Battery Electric Propulsion Systems for Competition Racing Applications

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Additional information is available at the end of the chapter

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Abstract

Electric propulsion systems applied in racing karts is a matured technology. This is confirmed by the fact that the Fédération Internationale de l'Automobile (FIA) has established a recognised technical formula for sanctioned competitive electric kart racing. Electric kart racing was introduced into Europe in 2017 with a set of technical regulations that are quite open at this early stage. This allows for experimentation of different electric powertrain configurations to enhance their development. The recent introduction of electric kart racing has provided the incentive to further develop electric powertrains to maximise their performance potential. The design and construction procedure necessary that was undertaken in the process of engineering a high-performance battery electric powertrain for a racing kart application for competitions is presented in this chapter. The design ensures that the electric propulsion system is capable of matching the performance characteristics of a comparable racing kart powered by an internal combustion engine (ICE). The implementation process of the design on a recognised, competition racing kart rolling chassis together with its performance evaluation data is also presented.

Keywords: battery, electric propulsion, racing kart, drive, controller

1. Introduction

Electric propulsion systems applied in competition racing karts are at a point of their development such that the technology is ready to be introduced into electric kart racing for sanctioned competitions. The following discussion in this chapter provides a basic approach to the design and construction process that is required in engineering an electric powertrain dedicated to a racing kart application for competitions. The procedure is demonstrated through a working

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example of an electric propulsion system orientated for high performance. The objective is to make this a stimulus for encouraging further development of more advanced electric powertrains suited to competition applications.

The final objective of the design is to end up with an electric powertrain that is capable of at least matching the competition racing cart performance characteristics powered by an internal combustion engine (ICE) with similar capacity. The chapter presents the documentation of the design procedure required, construction, and testing carried out to determine the actual performance. The electric powertrain will be installed into an existing rolling kart chassis, which has been designed specifically for the sport of kart racing.

In order to ensure functionality, reliability and minimised project costs at this introductory level, only proven electric vehicle (EV) technologies, which are readily commercially available have been integrated in the design and construction process.

The following main outcomes will be delivered by the overall research project:

- Specifications of an EV propulsion system applicable on an electric kart platform suitable for the lower levels of competition kart racing
- Produce a ***working prototype*** of an electric vehicle powertrain from an engineering design to meet a specific vehicle performance specification suitable for racetrack competition
- Results obtained through experimental verifications to confirm the dynamic performance capabilities achieved by the complete electric powered vehicle system.

2. Methodology

This research project must work within the following parameters to assist in achieving the working prototype outcome:

- Proceed with a simple design with proven reliable technology to handle the continuous high speed operation inherent to a competition environment
- Designed and constructed from ‘off the shelf’ readily available commercial products and components to facilitate easy construction, reliable operation and regular maintenance requirements
- Robust and reliable components from reputable manufacturers and suppliers to survive the rigours of an unforgiving and sometimes punishing operating environment
- Minimising the cost

The above constraints lead into the inevitable comparison between a battery electric powered kart and an ICE powered machine. The latter is indeed a very simple yet powerful mechanical vehicle for its compact size, with a high power to weight ratio indicative of the sport. It is these performance attributes that make the ICE powered racing kart so attractive as an introduction to the sport of competitive motor racing. In order to compete with the status quo, and present an attractive viable alternative, the proposed electric kart must exhibit similar characteristics.

This research project requires achieving three main work functions:

1. The design that includes modelling of the components and verification through simulations
2. The fabrication followed by assembly of the powertrain into the kart chassis
3. Testing and evaluation from on track performance data

The flow chart in **Figure 1** summarises the method of how the design and development was carried out to achieve the final outcomes.

The process commences with the establishment of the preferred EV platform and architecture [1] followed by an initial performance specification to set the performance goals for the electric vehicle as a complete unit with the powertrain installed.

