limit imposed by the available mass as discussed in the next section. There is also a lower limit given by the maximum gradient, from (1) and (2) at $v = 0$, $a = 0$, and $\theta = \theta_m$ this is 375 Nm.

Safety concerns under a motor fault are of concern for a vehicle with separately driven wheels, as they are for a

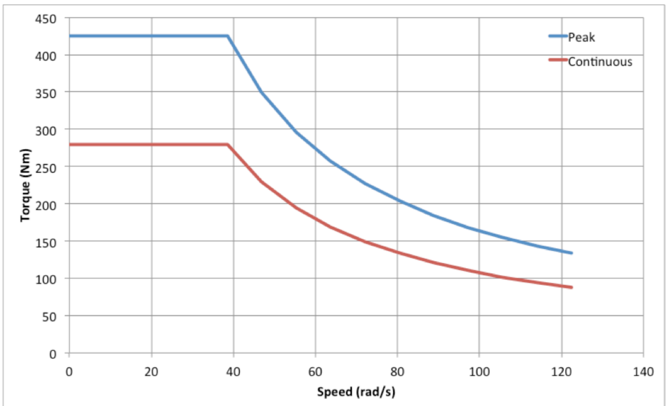

Fig. 1. Motor Characteristics; showing both actual values and the general characteristics of a peak and continuous rating with a maximum torque for each rating up to a common base speed and then a constant power profile.

vehicle with separate brakes on each wheel (hence crossed dual circuit brakes are mandated). Dealing with a loss in power due to a fault is difficult for DDIW motor vehicles and a supervisory controller that prevents too much speed differential between the driven wheels is necessary [10]. Ref. [10] discusses a complete loss in torque, however the specification allows a more severe fault condition where some negative torque is applied (i.e. the wheel is braked). A Permanent Magnet (PM) motor under fault conditions applies some negative torque and the next section discusses the implications of this.

To calculate the peak ratings is more involved and requires the motor type to be selected because the cost of the motor is a requirement for determining the lowest cost peak ratings consistent with the specification.

III. MOTOR

For traction applications a motor's peak and continuous requirements can be described by its maximum torque, which it holds to a base speed, and then the torque falls following a constant power characteristic up to its maximum speed, as shown in Fig. 1. Because the electronics cost is approximately determined by the power and the torque approximately determines the motor cost, it is usual to have these regions of constant torque and constant power (the trade off between the two is discussed below). (Conventional vehicles with a combustion engine adopt the later choice with an approximate constant power characteristic via a variable ratio transmission.)

Because of the mass limitations and a desire for high efficiency, it is tempting to use rare-earth permanent magnets [4]. These have two cost downsides: cost of the magnets themselves and cost of the power electronics.

The cost of the rare-earth magnets themselves stems from the use of expensive raw materials, a difficult manufacturing process, and relatively little supplier competition [11].

The cost of the electronics is approximately determined by the motor power (as previously discussed), which in turns requires an electric motor with a saliency ratio [12]. Ref. [12] recommends controlling the saliency ratio of a permanent magnet motor by embedding the magnets so that some proportion of the torque comes from reluctance and some from the magnets. This approach works provided that the constant power speed range is relatively small, say a factor of 2, but once the speed range becomes large the majority of the torque is provided by the variable reluctance of the rotor. Even for modest vehicle performance, [13], the required constant power ratio is 2 and therefore for most vehicle applications it is larger. The reluctance effect in embedded permanent magnet motors is identical to that in synchronous reluctance motors [12] and synchronous reluctance motors are known to have less output for a given mass than the equivalent Switched Reluctance (SR) motor [13].

A further problem for the permanent magnet motor is that under fault conditions, i.e. a shorted winding, it applies a braking torque to the motor. In the target specification this is limited to -78 Nm (1/3 of the wet weather maximum torque before sliding) and it is noted in [10] that even zero braking torque is difficult to control safely and therefore this limit of 1/3 slippage is generous to the permanent magnet motor. The fault limit implies a ratio of reluctance to permanent magnet torque of $(375 - 78)/78 = 3.8$ that is much larger than the factor of 2 noted above as a practical limit.

Another motor type that might be suitable is the induction motor, but as noted in [14] the induction motor has less output than the SR motor. Therefore the appropriate choice of motor type considering cost, mass, and safety is the SR motor.

