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Configuration Study of Hybrid Electric Power Pack for Tracked Combat Vehicles

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ABSTRACT

In recent years, there is growing interest in hybridisation of military vehicles due to the features and advantages offered by the technology. Generally, the hybrid electric vehicle (HEV) is propelled by a combination of electric motors and internal combustion engine (ICE). Hybrid electric combat vehicles, when compared with conventional vehicles, have the advantages of improved fuel efficiency and drivability due to optimal operation of ICE, regenerative braking and silent operation capability. Limitations related to key technologies such as compact electric motors/generators, power electronics and energy storage systems that are required to operate under extreme environmental conditions pose challenges to the development of hybrid electric power pack. Technical challenges of HEV technologies considering futuristic applications of combat vehicles is described. The configuration specification of hybrid electric power train architecture suited to deliver high automotive performance and power demands for infantry combat vehicles (ICV) is also discussed.

Keywords: Hybrid electric combat vehicle; Batteries; Electric motor; Integrated starter generator; Power electronics; Controller

1. INTRODUCTION

Hybrid electric vehicle (HEV) is gaining importance due to its reduced fuel consumption. The word 'hybrid' refers to the fact that the vehicle offers a combination of energy sources for propulsion. Internal combustion engine and electric machine are used to propel the vehicle. The purpose of the electric motor/generator and battery is to shift the operation of the ICE closer to its optimum operating point and enable regenerative braking.

1.1 Need for Hybridisation and Potential Benefits

The necessity for implementing HEV technology in military vehicles is different from the civilian automotive application. The potential advantages that can be achieved by implementing HEV technology in military vehicles and the major technical challenges have been described in detail[1]. The resulting improvements in vehicle performance and the severity of the technical challenges depend on vehicle weight, size, configuration, tracked or wheeled, etc. Significant advantages of Hybridisation include increased availability of on-board electric power, improved fuel economy, improved vehicle design and architecture, silent mobility and silent watch capability.

1.2 Technical Challenges in Hybridisation

The important technical challenges for military HEVs are related to key enabling technologies such as

- High torque and power density traction motors
- High operating temperature power electronics
- High energy density storage devices

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2. HEV ARCHITECTURES AND LEVELS OF HYBRIDISATION

HEV can be basically classified as series HEV and parallel HEV depending on the selection of the main propulsion power. However, with the improvements in vehicle technologies, new HEVs are designed using combinations of these two basic concepts and extended the classification of HEVs to four: series, parallel, series-parallel and complex. The hybrids are further classified in terms of level of hybridisation depending upon how balanced the different portions are at providing driving power namely micro, mild, full and plug in hybrid as shown in Table 1. Hence different configurations of hybrid propulsion system can be conceptualised based on the vehicle platform and different propulsion architecture can be worked out depending on the performance requirement, application, complexity, weight and volume availability.

2.1 Series Hybrid System

The mechanical output of internal combustion engine (ICE) is first converted into electrical energy using a generator in the case of series hybrid system. The converted electrical energy either charges the battery or propels the wheels through the motor and transmission. The series hybrid drive trains possess the advantages of mechanical decoupling between the ICE and driven wheels which enables the optimal operation of the ICE in a very narrow region and the torque-speed characteristics of electric motor to avoid multi gear transmission.

Table 1. Levels of hybridisation

	Start/ Stop	Micro hybrid	Mild hybrid	Full hybrid-parallel	Full hybrid-serial	Full electric
Start/stop mode	✓		✓	✓		
Regenerative braking		✓	✓	✓	✓	✓
Electric torque assist			✓	✓		
Electric and ICE mode				✓		
Fully electric mode					✓	✓
Plug-in capability				✓	✓	✓

2.2 Parallel Hybrid System

In a parallel hybrid configuration, both ICE and electric motor are used simultaneously to drive the wheels. Since both the ICE and electric motor are coupled to the drive shaft of the wheels through two clutches, the propulsive power may be provided either by the ICE or motor, alone, or by both the ICE and motor. The electric motor can operate as a generator charging the battery during regenerative braking. The motor can also take power from the ICE, when its output is larger than that required to drive the wheels. The advantages of parallel hybrid drive train are that, both the engine and the electric motor directly supply torques to the driven wheels and no energy form conversion occurs, hence losses are less, compactness, since generator is not required and a traction motor, comparatively of a smaller size, is required[2].