This is followed by an initial determination of all resistive forces acting on the kart to establish the tractive effort [2] required to propel the vehicle forward to comply with the intended

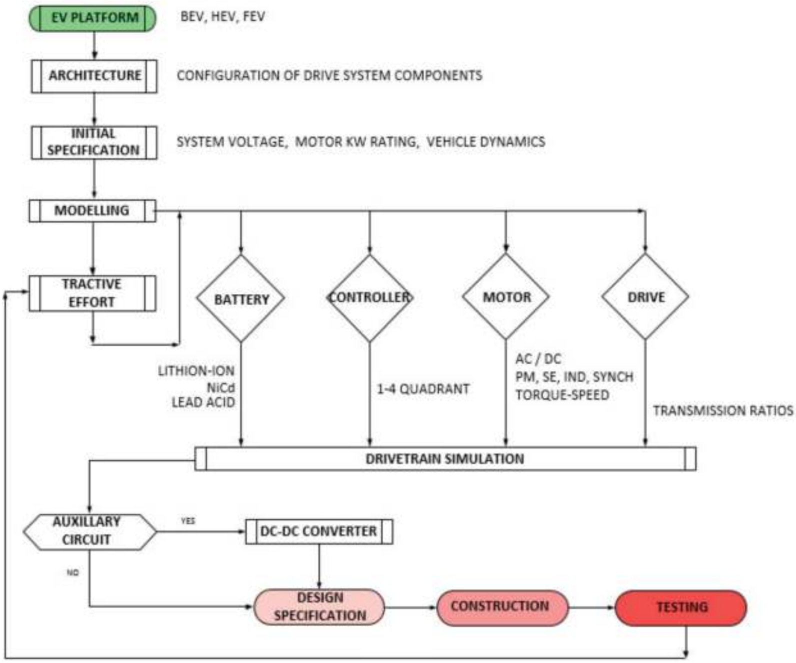


Figure 1. Methodology flow chart.

performance specification. Otherwise known as force modelling, this is a well-known and extensively documented design method employed by electric vehicle designers.

The main components identified in the architectural arrangement are either modelled or simulated individually with alternate options from different manufacturers to select the most appropriate items to achieve the vehicle's performance criteria. All chosen components are then brought together into the powertrain simulation to confirm their performance potential as a complete system.

The selected components represent the final design and are subsequently sourced from both national and international suppliers for assembly into the electric powertrain mounted within the rolling kart chassis. The complete vehicle is then bench tested and finally road tested to confirm the actual performance data with the initial specifications set down at the beginning of the research project.

3. Platform and architecture

In current practice, pure DC motor-powered drivetrains are in decline [3] and are limited to light recreational type electric vehicles only. AC motor-driven powertrains are without doubt the preferred method for all new battery electric vehicle (BEV) and hybrid electric vehicle (HEV) drive systems. This is especially true when designing both full-size passenger road vehicles as well as racetrack performance orientated-type vehicles.

However, there is a small exception to the above rule particularly when the financial cost, robustness, reliability, powertrain simplicity and commercial availability are factored into the argument. It all centres around the development of a particular type of DC motor—the axial flux (AF) brushed permanent magnet DC (PMDC) motor. With this particular motor installed as part of a DC powertrain platform, it is especially suited for high-performance light electric vehicles such as the competition-configured racing karts and motor bikes.

Therefore, the motor selection should be undertaken while determining the vehicles platform and architecture. Inevitably, the selected motor type will determine the platform and hence the make-up of the powertrain system. Section 6 of this chapter titled "Battery, BMS, controller and final drive" provides further detail on the approach taken.

Combined with the PMDC motor selection, the DC architecture has been chosen since this technology is matured and simple in its operation and construction and also because of the availability of light weight electric vehicle components that are suitable and compact. An AC system, with all of its inherent performance and maintenance advantages lacks a suitable small capacity motor (less than 20 kW), which can compete with the AF PMDC motor at this stage.

The BEV DC architecture consists of the following: a battery pack as the power source, DC-DC motor controller handling speed regulation and torque, a PMDC traction motor generating the angular velocity and torque, and a coupling mechanism to transfer the mechanical power output of the motor to the rear axle for the purpose of driving the vehicle forward. An

