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The Design and Construction of a Battery Electric Vehicle Propulsion System - High Performance Electric Kart Application

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Abstract. This paper presents an electric propulsion system designed specifically to meet the performance specification for a competition racing kart application. The paper presents the procedure for the engineering design, construction and testing of the electric powertrain of the vehicle. High performance electric Go-Kart is not an established technology within Australia. It is expected that this work will provide design guidelines for a high performance electric propulsion system with the capability of forming the basis of a competitive electric kart racing formula for Australian conditions.

1. Introduction

Electric propulsion systems for competition racing karts have not yet reached the point in their development cycle whereby a recognised technical formula has been achieved for their introduction into sanctioned competitive electric kart racing. This is particularly true in Australia where there is no existing or proposed category for electric kart racing under the control of the governing body of this sport.

This paper attempts to provide an insight into the design and construction procedure that is necessary when engineering a high performance electric powertrain specifically for a competition karting application. In doing so it will provide a working example of a high performance orientated electric propulsion system with the capability of forming the basis of a competitive electric kart racing formula for Australian conditions.

The procedure requires the documentation of the design, construction and testing of an electric powertrain to determine if indeed it has the capacity to at least match the performance characteristics of a comparable competition Internal Combustion Engine (ICE) powered vehicle. This will be accomplished with the installation of the designed and constructed powertrain into an Australian Karting Association (AKA) level, competition rolling kart chassis for testing and evaluation.

At this introductory level, in order to minimise costs of the project, only proven Electric Vehicle (EV) technology will be incorporated in the design and construction of the propulsion system. However it is envisaged that this research project will form a platform for further development into more advanced EV traction systems ideally suited to competition applications.

The overall research project will deliver the following main outcomes;

- A specification for an EV propulsion system commensurate with an electric kart platform.
- A complete and working EV propulsion system manufactured and installed into an AKA level kart rolling chassis.
- A set of test results confirming the dynamic performance of the electric powered kart as a complete vehicle system.
- A basic operator's manual.

2. Methodology

There are three main work functions required for this assignment: (1) design which includes modelling and simulation, (2) construction and assembly of the powertrain, (3) testing and evaluation.

The design phase follows the sequence outlined in Figure 1 below.

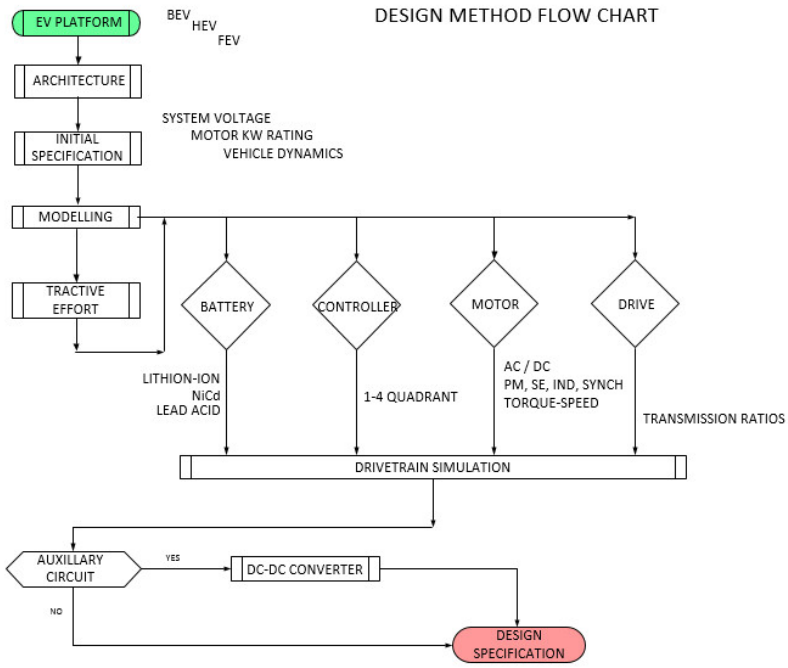


Figure 1. Design method flow chart.

3. Electric vehicle platform & architecture

The platform adopted for the kart will be battery electric vehicle (BEV) [1], [2], with a standard DC electric powertrain architecture as shown in Figure 2.

The propulsion system consists of a battery pack for the power source, motor controller for torque, and speed regulation, an electric traction motor to generate the torque and angular velocity, and a final drive to transfer the motor's output mechanical power to the rear axle to drive the vehicle forward. An auxiliary circuit to control any vehicle accessories not associated with the operation of the powertrain is an optional extra.