In order to achieve the average acceleration specification there is a choice of steady acceleration at the average rate or rapid initial acceleration followed by reduced acceleration under constant power. The correct decision for a DDIW motor depends upon cost, c, motor mass, and the resulting average acceleration which are given by

$$c = K_{mc}\,\tau_m + K_{pc}\frac{P_p}{K_{pf}} \quad (8)$$

$$\tau_m \le m_m\,K_{mm} \quad (9)$$

$$\tau_m \ge m_v\,g\,\sin\theta_m \quad (10)$$

$$v \ge a_a\,t_a \quad (11)$$

where τ_m is the peak torque of the motor. In practice the efficiency of the motor and power electronics will affect the cost of the battery pack. However from trial designs the efficiency of both the motor and the power electronics exceeds the specification and varies little, therefore battery cost is assumed constant and therefore not part of the optimization. Further the optimization, by omitting battery cost, tacitly assumes that the battery is not peak power limited, which is true for this application. The cost factors, K_{mc} and K_{pc}, are highly variable due to market forces and inflation, however the ratio of these factors is more stable and it is their relative sizes that are important.

The absolute values for K_{mc} and K_{mm} also depend on the motor technology; the values given are suitable for an SR

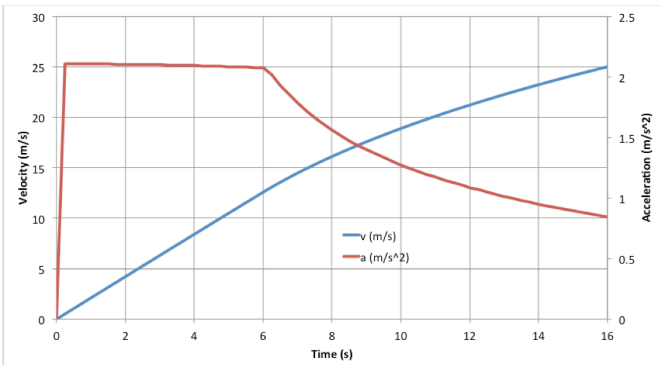

Fig. 2. Vehicle acceleration simulation for optimum values of τ_m and ω_b.

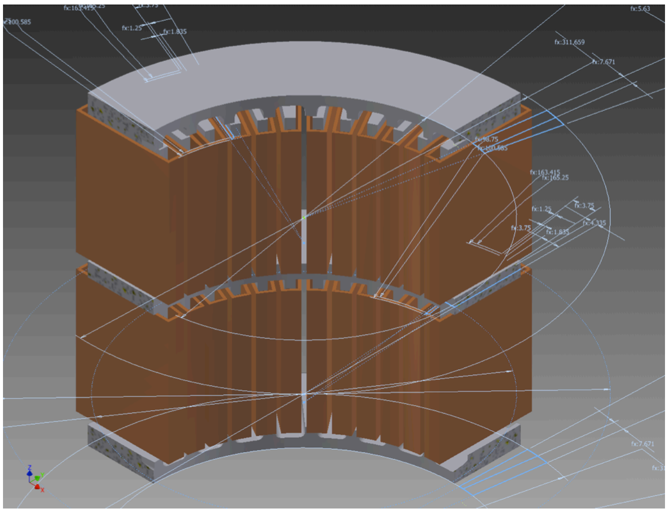

Fig. 3. Motor design; quarter model view (not final dimensions).

motor. For K_{mc} the value is suitable for a dual air-gap SR motor.

Eq. (9) gives a torque constraint of 425 Nm maximum and (10) gives a minimum of 375 Nm (inclination constraint previously discussed) and (11) a speed constraint of 25 m/s minimum. Eq's (1) and (4) can be repeatedly solved finding v whilst minimize (8) subject to the constraints (9) and (11) with optimization parameters τ_m and ω_b (motor base speed).

The solving procedure is to make an initial guess for τ_m and ω_b and then solve Eq's (1) to (8) numerically starting at $t = 0$, $v = 0$, and $a = 0$ up to $t = t_a$. The constraints are checked and the process repeated until optimum values (minimum (8)) are found. This solution process was coded in an Excel spreadsheet and the optimum run is shown in Fig. 2.

From this optimization the optimum parameters are $\tau_m = 425$ Nm (the upper constraint) and $\omega_b = 38.5$ rad/s and the minimum cost is $c = 458$ US\$ (motor cost, $c_m = 43$ US\$ and power electronics cost, $c_p = 416$ US\$). Since the torque constraint is active the motor mass is 25 kg and thus both an acceptable mass and a low cost are achieved. The use of an SR motor is highly effective at reducing the motor cost to the point where the total cost is dominated by the electronics cost.

The proposed novel motor design is shown in Fig. 3. The flux flows axially (vertically in the figure) and there are two

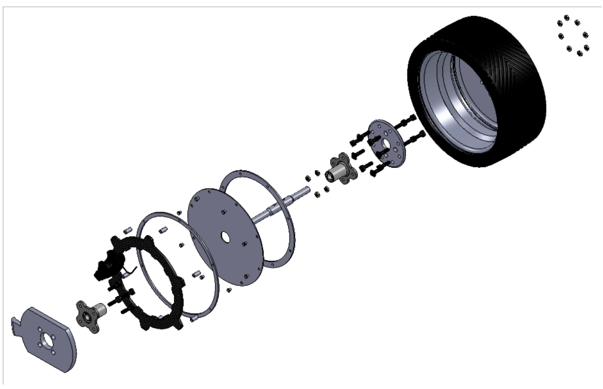

Fig. 5. Exploded view of wheel; main parts only and not showing motor.