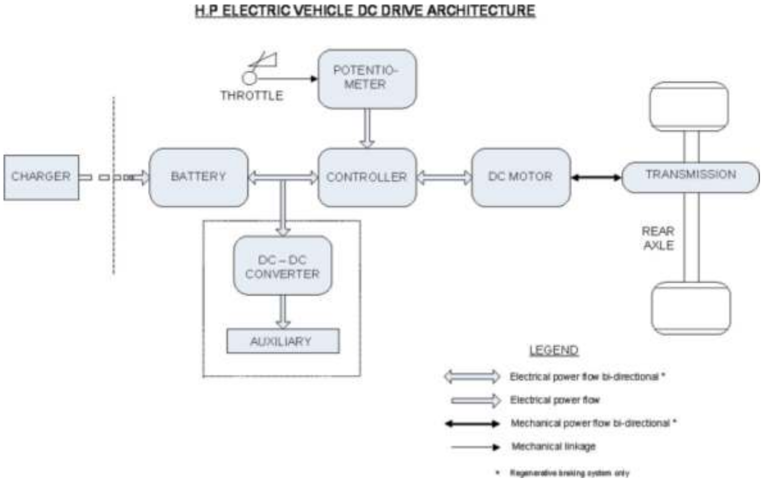


Figure 2. BEV DC drivetrain architecture.

optional inclusion could be an auxiliary circuit that controls any other vehicle accessories not directly associated with the operation of the electric drivetrain. **Figure 2** diagrammatically summarises this arrangement.

4. Initial specification

Since the objective of this research project is targeted at the introductory stage of sport karting, it is assumed that the only necessary requirement is to produce an electric kart system that has similar performance characteristics that are comparable with an equivalent ICE-powered kart competing in the senior entry-level classes of the sport at present. Performance characteristics of this class are the following:

Power plant: Yamaha or IAME air-cooled 100 cc ICE, restricted to 11 hp. (8.2 kW), or unrestricted to 16 hp (11.9 kW) [4].

Top speed: 77–104 km/h depending on port restrictions and track layout [5].

Acceleration: ICE acceleration figures unavailable. The recently released Bosch® e-kart rated at 20 kW 48 V has a claimed acceleration figure of 5.5 ms^{-2} for 0–100 km/h [6].

The above speed and acceleration figures are very much dependent on mass, engine horsepower, gear ratio, and the combined forces retarding forward motion. Bearing in mind these limitations, they do however provide a realistic base line from which this research project can aim for in its attempt to at least replicate comparable performance data. With the unavailability of any acceleration figures for an ICE powered kart, the Bosch® e-kart acceleration figure has been utilised instead and scaled according to the rated output power of the motor.

Criteria	Objective
Velocity	75–85 km/h
Acceleration	2.7–4 ms^{-2}
Range	10 km min

Table 1. Vehicle performance specification.

Vehicle range, or the total distance travelled before battery recharge is required is not a major concern with this particular EV application, due to the short track distance and limited number of laps associated with each race for such vehicles. A nominal range of 10 km has been nominated based on the short driving cycle experienced by these machines. Performance specifications of the vehicle are listed in **Table 1**.

The electric powertrain parameters are specified according to the desired platform operating voltage level and the main architecture component requirements, that is, the battery pack, battery management system (BMS), controller, traction motor and final drive. The desired voltage level is a trade-off between maximum power requirements and project cost. The higher voltage level results in more expensive powertrain components to handle the increased load currents. Commercially available components for light electric vehicles are readily available up to 72 and 96 V in some cases depending on the platform adopted. At the other end of the voltage scale, system levels at 36 V and below are more suited to the slower-paced recreational leisure type vehicles, which are definitely well short of performance objectives of the scope of this research project.

Consequently, a voltage range of between 48 and 72 V appears to be the level which is sustainable for vehicle type and DC platform of this research project. The remainder of the powertrain components are specified from a review of the available technology and their suitability to the DC platform. **Table 2** summarises the powertrain parameters.

Component	Type
Platform and architecture	BEV with DC powertrain
System voltage	48–72 V
Rated motor power and type	10–15 kW PMDC brushed
Controller	‘Chopper’ PWM 1–4 quadrant
Battery pack	Lithium-ion
Battery management system (BMS)	Cell balancing with pack voltage limits
Final drive	Single gear chain/belt drive

Table 2. Powertrain specification.

5. Modelling and simulation

Intended operating environment must first be evaluated for the design of the EV powertrain to satisfy the given design specifications. There are a number of opposing forces resisting the forward motion of any electric vehicle by virtue of its application. There is a direct impact of these same forces on the capability of the powertrain to overcome them, while producing high enough momentum in the forward direction to drive the vehicle forward, meeting a predetermined cruising velocity and rate of acceleration [6]. Hence, it is crucial to determine the feasible final velocity and acceleration performance characteristics associated with a particular powertrain configuration in relation to the vehicle, to which the power train is going to provide traction drive capability.