The DC architecture has been chosen because of its mature technology, simplicity in its operation and construction and availability of suitable light weight and compact EV components. An AC system, though providing superior torque speed characteristics, is more suited to full size production passenger road vehicles.

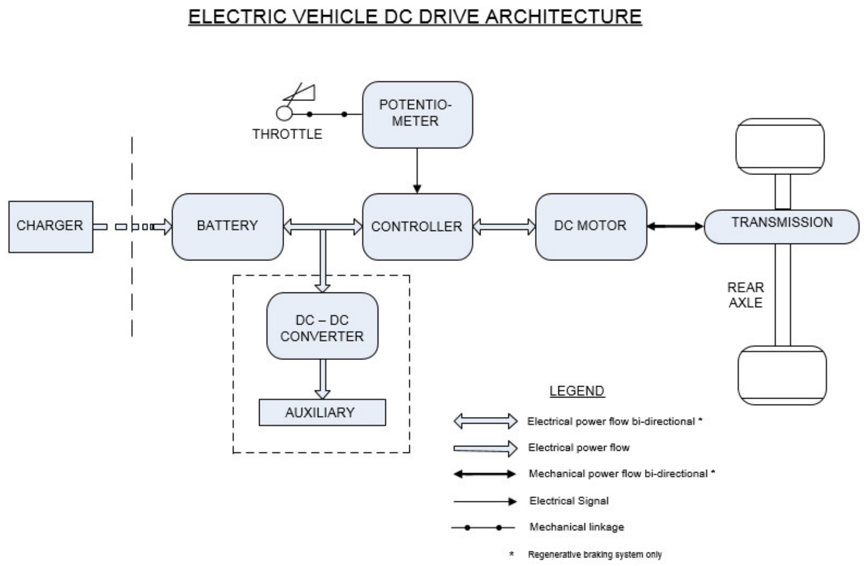


Figure 2. Electric kart powertrain architecture

4. Initial design specification

As this research project is primarily intended at the introductory level of the sport, it is only necessary to produce a machine which has the performance characteristics comparable to an equivalent ICE powered vehicle currently competing in the senior entry level class of the sport. This corresponds to the existing AKA class of karting, known as National or KA4. This class has the following performance characteristics:

- Power plant: IAME or Yamaha 100 cc air cooled ICE, restricted to 13 h.p. (9.7kW), or unrestricted to 22 h.p. (16.4kW) [3].
- Max speed: 77 to 104 kph depending on port restrictions [4].
- Acceleration: ICE acceleration figures unavailable. Therefore figures based on 50 to 75% of the recently released Bosch e-kart which has a claimed figure of 5.36 ms^{-2} with a 20kW motor [5].

The remainder of the specification relating to the major powertrain components has been determined from a literature review of the available technology applicable to the application. Hence the initial design specification can be summarised by the following criteria:

<u>Initial Vehicle Dynamic Performance Specification</u>

- Maximum velocity: 75 – 85 kph
- Acceleration: 2.68 – 4.02 ms^{-2}
- Range: 10 km minimum

<u>Initial Powertrain Specification</u>

- EV platform: DC BEV battery electric vehicle
- EV architecture: refer to Figure 2
- System voltage: 48V to 72V
- Rated motor power: 10 to 15 kW
- Motor type: DC brushed/brushless
- Controller: Electronic semi-conductor type with either 1 to 2 quadrant operation

- Battery pack: lead acid, nickel metal based or lithium metal based chemistries
- Final drive: Chain drive (gear ratio determined from modelling)

5. Traction Forces

In order for the design of an EV powertrain to satisfy a design specification, it must first be evaluated in the context of its intended operating environment. Any electric vehicle by virtue of its application is subjected to a number of resistive forces which oppose its forward motion. These same forces have a direct impact on the ability of the powertrain to overcome those resistive forces and in turn produce enough forward momentum to drive the vehicle forward to meet a predetermined rate of acceleration and final velocity [6]. Hence it is imperative to determine which acceleration and final velocity performance characteristics are feasible with a particular powertrain configuration relative to the vehicle to which it is providing a traction drive capability. Table 1 below summarises the traction forces applicable to the electric kart application researched in this project.

Table 1. Total tractive effort.

