

University of Wales Trinity Saint David

School of Engineering - M.Sc. Motorcycle Engineering



Series Hybrid Vehicle Coursework II

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Hybrid Powertrain and control

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1. Abstract

In the previous simulated study, the duty cycle of Renegade dx 10C ICE was generated to understand the performance characteristics and fuel consumption on a dual-purpose terrain course under normal driving conditions during a corporate event. The torque-oriented powertrain was subjected to terrains under varying and competitive tractive effort subjected to aerodynamic, gradient and rolling resistive forces. In this proposed analysis, buggy is converted into a series hybrid powertrain with introduction of necessary components that meets the requirement of the present powertrain and fuel efficiency is calculated as a proposed solution for energy storage and its conservation.

2. Introduction

Energy storage technologies are gaining traction rapidly, and they are being applied to a wide range of industries. Design and development of a hybrid powertrain needs a closer look into the tractive effort with the introduction of new components due to increase in the total weight and competitive terrain conditions. A series hybrid powertrain of Renegade consists of multiple sources of power generation (ICE and Battery) in the same chassis with possible outcome on improving the efficiency, fuel consumption and reducing emissions.

The design of the system works under two performance control strategy for the test. ICE will operate throughout the session without disconnecting itself from final drive. The battery is stored with energy below 5.6 kW power whereas both battery and ICE works together to generate final rotation over 5.6 kW. The components that are meant to be introduced for current simulation is described on figure 1. This includes introduction of a new Internal combustion engine, generator, power converter/controller, Battery as the energy storage device, electric motor and Final drivetrain.

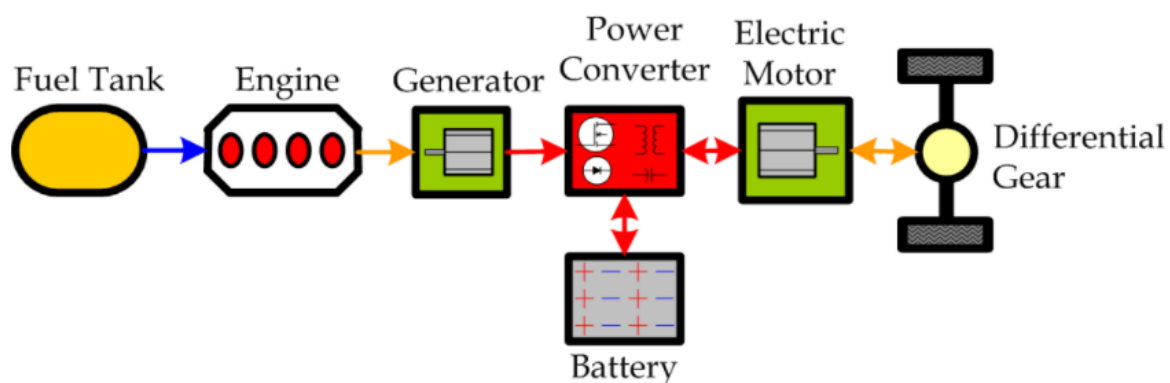


Figure 1: Components of a Series Hybrid Powertrain System (de Lucena, 2011)

Series hybrid EV power-trains are mechanically disconnected from the ICE, and therefore independent of vehicle speed. As shown schematically, the onboard fuel is converted into mechanical energy via the ICE, and the mechanical energy is converted into electrical energy via an engine-mounted generator.

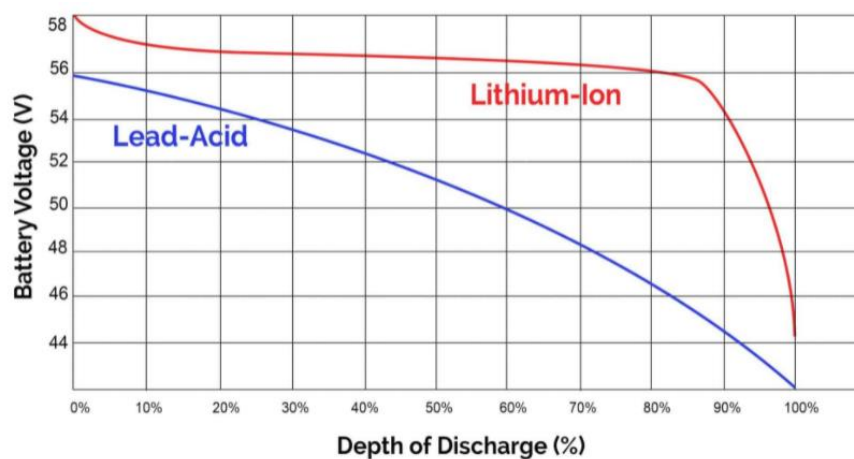
In the previous simulation of ICE, the fuel efficiency over the performance is a quite concern with the perspective of developing the buggy for competitive terrains and controlling emissions. The direction of the report is to simulate the newly designed series hybrid powertrain around a current renegade chassis as the renegade DX-10C buggy which meet requirement of long-distance adventure driving in competitive terrain conditions conserving energy with efficiency.