The force modelling procedure in its various formats is well known to vehicle designers and has been extensively documented elsewhere. The procedure is summarised in the main equations described below:

The main Equations [2] associated with the force modelling procedure and applied to the design of the powertrain system include the following:

$$F_{rr} = \mu_{rr} mg \text{ (rolling resistance force)} \tag{1}$$

$$F_{ad} = \frac{1}{2} \rho A C_d v^2 \text{ (aerodynamic drag)} \tag{2}$$

$$F_{hc} = mg \sin(\psi) \text{ (hill climbing force)} \tag{3}$$

$$F_{la} = ma \text{ (linear acceleration force)} \tag{4}$$

$$F_{\omega\alpha} = I \frac{G^2}{n_g r^2} a \text{ (motor angular acceleration force)} \tag{5}$$

Combining Eqs. (1)–(5) results in the total tractive effort described in Eq. (6) to propel the kart forward

$$F_{te} = F_{rr} + F_{ad} + F_{hc} + F_{la} + F_{\omega a} \tag{6}$$

The motor power requirements at a given velocity is then determined from Eq. (7) taking into account efficiency losses in the drivetrain and can be described as

$$P_{te} = \frac{F_{te} \times v}{\eta_g} \tag{7}$$

Motor torque and speed relationship for a DC motor is given by Eq. (8), which takes into account the back EMF generated by the motor.

$$T = \frac{K_m \phi E_s}{R_a} - \frac{(K_m \phi)^2}{R_a} \omega \tag{8}$$

The equation describes the linear correlation between a decreasing speed with increasing torque depending on the rotor or armature resistance and the resultant back EMF. This type of torque-speed relationship creates an ideal condition for the regulation of motor speed via a DC motor controller.

Eq. (8) can subsequently be modified into the characteristic torque Eq. (9) below with the inclusion of the rated current specified by the motor manufacturer to calculate the rated torque value:

$$T = K_m \phi I \tag{9}$$

The all-important acceleration potential of the vehicle can then be modelled using Eq. (10)

$$\frac{G}{r} T_{max} n_g = \mu_{rr} mg + \frac{1}{2} \rho A C_d v^2 + \left(m + 1 \frac{G^2}{\eta_g r^2} \right) \frac{d_v}{d_t} \tag{10}$$

The force modelling and simulation were performed using a combination of calculations in MS Excel®, which were then applied into the Matlab/Simulink® applications for evaluation of the dynamic behaviour of the vehicle.

Simulated output velocity results for the acceleration process are displayed below in **Figure 3**.

The modelling and simulation from **Figure 3** confirmed that a minimum motor power rating of 10 kW will be required for this application and hence three commercially available AFPM

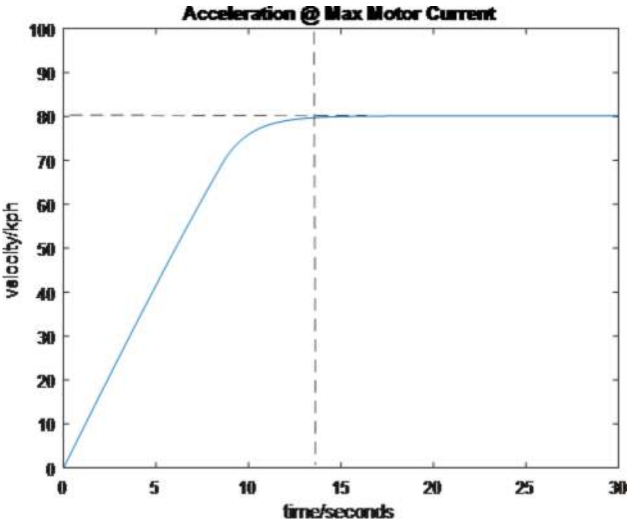


Figure 3. Vehicle acceleration under maximum load.

motors were selected for comparison. **Table 3** presents the ratings of one example of the three motor types, which were evaluated for the project kart. The motors listed in **Table 3** are by no means limited to these three examples. A limited number of model variants are available for selection from each manufacturer, with varying levels of power, torque and voltage ratings depending on the design requirement.

The selection of a traction motor for this project required the following points in the order of priority to be taken into consideration:

- Cost and commercial availability
- Performance characteristics, such as power to weight ratio, power density, efficiency, torque, speed.
- Compact, robust, proven and reliable design
- Motor control technology and simplicity
- Motor cooling requirements, air or liquid cooled.
- Motor to driven wheel final drive mechanical coupling arrangement.