Total Tractive Effort $$\mathbf{F_{te}} = \mathbf{F_{rr}} + \mathbf{F_{ad}} + \mathbf{F_{he}} + \mathbf{F_{la}} + \mathbf{F_{wa}} \quad (1)$$

Total Tractive Effort F_{te}***(N)***	***Rolling Resistance*** F_{rr} ***(N)***	***Aerodynamic Drag*** F_{ad}***(N)***	***Hill Climbing*** F_{hc} ***(N)***	***Linear Acc.*** F_{la} ***(N)***	***Angular Acc.*** $F_{\omega a}$ ***(N)***
619.88	27.95	172.39	refer note 1	419.54	refer note 2

Notes:
1. Calculations based on flat ground hence $F_{hc} = 0$
2. Angular acceleration has been included into linear acceleration with an additional 5% mass to allow for indeterminate rotational inertia quantities.

The instantaneous traction power required to move the vehicle forward at a given velocity is given by the equation,

$$P_{te} = (F_{te} \times v) / n_g \quad (2)$$

$P_{te} =$ motor output power?
$v =$ vehicle velocity
$n_g =$ drivetrain efficiency ~ 0.9

Assuming a maximum velocity of 85 kph or 22.2 m/s is required from the vehicle, the total motor power requirements P_{te}= 15.29 kW. It must be noted here that more advanced differential drive applications have also been reported in scientific literature [7].

6. Battery pack

When selecting a battery power source for a performance orientated EV drive, there are a number of criteria which require an assessment before any attempt at battery selection can be undertaken. There is sufficient previously published work also in the area of selecting various battery technologies for electric kart applications [8]. The following items make up the assessment criteria and include,

- Commercial availability and associated cost.

- Physical properties of weight and volume.
- Static electrical energy properties.
- Dynamic electrical energy properties.
  - Constant current discharge rate – the effect on battery voltage from a number of current discharge C rates which determines the corresponding amp hour (Ah) rating of the battery cell.
  - Constant power discharge rate to meet motor electrical power requirements.
  - Peukert Coefficient – the mathematical relationship describing the effect which an increasing discharge rate will have on a corresponding decrease in the available battery capacity. As a general rule, the lower the value the more efficient the battery.
- Battery charging and balancing requirements.

It must be stipulated that when evaluating battery behaviour, any results obtained must be taken as a guide only. The indeterminate nature of the chemical make-up of most battery types leads to a wide ranging disparity in their performance characteristics from battery manufacturers and suppliers alike. Hence any modelling or predication of a battery's behaviour is only an approximation and should be treated as an indication of their performance potential [6].

At the completion of the assessment process there is only one real contender for this application – the lithium chemistry based batteries. There are a number of different subtypes in this chemistry, however the most popular and readily available is Lithium-Iron Phosphate LiFePO4. This battery type exhibits a very flat discharge curve Figure. 3, which contributes to its high energy density characteristic.

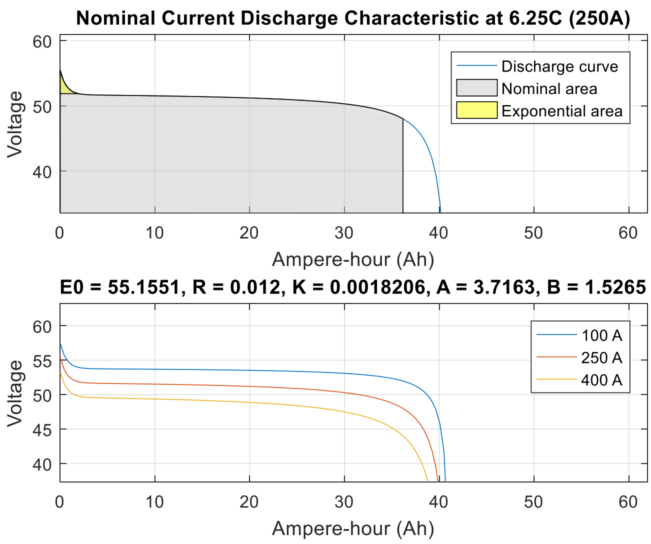


Figure 3. Typical 48V 40Ah LiFePO4 Current Discharge Curve.

The $LiFePO_4$ in a 40 to 60 Ah rating is the preferred battery chemistry and rating for the EV kart application.