3.Literature Review

3.1 Energy Storage

3.1.1 Battery Storage System

The capacity of a battery determines how much energy can be stored (and eventually released). Battery capacity varies between manufacturers and models, but lithium-ion batteries are widely recognized as having a much higher energy density than lead acid batteries. Apart from the higher cost Lithium-Ion battery have higher energy density, low self-discharge rate with increased number of cycles, higher cell voltage, lower maintenance with reasonably good load characteristics without priming. (Electronics notes, 2020). A common characteristic of all types of batteries is that the voltage at their terminals changes with their charge level. The voltage will be highest when the battery is fully charged and lowest when it is empty. This relationship between voltage and State of Charge (SOC) depends directly on the battery technology used as mentioned in figure 2. (Powertech systems, 2022)



Graph 1 : Discharge curve: Lithium-ion vs Lead acid (GoSolarQuotes, 2022)

Specifications	Lithium Ion	Lead Acid Battery
Usable Capacity	80%+	30-50 %
Life Cycles	2000-5000	500-1000
Voltage per cell	3.2 V	2 V
Capacity @0 Degree	90 %	50-68 %
Wasted Energy	0%	15%
Size and Weight	Small	Big
Temperature sensitivity	Degrades over 45 Degrees	Degrades over 25 Degrees
Maintenance Requirements	Basic Annual maintenance	Every 3 Months
Charge time	1-3 Hours	6-12 Hours

Table 1 : Comparison of Lead Acid battery against Lithium-Ion battery. (Rpenainc, 2016) (Relion, 2022)

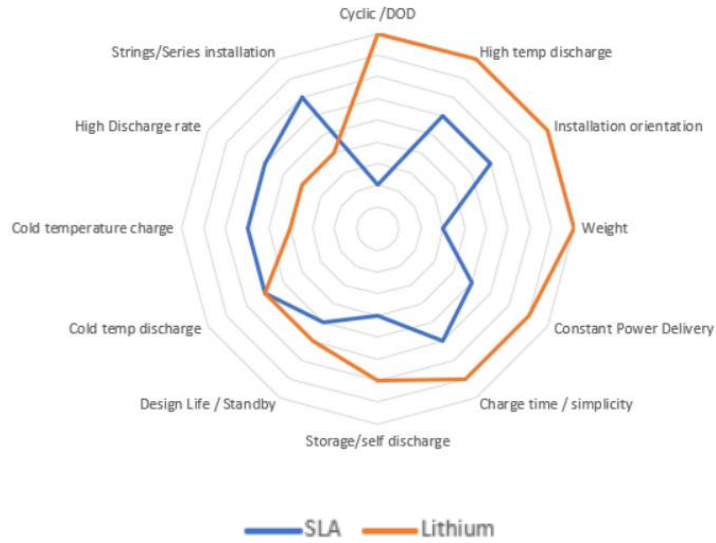


Figure 2: Performance attributes of Lithium-ion vs Lead acid battery (PowerSonic, 2022)

3.1.2 Capacitors

A supercapacitor is an electrochemical capacitor that includes pseudo capacitors, electrochemical double-layer capacitors (EDLC), and hybrid capacitors where they are categorised by the energy storage principle (Burke, 2000) . EDLC type capacitors so called supercapacitors are commonly used energy storage systems in hybrid vehicles which consists of two porous electrodes immersed in electrochemical solution. The ions generate a diffused layer in the surface of the electrolyte called as double layer effect. (Arani A.K., 2017)

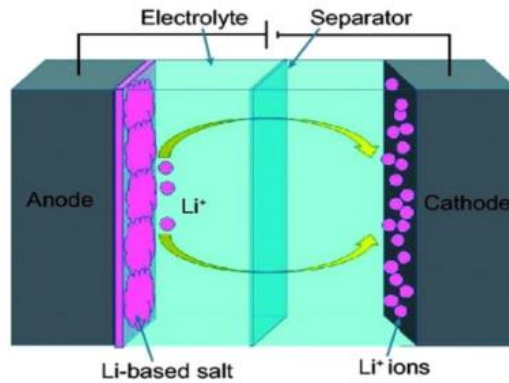


Figure 3 : Schematic diagram of a Hybrid Supercapacitor (X. Chen, 2017)

The Energy stored in a capacitor is directly proportional to capacitance and square of voltage as in following equation.

$$E = \frac{1}{2} * C * V^2$$

Equation 1 : Energy stored in a capacitor

$$\text{Where } C = \epsilon_1 * \epsilon_2 * \frac{A}{d}$$

Equation 2 :Formula for Capacitance

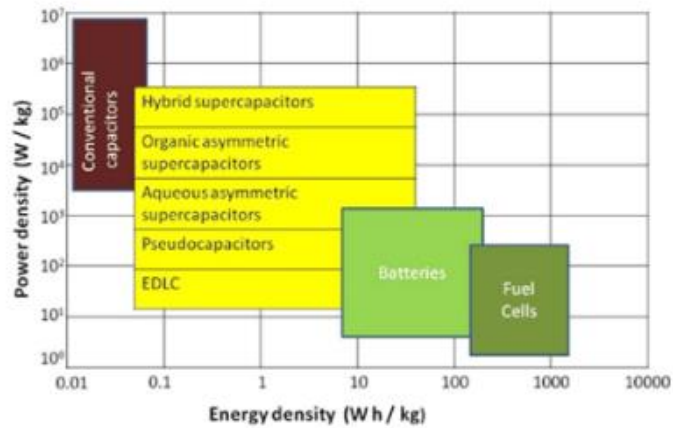


Figure 4: Power and Energy density of energy storage devices (B.K. Kim, 2014)