Motor type	PM DC	PM SM	Yokeless DD
Manufacturer	LMC®	Motenergy®	YASA Motors®
Model No.	LEM-200 95	ME-1114	YASA-400
Voltage rated (V)	48	48	400
Voltage peak (V)	60	72	
Power rated (kW)	10	10	50–70
Power peak (kW)	18	24	90
Current cont. (A)	250	180 DC/125 AC	
Current max. (A)	400	600 DC/420 AC	
Efficiency peak (%)	92	92	95
Power to weight rated/peak (kW/kg)	0.90/1.636	0.63/1.512	2.1/3.75
Torque rated (Nm)	28	65	250
Commutation	Brushed	Sine/cosine encoder	
Control technology	PWM voltage/speed current/ torque	PWM frequency inverter	
Country of origin	UK	USA/China	UK
Application examples (published)	Sodikart®, Zerokart®	EV power®	

An equivalent motor is also manufactured by Saietta Group Limited in the UK.

Table 3. Motor comparison.

5.1. A motor with similar characteristics is also manufactured by Magnax in Belgium. Yokeless DD motor

The Yokeless DD motor has been a recent innovation designed for full-size electric vehicles in mind with a higher voltage level and with the preferred mechanical coupling via 'in wheel' direct drive. This drive method eliminates the requirement for a geared coupling, should that be the desired outcome. Clearly, this method is not currently practical for an electric kart situation, due to the small diameter wheels fitted onto the rolling chassis. For an electric kart to take advantage of a DD-type motor, it will require a complete redesign of the rear axle assembly. This will involve mounting the motor directly onto the rear axle through a splined hub, thus eliminating the need for the pinion drive and chain driven sprocket assembly currently in existence. This arrangement will have the added benefit of increasing drivetrain efficiency with the elimination of the geared reduction drive.

The DD motor typically operates between 200 and 400 V. Installed into a kart chassis, the motor will need to run at a lower system voltage level of around 100 V or less. This is necessary to maintain an acceptable battery mass within the limitations of the physical dimensions of the vehicle. This motor requires oil cooling to maintain a desirable operating temperature. The addition of an oil reservoir, pump, power supply and associated hosing may be problematic with available space limitations and increased weight penalty.

Though the topology of the motor is quite simple, the manufacturing process required to produce such a motor can be quite complex and expensive depending on the design adopted by the particular manufacturer. This motor has been included because it represents the future direction in electric vehicle powertrains with its high performance capabilities and compact design [7, 8].

5.2. Permanent magnet synchronous motor

On the other hand, the axial flux permanent magnet synchronous motor (AF PMSM) is very adaptable for an electric kart application, albeit from only a single manufacturer. Readily available from commercial retailers in a number of different power ratings, it provides a very cost-effective alternative. It also displays superior torque speed characteristics compared to its DC counterpart. Previous models of the motor listed in **Table 3** employed a single stator and a single rotor topology with an inbuilt cooling fan using Hall sensor control feedback on rotor position. Later versions of the same motor have been upgraded with a single stator dual rotor with the Hall sensors replaced with a sine/cosine encoder for higher resolution rotor position feedback.

The disadvantages of the PMSM include a lower power to weight ratio and a requirement for an internal fan for cooling purposes. The control of these types of electrical machines requires feedback algorithms incorporating famous synchronous frame (dq) control strategies with variable speed drives. The AC platform, which the PMSM finds integral to its operation, could be somewhat more susceptible to the effects of the harsh operating environment, typified for racing karts. The sensitive feedback electronics in the motor and controller will need to withstand a high impact, high vibration environment of risk and early failure.

5.3. Brushed PMDC motor

The obvious disadvantage with this type of motor is the brushed commutation, which hindered the efficiency in the older traditional radial flux (RF) motors. With advances in brush metallurgy and an inclined brushed mounting arrangement, this problem has been somewhat reduced [10]. Regular brush maintenance is still required to maintain the motor at its peak efficiency [11].