7. Controller

The rpm speed and torque control of a DC motor can be undertaken by varying the motor's supply voltage or by flux weakening in the case of the separately excited DC motor. Either method results in a variation of the motor's armature current by means of a device more commonly known as a DC-DC converter or a DC "chopper". The chopper is so called because it takes a constant input DC source voltage and combined with high speed semiconducting switching, transforms the output voltage into a

chopped or segmented waveform. The variation in the time duration of the switching is the means of providing the variable DC voltage for motor control. Motor speed is proportional to voltage while torque is proportional to current [6].
The features of a ready-made commercial EV power electronics controller include:

- MOSFET, IGBT or GTO based high speed switching.
- Microprocessor control.
- Requires and external 5 K-Ohm throttle potentiometer.
- Automatic motor current limiting.
- Thermal protection.
- Under/over voltage protection.
- Programmable control of throttle response to motor speed control.

The controller is required to operate in either one or two quadrant mode of operation to obtain the desired direction of motion and or generator capabilities from the traction motor. In order to obtain both forward motoring and forward regenerative braking, two-quadrant operation is required. Figure 4 below details the basic circuitry and waveforms for a class C two quadrant chopper.

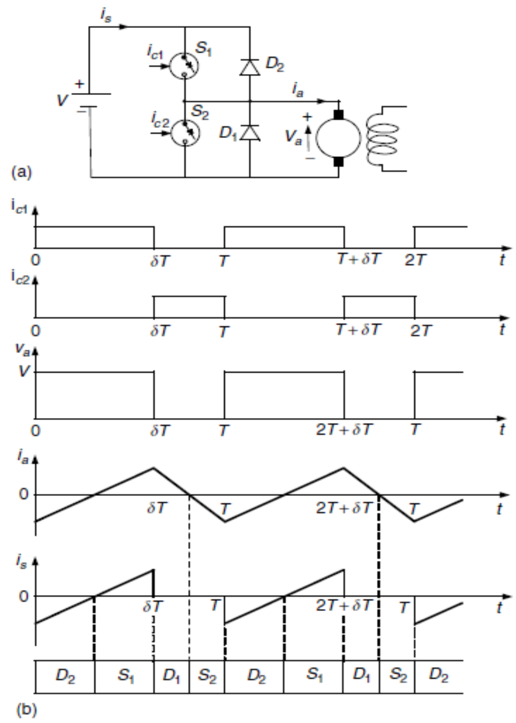


Figure 4. Two quadrant "Chopper" (a) circuit & (b) waveforms, source: [3]

The selection of a motor controller is therefore quite straight forward with a number of manufacturers such as Alltrax®, Curtis® and Sevcon® providing the latest in power electronic controllers for both AC and DC motors. In this instance, the controller is simply matched to the system voltage and max motor current ratings of the corresponding DC motor in the powertrain. A comparison of recognised DC controllers designed for traction applications is shown in Table 2 below. The preferred controller is the Sevcon due to its high current ratings and quadrant 2 forward regenerative braking capability.

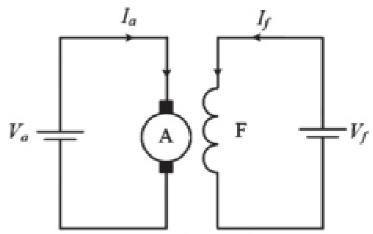
Table 2. DC controller comparison

	Voltage range	Current limit 1 min rating	Current limit 1 hr.	Plug braking	Quadrant
Alltrax	12 - 72	300-450	125-250	optional	1
Curtis	36 - 144	250-550	-	standard	1
Sevcon	36-72	300-600	400-550	n/a	4

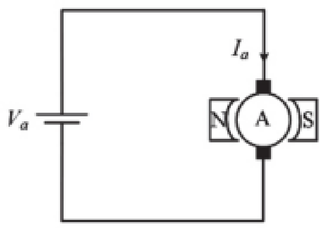
8. Motor and final drive

The parameters for choosing an electric drive for an electric kart application can be found in [9]. The circuitry of DC motors which are well suited to EV traction drive applications are shown in Figure 5 below. These include the brushed separately excited, permanent magnet and the brushless BLDC motors depicted in the circuit diagrams (a) (b) (c). There suitability is primarily due to the ease at which the speed and torque of each motor can be controlled to obtain a drive system which is very flexible and ideally suited to the demands of a modern motor vehicle.