For supercapacitors, if they are exposed to fire or an ignition source, or if a particular failure mode occurs, the internal components can decompose and emit toxic gases. Due to the fact that a supercapacitor stores energy electrostatically, it can charge and discharge very quickly and with little degradation of efficiency

Characteristics	Super Capacitors (SESS)	Flywheel (FESS)
Efficiency	90-98 %	93-97%
Life Span	5-15 Years	15-20 Years
Life Cycles	100000-1000000	50000-100000
Discharge Time	.002-12	.002-12
Self Discharge Rate (% per Day)	80 to 20%	100 to 90 %
Operating Temperature	-40 to 60 Degrees	-40 to 30 Degrees

Table 2 :Comparison of characteristics of SESS and FESS (Khodaparastan M, 2019)

3.1.3 Flywheel

Flywheel energy storage systems generally consist of a rotating mass, a motor/generator set, bearings, containment, and an electronic converter as illustrated in figure 5. Flywheel energy storages are of two types according to their application. low-speed (rotation speed below 10,000 rpm) and high-speed (for rotation speed above 10,000 rpm). In series hybrid vehicles low speed FESS is used as the ICE output will be less than 10000 rpm which itself is used for power quality enhancement.

The rotating mass of flywheels stores energy mechanically. During charging, the rotating mass is accelerated, and during discharging it is slowed down. Amount of energy stored in the flywheel is directly proportional to the rotating mass inertia and speed of rotation.

$$\text{Energy Stored (E)} = \frac{1}{2} * J(\text{rotational mass}) * \omega^2(\text{Rotational speed of flywheel})$$

Equation 3 : Energy stored in a flywheel

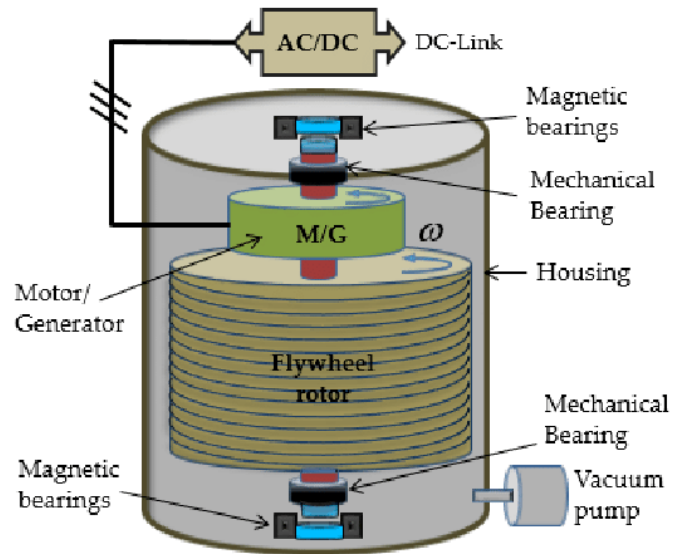


Figure 5 : Schematic diagram of a FESS (Flywheel Energy Storage System) (Amiryar, 2020) (Buchroithner, 2017)

The operation speed of a flywheel is pre-set, limited between the minimum and maximum rotational speed in order to regulate excessive voltage generation and slow the process during discharging (Östergard, 2011). The power of Flywheel energy storage system is as calculated as follows. A flywheel can release a certain amount of power depending on its rating and its power electronic interface

$$P(\text{Power}) = \frac{T(\text{Torque})}{\omega(\text{Rotational speed})}$$

Equation 4 : Power of FESS

	Efficiency level	Life	Discharge speed	Energy density (Wh/kg)
Flywheels	95 %	20 years	0.1–20 minutes	200
SMES	90 %	30–50,000 cycles	1–8 seconds	40–60
Supercapacitors	95 %	1,000,000+ cycles	0.001–3 seconds	1–30

Table 3: Comparison of modern energy storage devices (Ferrell, 2021)

3.2 Generator

An AC generator works under the principle of Faraday's law of electromagnetic induction. EMF is induced across a conductor when it moves through a magnetic field. A generator is connected towards internal combustion engine where mechanical energy is converted into electrical energy by harvesting into 3 phase output, which is later stored in battery or used for the direct drive of electric motor.

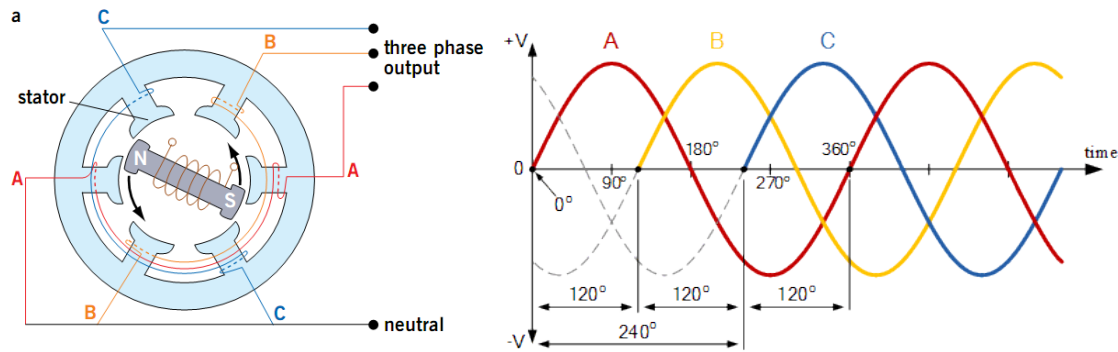


Figure 6: 3 Phase AC generator and its one voltage cycle (toppr, n.d.)