The advantages of this motor outweigh the brush maintenance issue at least at the beginning of its serviceable life. With a high power to weight ratio, good torque speed characteristics, unforced air cooling, compact aspect ratio and robust high quality construction, it is an ideal motor for electric kart applications. In addition, with the motor operating at the lower voltage levels of 48 and 60 V, it is still possible to obtain respectable overall vehicle performance. The lower voltages require less battery mass, thereby assisting in reducing the total powertrain weight. In conjunction with a light weight AF PMDC motor, the end result is a kart with a gross vehicle mass of 82 kg, which is of similar weight to an equivalent ICE powered machine and meets the FIA minimum weight restriction of 80 kg [12].

Combined with simple open-loop torque/speed control from a matched controller, the brushed PMDC motor is a straight forward installation with minimal complexity involved. This simplicity is in line with the overall philosophy of competitive kart racing, which is noted for its minimalist yet robust engineering.

6. Battery, BMS, controller and final drive

6.1. Battery pack

The lithium-ion based chemistry is the most viable chemistry with high power density [9], which can be applied to the battery pack requirements for high performance vehicle applications [13].

There were two common types of lithium-ion chemistries available to choose from when determining the battery pack configuration; Lithium-ion phosphate ($LiFePO_4$) and the lithium-nickel-cobalt-manganese-oxide (LNCM) [14, 15]. The latter has a higher specific energy and performance ratings but can be considerably more expensive to obtain. The $LiFePO_4$ was selected due to lower cost and a recent upgrade in the manufacturers production techniques resulted in an increase in specific energy.

The $LiFePO_4$ battery pack consists of 16 cells with 20 Ah rating at a nominal voltage of 3.2 V for a total nominal pack voltage of 48 V. Various constant current discharge (C) rates have been modelled in Matlab® to provide an estimation of time to 80% Depth of Discharge (DoD) for the battery pack. **Figure 4** provides the details. It must be noted here that it is possible to obtain similar information readily from the battery manufacturers.

It is important to choose the battery supplier/manufacturer wisely by doing some preliminary research on failure rates experienced in the field on any particular brand of battery. Other factors to consider are

- The chemical stability of lithium based batteries is limited over a narrow temperature range
- Maintain each cell voltage within manufacturers upper and lower limits during both charging and discharging
- Maintain voltage and charge equilibrium between individual battery cells

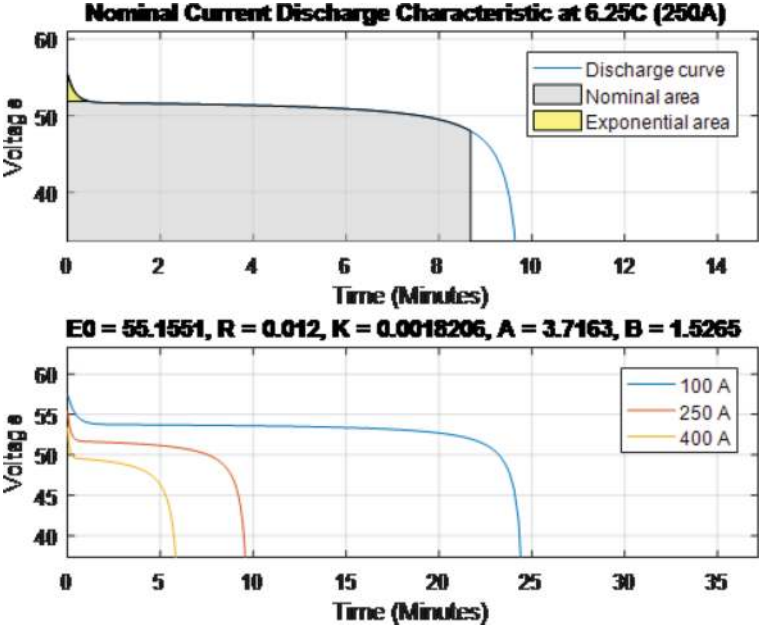


Figure 4. Battery discharge rates.

- Installation of a battery management system (BMS) is mandatory (in order to successfully maintain the conditions mentioned in the two previous points) to avoid premature battery cell/pack failure.
- The battery pack must be housed in a robust IP54 rated housing to prevent mechanical damage

6.2. Battery management system

The BMS consists of 2 × (120 A 51.2 V) modules connected in parallel with each module having the following specification:

- Overvoltage protection 3.75 V per cell
- Under voltage protection 2.1 V per cell
- Full battery pack charge voltage 3.6 V × 16 = 57.6 V
- Balance voltage 3.6 V
- Continuous rated current 120 A
- Over current protection 240 A
- Short circuit protection 320 μs
- Over temperature protection 70°C

6.3. Controller

The PMDC motor requires the simplest of electronic semi-conductor control circuits of all the motor variants previously listed. In a PMDC motor, the speed is governed by output voltage from the controller, which in turn determines armature current for motor torque. The voltage output from controller to the motor is a square wave pulse width modulated (PWM) signal, which produces the voltage variation and hence motor speed regulation, otherwise known as a 'chopper', where the switching frequency of a MOSFET controls the average voltage output with a segmented square waveform.