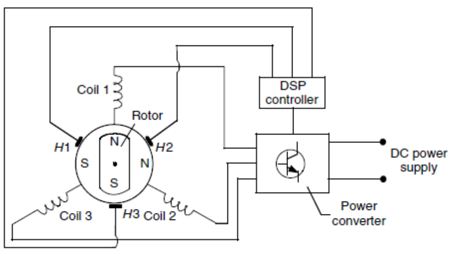
The selected motors all exhibit the same inverse linear torque-rotational speed relationship as shown in Figure 5 (d). These include the characteristic high stall torque decreasing linearly to a no load value at maximum rpm. It is this simple straight line torque-speed characteristic which lends itself to ease of control and which makes it so attractive to a traction motor application over other motor types.



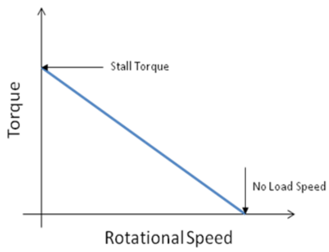
(a) Separately Excited
Source: [1]



(b) Permanent Magnet
Source: [1]



(c) Brushless DC (BLDC)
Source: [3]



(d) Torque Speed Curve
Source: NI Instruments

Figure 5. EV DC traction motor options

A Permanent Magnet (PM) motor has been selected on the basis of its high kW and current ratings providing superior torque speed, combined with light weight, compact dimensions and commercial availability.

For a single gear transmission, a 2.6:1 final drive gear ratio has been selected based on the relationship between motor rpm, desired top speed (85 kph) and driven wheel diameter.

9. Modelling and simulation

Ideally a complete vehicle model containing drive cycles, control systems, powertrain components, mechanical drivetrain and longitudinal vehicle dynamics is the preferred simulation method for determining the vehicle's performance capabilities. In the absence of such a complex model, a rather more basic approach has been followed.

The basic steps include modelling the main propulsion system components to compare various options as undertaken in previous sections 6, 7 and 8, followed by the modelling of the vehicle dynamics to evaluate performance capability. Finally a complete powertrain model is employed to confirm the motor's response to an applied torque at the rear wheels.

The vehicle dynamics must be evaluated to ensure the drive system has sufficient capacity to deliver the mechanical power required to meet the initial performance specification listed in section 4. Hence the tractive forces opposing forward motion explained in section 5 are incorporated into a model to determine acceleration, velocity and range potential for a given electric motor, gear ratio and total vehicle mass configuration. The torque speed characteristics of the motor must also be included into the calculation using the first order differential equation (3) of the following form [10].

$$\frac{G}{r}T_{\max}\eta_g = \mu_{rr}mg + \frac{1}{2}\rho AC_d v^2 + \left(m + I\frac{G^2}{\eta_g r^2}\right)\frac{dv}{dt} \tag{3}$$

$$G = \text{gear ratio}$$
$$r = \text{radius of drive wheel}$$
$$T = \frac{K_m \Phi E_s}{R_a} - \frac{\left(K_m \Phi\right)^2}{R_a}\omega = \text{motor torque}$$
$$\mu_{rr}mg = \text{rolling resistance}$$
$$\frac{1}{2}\rho AC_d v^2 = \text{aerodynamic drag}$$

The application of (3) results in the Figure 6 Matlab® plots of velocity and acceleration capability of the vehicle.