The power transfer of the series hybrid powertrain is achieved by converting the obtained 3phase alternating current to DC current by a 6-diode rectifier controller system which is then transferred to electric motor or battery.

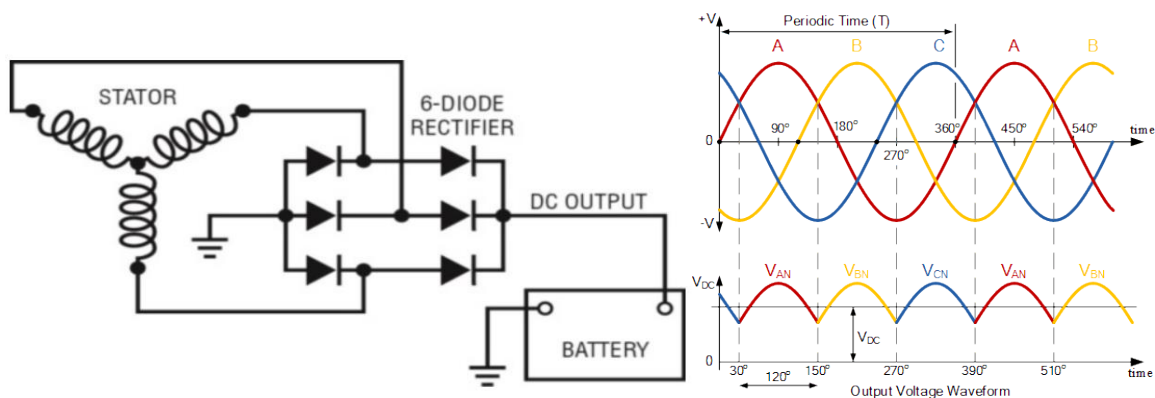


Figure 7: Conversion of AC to DC using controller and output waveform to Battery/Motor

3.3 Electric Motor

It is imperative that advanced motors and generators are developed to meet HEV targets related to efficiency, power density, and cost. The reliability, ruggedness, low maintenance and high efficiency of induction motor make them a highly desirable propulsion system for EVs. In theory, Brushless DC motors can be produced by reversing the stator and rotor of Permanent magnet DC motors with major advantages as higher energy density, compactness and efficiency. (Krishna Veer Singh, 2019)

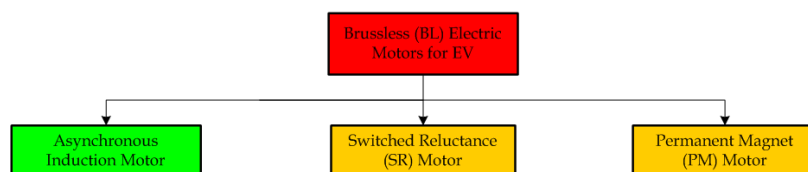
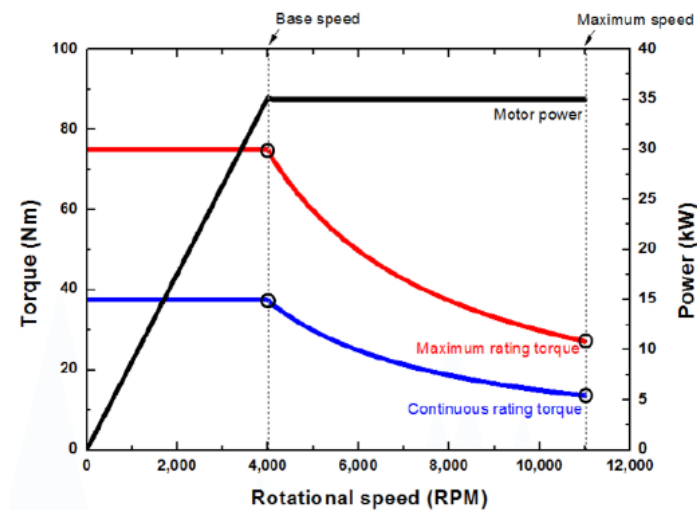


Figure 8: Types of Electric Motors for Electric vehicle powertrain (de Lucena, 2011)

Asynchronous Reluctance Motor	Switched Reluctance Motor	Permanent magnet excited motor	Hybrid field Excited Permanent magnet motor
Low production cost	Very low production cost	Higher efficiency and power Density	Good High-speed performance
Higher robustness	Higher fluctuation in torque	Lower weight	Intrinsically safe
Vector controlled three phase	Noisy during operation	Compact sizing	
High dynamic performance		Poor High speed Performance	
Complex control		Simplified Hardware	

Figure 9 : Comparison of Brushless electric motor types (de Lucena, 2011)



Graph 2 : T-N curve of an in-wheel Motor (Lim D.H, 2014)