A DC 450 A controller with single quadrant (Q1) forward motoring capability only was initially selected with the following representative circuit in **Figure 5**.

The controller circuit depicted in **Figure 5** does not provide regeneration capability, whereby when the motor is producing negative torque it will act as a generator and recharge the battery pack via the DC controller. To achieve this function and enhance the charge capability of the battery in the order of 15% or more, a controller with the full bridge circuit depicted in **Figure 6** is required.

Otherwise known as a four quadrant (Q4) controller, it will provide both forward and reverse motoring as well as forward and reverse regeneration capability.

The controller is the one critical device in the complete powertrain which is susceptible to early failure, or underperformance, from poor workmanship, abuse or incorrect setup. Therefore when selecting a suitable controller, the following points were taken into consideration:

- Preference given to controllers which are built for Q4 operation.
- Controllers and their respective circuitry are manufactured to operate with a specific type of electric motor. Each motor type listed above in Section 6 Traction Motor requires its own individually matched controller for successful operation.
- The high frequency switching operation from the MOSFETs can generate considerable heat during high vehicle speed, and high amperage loading situations so inherent in a competition setting. The controller must be mounted in a location with good airflow for heat dissipation.

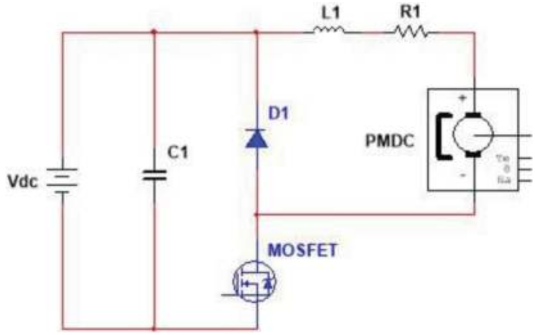


Figure 5. DC Q1 drive circuit.

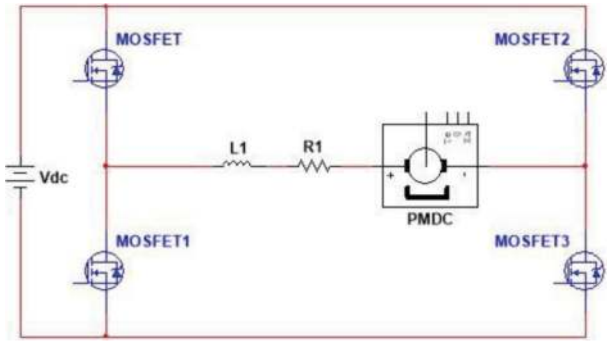


Figure 6. DC Q4 drive circuit.

- The controller must be rated above the maximum current rating of the motor.
- Most controllers are programmable for various functions relating to the operation of the motor. The programming software can either be freely available and user friendly with minimum hardware requirements or quite expensive with specific hardware and software requiring complicated programming techniques. Support from the manufacturer/supplier may not be forthcoming in some instances.
- The controller for the project kart was selected from a well-known brand name manufacturer with an established reputation in the electric vehicle industry. The additional cost paid dividends with ease of setup, technical support and reliability.

6.4. Final drive

The final drive fitted to the kart consists of a pinion gear on the output shaft of the motor driving a chain driven sprocket on the rear axle—a very simple arrangement though subject to drivetrain losses particularly with the chain drive component.

The final drive arrangement can be utilised to modify the speed and torque characteristics of the electric motor to values more in tune to the kart's performance potential to suit a particular racetrack setting. That is to say that the kart can be provided with additional top speed at the expense of torque on a fast-flowing racetrack where maximum velocity is more important than acceleration. And the opposite is the case when the situation is reversed. A slow track with many corners will demand more torque for acceleration as opposed to a high terminal velocity for the vehicle. A simple change in gear ratio between the motor output shaft pinion gear and rear axle sprocket will achieve this result.