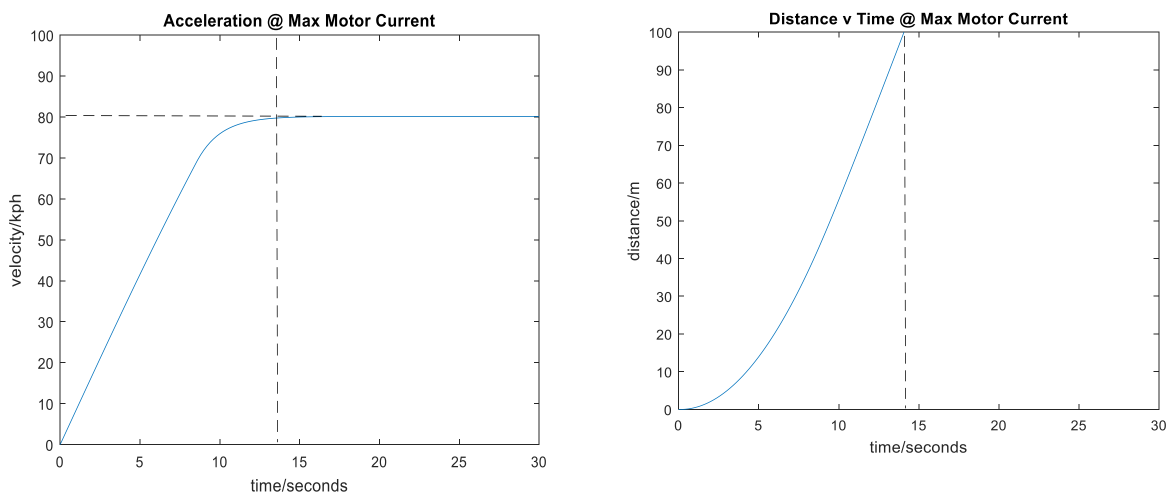


Figure 6. Vehicle dynamic modelling

The Matlab® Simscape® powertrain model as depicted in Figure 7 below has been utilised to simulate the traction motor's power, input current and rpm response to various torque applications at the rear wheels.

10. Final design specification

Table 3 below provides a summary of the final design specification resulting from the previous modelling simulations, with adjustments carried out during the procurement of components. The adjustments were necessary for reasons of cost and availability in order to fulfil the practical requirement of building a working prototype of the EV powertrain.