2.3 Series-Parallel System

The features of both the series and parallel HEVs are included in the series-parallel hybrid configuration. The control mechanism in this configuration is complex, since it requires an additional electric machine and a planetary gear.

2.4 Complex Hybrid System

The complex hybrid is similar to the series-parallel hybrid configuration except that the power flow in the electric motor is bidirectional, while the power flow of the generator in series-parallel hybrid is unidirectional. Higher complexity is the major disadvantage of complex hybrid configuration[5].

3. GLOBAL SCENARIO OF MILITARY HEV PROGRAMMES

Development of hybrid propulsion drive for military tracked is very limited and very few manufacturers have attempted for hybrid electric propulsion drive for the military tracked vehicle. RENK, Gmbh, one of the prominent European manufacturers for Tracked vehicle transmission has reconfigured its already existing Hydro mechanical transmission HSWL 106 C and converted it in to hybrid drive and they used the power split /complex hybrid concept for the hybrid drive called the REX transmission. QinetiQ, UK has a hybrid solution for the tracked vehicle which was developed as part of the US FCS program and some prototypes of EX-drive Hybrid transmission Table 2 shows the worldwide scenario of military HEV programs[3].

4. HYBRID POWER PACK TECHNOLOGIES

4.1 Powerpack (Engine and Transmission)

The power pack for the modern tracked vehicle comprises of high power density engine, automatic transmission & cooling system as integrated modular system**.** The size and volume of the power pack dictates the overall vehicle sizing and weight. Hybrid propulsion system provides flexibility in the vehicle

Table 2. Global scenario of military HEV programs

Vehicle name	Country	Type	HEV topology	IC engine power	Motor/generator	Energy storage
CV90 IFV		Tracked		550 hp - 810 hp		
BAE system Hagglund-SEP	Sweden	Wheeled/tracked	Series	2x270 hp		Yes
GDLS-AHED	UK	Wheeled	Series	536 hp	PM motor	Li-ion
GDLS-AGMV	UK	Wheeled	Series		PM motor	Li-ion
DRS technology HE HMMWV	US	Wheeled	Series	190 hp	PM motor	Li-ion
Oshkosh HEMTT A3	US	Wheeled	Series	400 hp - 470 hp	Induction	Ultra-capacitor
FTTSUV	US	Wheeled	Parallel	220 hp		NiMH
Milenworks/Textron LUV	US	Wheeled	Parallel	215 hp		Li-ion
Rheinmetall Gefas HEV	Germany	Wheeled	Series		Induction	
Giat industries DPE 6x6	France	Wheeled	Series		PM motor	NiMH
GDLS-RSTV	UK	Wheeled	Parallel	114 kW		Li-ion
Allison	US	Wheeled civilian	Parallel		Induction motor	NiMH
QinetiQ ground combat vehicle	UK	Tracked	Series		PM motor	

architecture and design. The transmissions for the hybrid power train have a similar configuration as that of cross drive transmission. The transmission driveline configuration plays a key role in harnessing the potential benefits of the hybridisation especially for tracked vehicle application. High speed steering of tracked vehicle poses a serious problem of steer power that is generated due to the high lateral forces required to steer the vehicle at high speeds. This needs to be handled mechanically rather electrically and a proper configuration of the drive line is essential for the same. The engine for hybrid can be modified or selected based on the assessment criteria for converting existing engine to hybrid one. The major parameters considered for assessment are power reduction at high altitude, engine packaging with generator, fuel consumption, electronic engine controls, start/stop function, smoke emission, engine life, multi-fuel capability, noise and engine cost.

4.2 Traction Motor and Integrated Starter Generator

Selection of a traction motor is to be such that it can reduce/eliminate the use of gears/transmission and the associated weight, cost and inefficiencies. The traction motor should provide high torque at low speed during starting and at high speed, but it should be low and sufficient for cruising without or only with a single gear transmission economically together with a simplified cooling structure. Also it reduces the required power capacity of the on board energy storage such as the batteries.