3.4 Motor Controller

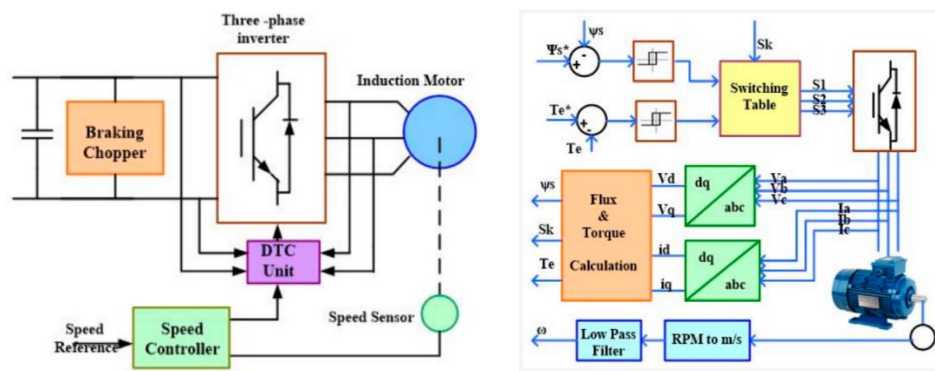


Figure 10 : Schematic diagram of a feedback channel of the electric drive controller (Khodaparastan, 2017)

Automotive applications use power converters to increase controllability and efficiency (S, 2015). The controller evaluates the tractive effort required by the vehicle by evaluating the frictional forces

(Aerodynamic forces, Rolling Resistance and acceleration forces, Gradient Resistive Forces) acting on the vehicle. The required torque and angular speed of the wheel are other parameters used to understand the characteristics of the vehicle and deliver necessary current flow to battery and motor depending upon the driving conditions.

4. Hybrid System Specifications

4.1 Internal Combustion Engine and Generator

An unconventional engine design without a mechanical connection between the crankshaft and differential is a design that allows improved combustion and less friction of sliding components. The design is far more efficient in generating electricity. The electricity generated is stored later on battery or directly drives the motor according to the operating conditions directed by the controller. In this proposed study we will be using the same ICE specifications of renegade dx-10c. Since the powertrain is used for rotation of generator the transmission losses are related to motor control.

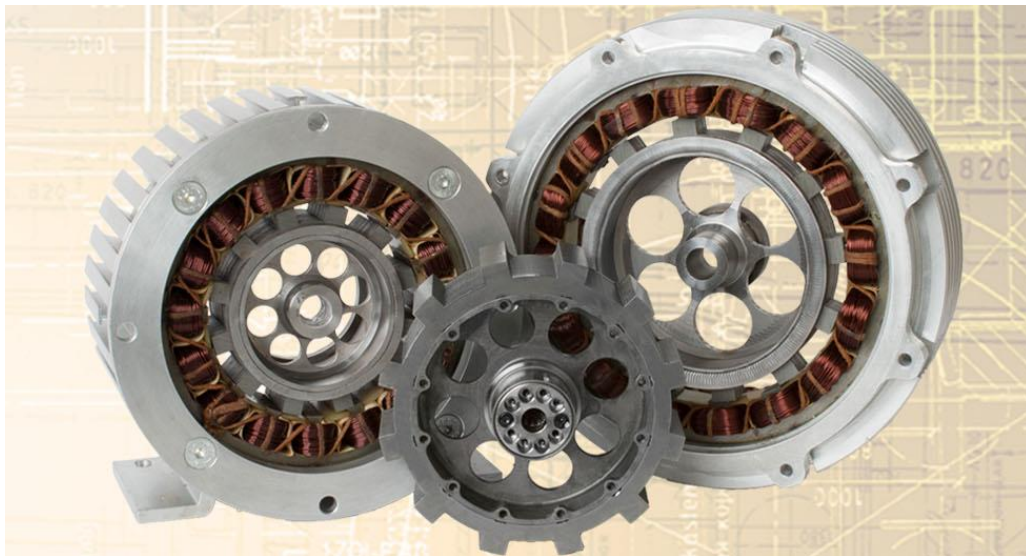


Figure 11 : Stator and rotor of proposed generator for series hybrid powertrain

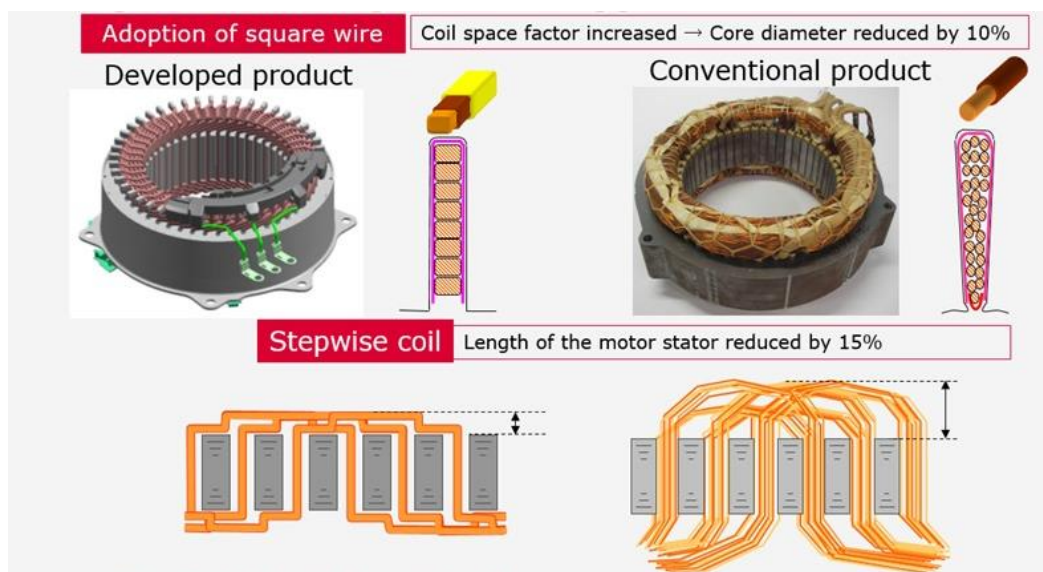


Figure 12 : Features of the Denso generator or series hybrid powertrain

The Denso generator opted for the application have an advanced design in the construction of stator. Stepwise coil arrangement reduces the length of the stator by 15% compared to conventional generators.