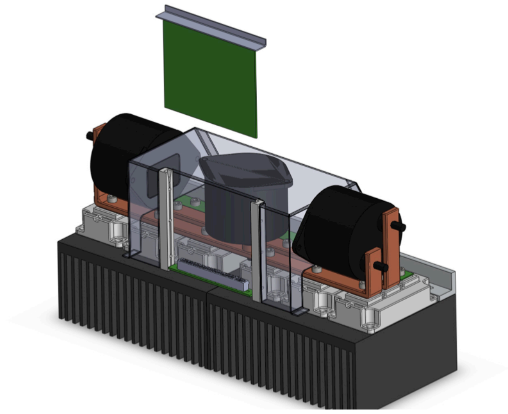

Fig. 4. Exploded view of power electronics; excluding case.

rotors, one attached to each side of the wheel (see next section). The required specification has been achieved, with details to be published elsewhere.

IV. WHEEL

The wheel houses the motor, holding the stator still via a hollow stationary shaft; the hollow center of which allows the motor wires into the wheel. The motor's two rotors are attached to the outside faces of the wheel and the mechanical brake is attached to the inside face of the wheel. The mechanical brake is retained for regulatory reasons. Having retained the mechanical brake there is no requirement for the electrical braking to achieve the braking necessary for an emergency stop. Fig. 5 shows an exploded view of the main parts of the wheel (excluding the motor).

An important consideration for the vehicle is unsprung weight reduction; to this end the motor does not have a separate case – it is housed entirely by the wheel, the motor is an integral part of the wheel. To enable the tire to be changed the wheel rim, but not the rest of the wheel, is detatchable (much like a truck tire is changed).

V. POWER ELECTRONICS

As noted above, the power electronics are the dominant incremental cost in the system; therefore, it is important to use their VA optimally. To this end, the SR-motor is optimally excited [15][16] to minimize the cost of the power components. A Field Programmable Gate Array (FPGA) is

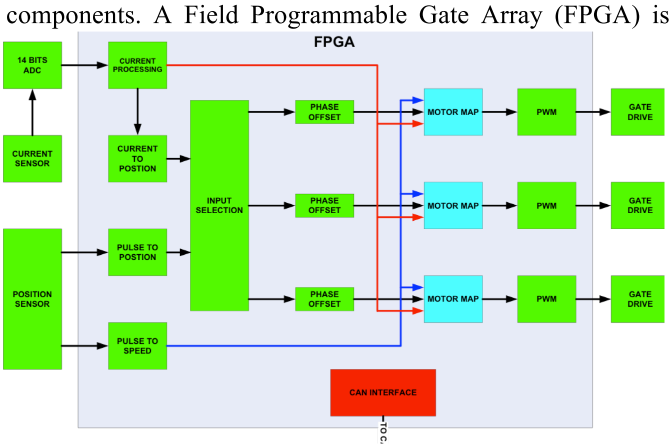

Fig. 6. Controller block diagram.

used to implement the motor control on a modest-sized and hence low-cost device. A block diagram of the control algorithm is shown in Fig. 6 and a mechanical model of the complete controller is shown in Fig. 4.

VI. SYSTEM ELECTRONICS

The system electronics coordinate the two motors, interface to the driver, and monitor the battery pack. They have an important safety role in that if a motor or a controller fails then the other motor must match the failed motor's speed to prevent vehicle pull or push [10]. This is achieved by continuously monitoring the two motor speeds.

VII. BATTERY PACK

The battery specifications fall out from the motor optimization and the other specifications. Its continuous rating is 26,575 W and its peak rating is 40,407 W. A suitable battery pack has been selected that consists of 72, 100 Ah, $LiFeMnPO_4$ cells.

VIII. VEHICLE

An A-sized, supercompact car that is front wheel drive will be converted to a rear wheel drive vehicle with the engine bay housing the batteries and the electronics in the spare-wheel well. The engine will be removed as will the engine driven accessories, electrically driven accessories will be fitted to the vehicle and the rear suspension modified to accommodate the extra wheel weight.

IX. CONCLUSIONS

In the introduction the difficulty of achieving a low cost, loss mass, DDIW motor is demonstrated and shown through the literature. The most important point noted is that production vehicles do not use DDIW motors because of their high cost and high mass. The rest of the paper then gives a detailed description with reasoned and referenced argument of how to work from a specification to achieve a low cost, low mass, DDIW motor. The given procedure is shown to achieve these aims.

This paper reports the first stage of a large project, where detailed designs are modeled and/or prototyped. In subsequent stages, the components are to be built and tested in the laboratory, followed by fitting to a vehicle for testing.

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