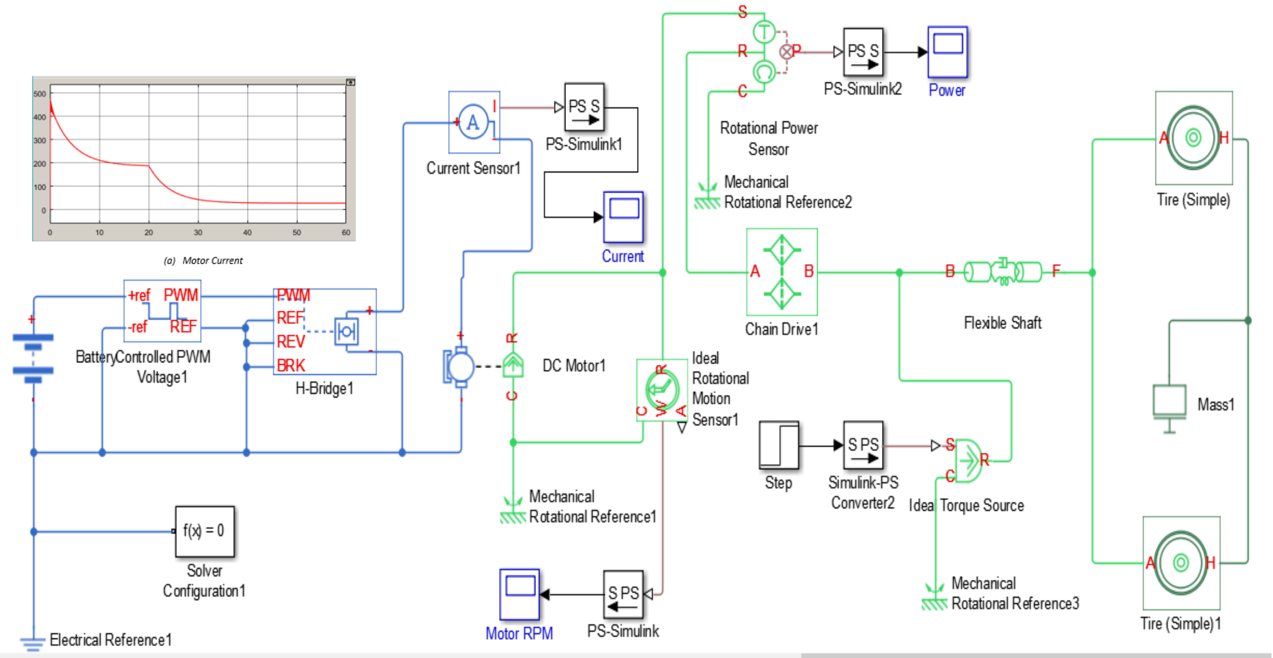


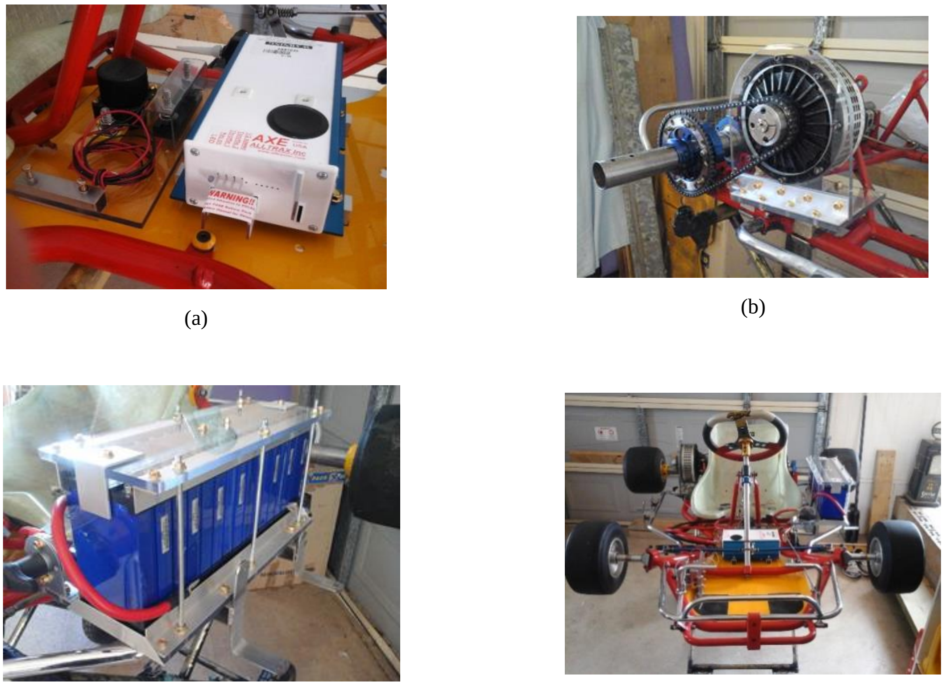
Figure 7. Matlab powertrain simulation

Table 3. Final design specification

	Initial Design Specification	**Final Design Specification**	Comments
EV platform & Architecture	BEV - DC	**BEV - DC**	
Performance.			
Max velocity	75 to 85 kph	**80 kph**	Flat gnd.
Acceleration	2.7 to 4.0 ms^{-2}	**2.33 ms^{-2}**	Flat gnd
Range	10 km	**12 km**	Full throttle
Powertrain			
Sys. voltage	48 to 72 V	**48 V**	60V optional
Battery pack	Lithium 40Ah	**$LiFePO_4$ 20Ah**	Cost restriction
Controller	Sevcon 2Q	**Alltrax 1Q**	Controller is specific to the motor type.
Motor	PM 10 to 15kW	**Lynch PM Brushed 10kW**	
Final drive	2.6:1	**2.3:1**	Availability

11. Construction testing and evaluation

The following photographs Figure 8 depict the construction phase culminating with the complete propulsion system installed in the kart Figure 9.



(a) (b)

(c) (d)

Figure 8. Construction (a) Contactor & controller, (b) Lynch pm motor & final drive, (c) LiFePO4 battery pack , (d) Installed powertrain

On road testing was undertaken on a short track of approximately 500 metres in total length which included a straight section of 225 metres. Within this limited distance the vehicle was able to accelerate to an average maximum recorded speed of 76 kph (and still accelerating) before the limited straight distance precluded any attempt to reach the design top speed of 80 kph.
Maximum acceleration times have been calculated at 1.95 ms^{-2} from recorded data.

Figure 9. Complete vehicle with functioning electric powertrain.

Though not previously discussed or depicted in Figures 8 (c) and 9 above, a battery management system (BMS) has since been installed adjacent to the battery pack on the vehicle. This is a necessary piece of equipment to ensure individual $LiFePO_4$ cell voltages are maintained within limits and balanced across the battery pack. Without a BMS the lithium based cells will suffer from premature failure resulting in a severe reduction in the battery pack's life cycle.

12. Conclusion

This research project has demonstrated that by using an engineering systems approach, an all-electric propulsion system is a viable alternative to the ICE, in so far as outright performance is concerned, for a karting application. This has been achieved using commercially available current state, electro-mechanical, power electronics and energy storage devices.

When evaluated on purely technical considerations, the electric powertrain has proven to be capable of achieving the performance goals set in the beginning of the project. Further development of a complete system model combined with the refinement of the powertrain componentry can only further enhance the performance potential of the above propulsion system.

Acknowledgement

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