4.2 Energy Storage System

According to the conventional energy storage system available for the series hybrid powertrain application lithium-ion battery with following specifications is preferred to use over the supercapacitors and flywheel energy storage system. The 300 Ah battery with 12 V gives a power of 3600 watts per one hour. If the power requested by the motor is 1000 watts, then the battery an power for 3.6 hours with the load applied.

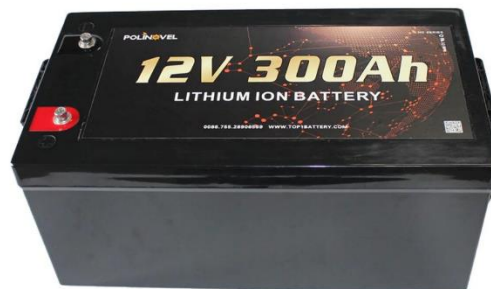


Figure 13 : Battery used for energy storage (Quality Source, 2019)

Battery Specification		
Brand		Polinovel Model HD12300
12V 300AH LiFePO4 Lithium Battery		
Battery Type		LiFePO4
Nominal Voltage		12.8V
Nominal Capacity		300 Ah
Energy		3.8 Kwh
Weight		35 kg
Cycle Life		> 2000 cycles
Add on		Battery Management System

Table 4 : Battery specifications (Quality Source, 2019)

4.4 Electric Motor

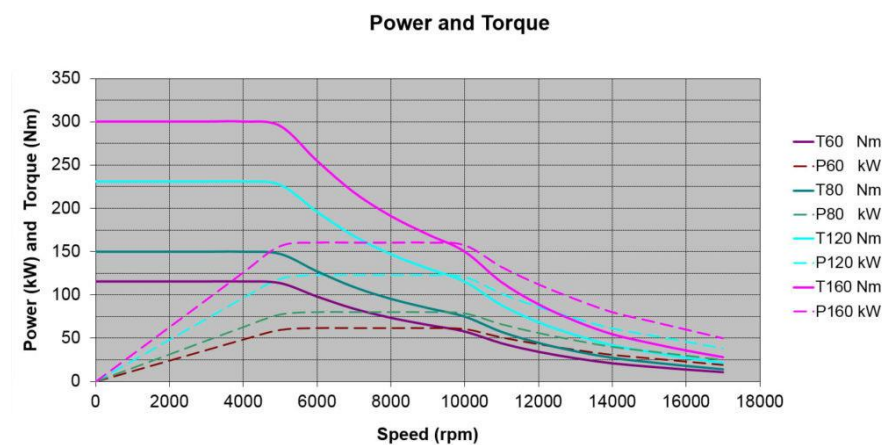
Cascade switched reluctance motors are the opted design of motor for the application as the motor is reliable compact which meets the requirement of the power transmission in multiple terrain conditions. The rated power and torque rating of the motor is discussed on Table 5. The 1:10 scaled performance of the motor gives a performance of 12 kw and 23 Nm which is the required performance of the buggy in the simulated race track. The downside of the motor is that it increases the total weight of the system by 10%. The advantages of the motor for the application are the higher reliability and efficiency with compactness.



Figure 14: Kaskode Switched reluctance motors (Kaskod, 2020)

Power, kW	Rated torque	Stator L (mm)	Weight (kg) rotor & stator	Efficiency (%)
120	230	170	47	96,1

Table 5: Unscaled Specifications of the motor (Kaskod, 2020)



Graph 3 : Power and torque characteristics of the motor (Kaskod, 2020)

4.5 Controller

The Switched Reluctance Sensor less motor Control system navigates the current flow of the developed hybrid system. The operation of the control system is categorised into 4 inputs given to CAN bus according to mode of operation in following table.

Modes of Operation - Series Hybrid Version		Process
1.Start and Low-Mid Range speed		Battery Charging
2.Driving under normal conditions		Not Charging
3.Sudden Acceleration		Battery discharging
4.Deceleration(Downhill)		Battery Charging

Table 6 : Series hybrid operation and energy flow



Figure 15: KASKOD MTRONIX controller

The specifications of the controller are mentioned on following table.

Control Specification		
Brand		KASKOD MTRONIX
Control		Switched Reluctance Sensorless
Max Phase Current		40A
Supply Voltage		48V
Communication		CAN interface
Operation Temperature		_ - 40°C to +85°C _
Dimension		129*115mm
weight		2 kg

Table 7 : Controller specification

4.6 Final Drive

The gearbox transmission of the system is eliminated and is replaced with the belt drive which is connected between output of the motor and wheels. Belt drive have following advantages as they can transmit power through a considerable distance. They are simple, economical and cheaper, durable with less maintenance and can absorb shock and absorb vibration. Operation is smooth and silent.