This requirement could be somewhat negated should the kart be fitted with a motor exhibiting sufficient torque speed capabilities such that all that would be required is a direct 1:1 ratio final drive.

This ideal situation does not exist in this instance, so a final drive consisting of a single reduction gear and chain drive onto the rear axle with a ratio of 2.3:1 is necessary to accommodate the above requirements. This particular gear ratio favours maximum velocity at the expense of torque (i.e., fast track setup) when taken from the rear axle.

7. Final design

The final design of the electric kart powertrain is a result of direct performance comparisons through modelling and simulation and the evaluation of particular products marketed for light electric vehicles. The technical and production expertise of each manufacturer was an important consideration, when evaluating competing products to ensure a reliable and robust powertrain. The final result is depicted in the schematic of **Figure 7**.

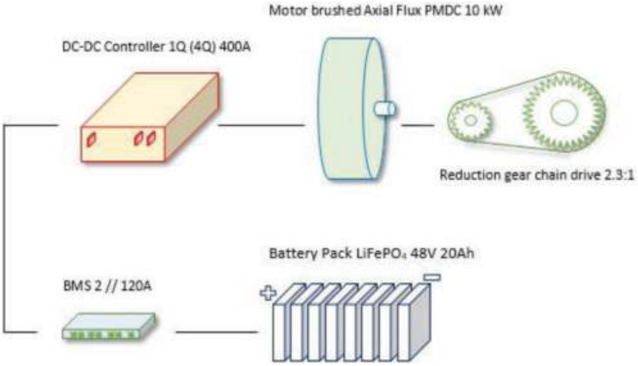


Figure 7. Final design summary.

8. Construction

The complete vehicle with the main powertrain components are depicted in **Figures 8** and **9**.

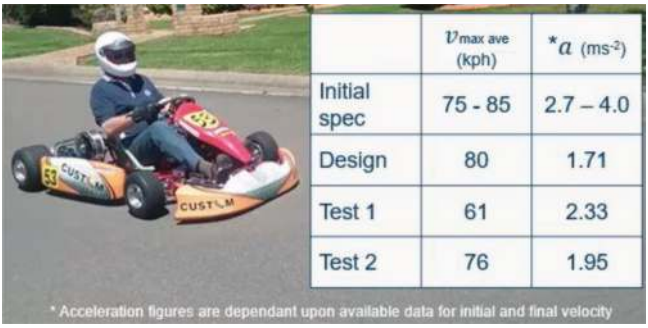
Figure 8. PMDC 10 kW motor and Q1 450 A controller.

9. On-track testing

The electric kart has been road tested to determine its performance drive potential. **Figure 10** provides a plot of velocity over distance for one such test session. A maximum speed of just over 90 km/h was obtained on a short road section with the vehicle still under acceleration.

Figure 9. 48 V Lithium-ion battery pack with BMS and the prototype electric kart.

Figure 10. Vehicle velocity plot.



	$v_{\text{max ave}}$ (kph)	*a (ms^{-2})
Initial spec	75 - 85	2.7 – 4.0
Design	80	1.71
Test 1	61	2.33
Test 2	76	1.95

* Acceleration figures are dependant upon available data for initial and final velocity

Figure 11. Vehicle performance test data.

A summary of all road test data is presented in **Figure 11** with a comparison against initial design data.

10. Conclusion

The DC 48–72 V platform with the brushed axial flux PMDC motor with a high power to weight ratio, simple torque speed control and compact construction is ideal at the introductory level for the sport of kart racing. However with the exception of the lithium-ion battery pack, the remaining DC components have probably limited scope for further development to improve their performance levels.

For the more advanced levels of the sport, preference should be given to a higher system voltage of 96 V using a PMSM with an axial flux design and closed-loop motor control. This will ensure the maximum performance potential is extracted from the electric vehicle platform utilising readily available EV technology.

The development of the DC electric powertrain detailed above for the application of competition karting provides an insight into what can be achieved with what is essentially well established, proven and reliable technology. Consequently, this particular DC powertrain should be ahead in the reliability stakes whenever it is required to operate at its maximum capability out on the racetrack. The harsh operating environment will quickly destroy any components, which are the least bit fragile in both their construction and operation. A light vehicle AC high-performance powertrain will also need to demonstrate the same qualities as its DC counterpart for it to succeed in this environment.

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