4.7 Total weight and Costing

Components Used	Brand	Model	Weight(kg)	Cost (Pound)
Battery	Polinovel	HD12300	35	1595
Generator	Denso Hybrid Generator		7	200
Controller	KASKOD MTRONIX	M 400-15K Switched Reluctance Module	2	252
Motor	KASKOD MTRONIX		47	464
Belt Drive	GATES POWERGRIP		0.5	80
			Net Weight (kg)	Costing
			91	2591

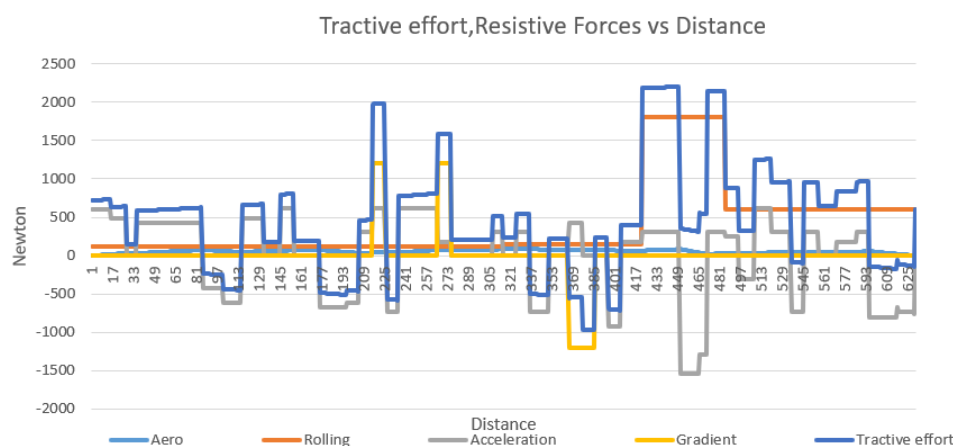
Table 8 : Components used in series powertrain and its costing

The addition of components to series hybrid powertrain increased the net weight of the buggy by 91 kg. The lithium-ion battery pack and motor contribute to the highest weight in the hybrid system. The overall cost of the buggy is increased by 50 % to 2590 pounds which is in turn the investment for lesser emission and higher efficiency.

5. Graphs

5.1 Tractive effort and resistive forces acting on series hybrid powertrain

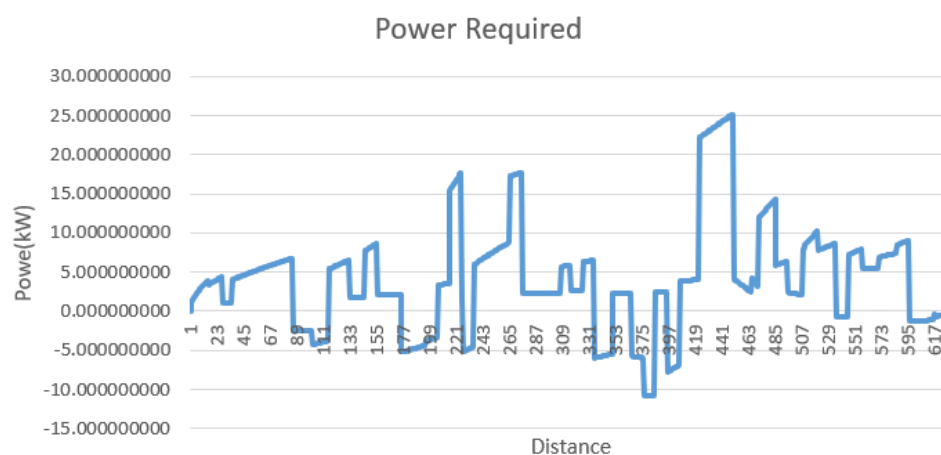
Graph 4 outlines the resistive forces acting on the new series hybrid powertrain. There is significant increase in rolling resistance and gradient resistance forces due to increase in the test mass of the vehicle. The introduction of components requisite more performance from the powertrain.



Graph 4 : Tractive effort, resistive forces vs distance due to increase in mass

5.2 Power required

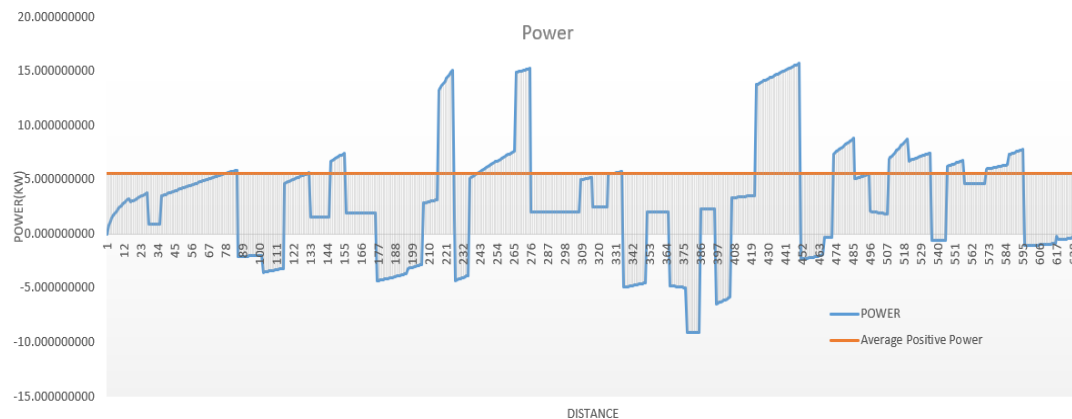
The minimum power required by the powertrain to accelerate the vehicle from steady state at different part of the circuit is in graph 5. The power required increased to that of the standard internal combustion engine due to introduction of new components.



Graph 5 : Power required due to increase in tractive effort and resistive forces in multiple terrain

5.3 Average Positive Power (ICE)

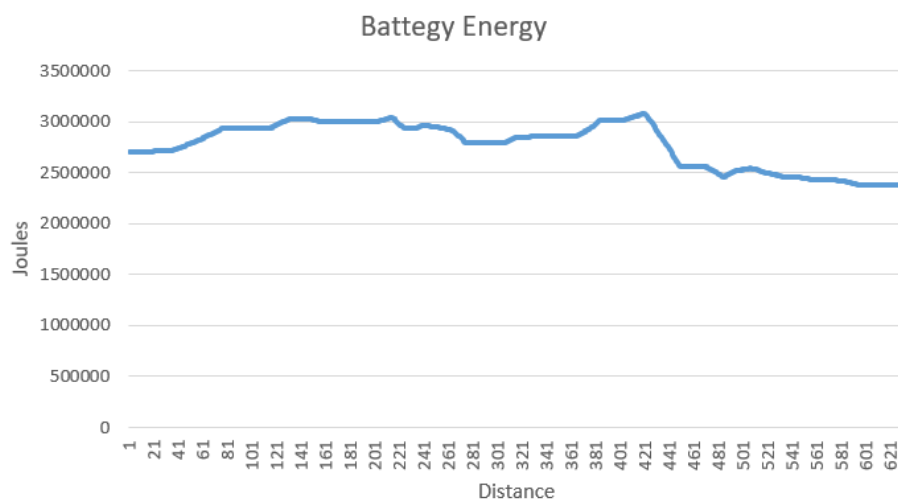
The average positive power of the internal combustion engine is obtained by taking average of positive power as in graph 6, considering the negative power being neglected due to deceleration and braking. The battery discharge and provides current to motor by working with Ice when power more than positive power is required. The Ice restricted to 5.6 kW throughout the lap where battery is charge for power required by the driver is 5.6 kW.



Graph 6 : Average Positive power of Internal combustion engine

5.4 Battery Energy Usage

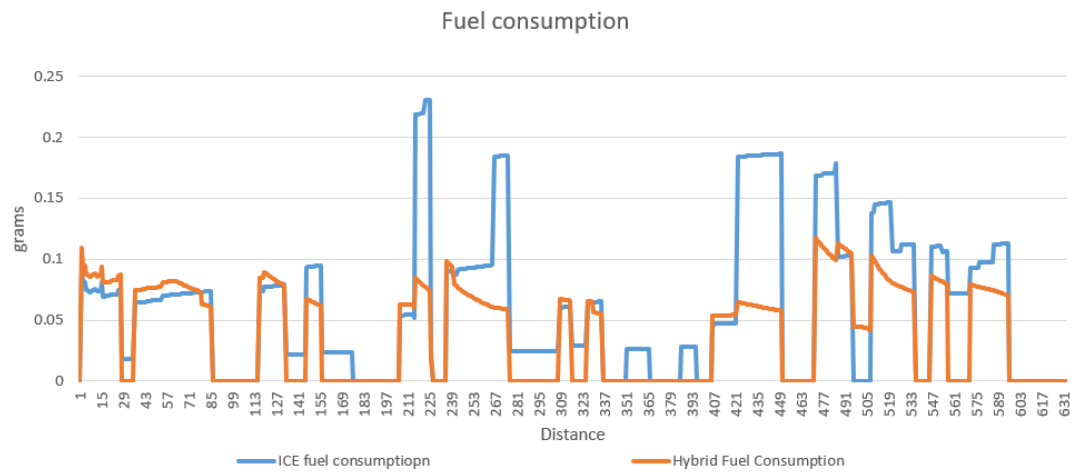
Graph 7 outlines the use of battery throughout the simulated lap where energy is stored and used at different conditions. Battery is charged when the ice is operating under 5.6 kW and drained due to higher performance request and higher tractive effort.



Graph 7: Battery energy usage/storage throughout the lap

5.5 Fuel consumption (ICE vs Series Hybrid)

Graph 8 outlines the comparison of fuel consumption of internal combustion engine and series hybrid powertrain. Introduction of battery energy storage system have a significant improvement in fuel consumption above average positive power.



Graph 8 : Fuel consumption of ICE vs Series Hybrid powertrain

6.Results and Conclusions

In this study, the introduction and application of energy storage solutions, electric motor, generator and controller is navigated and investigated by analysing the fuel efficiency of series hybrid powertrain over the Internal combustion engine on a dual-purpose race course. Examples and importance of different type of energy storage system and other components is presented and compared. The result of the simulation indicates that introduction of hybrid powertrain components increased the mass of the vehicle whereas the fuel efficiency is increased by 69.7 % to that of an Internal combustion engine. The fuel consumption of the internal combustion engine was 23.78 Kmpl (kilometres per litre) whereas the series hybrid powertrain with same internal combustion engine generated a fuel efficiency of 40.36 kmpl throughout the lap.

The Lithium-ion battery was used as energy storage device and the test was started with an assumption of 75% state of charge. After 1 lap with storage and discharge of energy from the battery a final state of charge of 66.2 % is noted with a maximum storage of 84.5% achieved.

This concludes that the proposed series hybrid powertrain is a replacement or highly efficient than that of the Internal combustion engine in terms of energy conservation and efficiency. The new solution is likely to reduce the Carbon dioxide emissions with respect to regulations as the engine consumes less fuel per lap.

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