4.2.1 Main Requirements of the HEV Drive Systems

The main requirements of a HEV drive system are: High torque density and power density, high torque output at the start, climbing and low speeds, very wide speed range, extended area of high efficiency, Strong overload capability, security and reliability, motor noise and torque ripple should be suppressed at reasonable costs. The torque and power requirements of electric drive systems are as shown in Fig. 1.

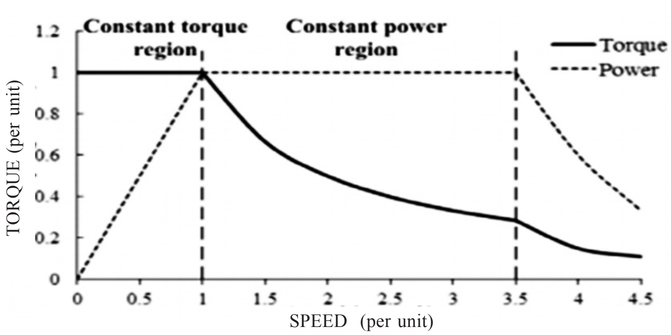

Figure 1. Torque and power requirements of electric drive systems.

4.2.2 Characteristics of Popular Traction Motors

The major motor technologies for HEV traction applications are permanent magnet synchronous motor (PMSM), switched reluctance motor (SRM) and induction motor (IM).

4.2.2.1 Permanent Magnet Synchronous Motors

These motors have high flux density (high torque handling capability). Compared to other electrical machines, the permanent magnet axial flux motors develop high torque and have highest intrinsic peak power efficiency of 96 per cent. These 'pancake' motors have a notably small ratio of axial length to diameter.

4.2.2.2 Switched Reluctance Motor

Hey can inherently operate with extended constant power range having speed ratio of around 6-8, which is highly suitable for vehicle applications. High speed operation causes high mechanical losses due to aerodynamic drag and viscosity losses. With current technology, these motors have high torque ripple. In addition, the high radial forces can create excessive noise levels.

4.2.2.3 Induction Motor

Magnetic Flux weakening enables operation of the motor in the extended speed range with constant power beyond base speed. Unlike PMSM, induction motors have better performance in the constant power mode of operation, lesser cogging, more robust and cheap due to the absence of rare earth magnets. Unlike SRMs, their torque ripple and acoustic noise is comparatively lower.

4.3 Power Electronics

For the inverters and converters used in HEV applications, the required current and voltage ratings of the IGBT (and diodes) are 100 A - 600 A and 600 V - 1200 V. The thermal management of these devices is very crucial and typically requires a dedicated cooling system. Wide band gap (WBG) semiconductors, such as silicon varbide (SiC) with a maximum operating temperature of 500 °C show greater promise for power electronics, but the technology is still developing. The most commonly DC-DC converters used in an HEV are:

4.3.1 Unidirectional Converter

This is required to connect the high-voltage battery to the conventional 24 V DC. The various onboard loads that are supplied to using a unidirectional converter are sensors, controls, utility and safety equipment.

4.3.2 Bidirectional Converter

Bidirectional converters play a major role in traction applications requiring battery charging and regenerative braking. There are two modes of operation of bidirectional converters: the buck and the boost mode of operation. In the boost mode of operation, power flows from a low voltage end such as battery or a super capacitor to a high voltage side. The buck mode of operation occurs usually during regenerative braking, where the power flows back to recharge the batteries through the low voltage bus.

4.3.3 Inverter

The main source of electrical power in a traction application is the battery which is a DC source, while most traction motors require AC supply. The DC output level of the battery is increased or decreased as per the requirement and then converted into AC using an inverter. An inverter is used to change the DC voltage to a symmetric AC voltage of required frequency and magnitude. Output voltage waveforms of practical inverters are usually not purely sinusoidal and contain certain harmonics.

4.4 Energy Storage and Management

Batteries and ultra-capacitors are the main energy storage technologies used in HEV. Batteries are used more extensively for their higher energy density and lower cost. Peak power is the main design parameter for a HEV, whereas the amount of energy stored typically is the most important parameter for an electric vehicle. Designing such a power supply with an appropriate size, weight, cost, cycle and life is a major challenge[4].

4.4.1 Batteries

The factors to be considered for selection of batteries are batteries with large energy capacity and higher power output- considering the thermal, structural and electromagnetic influences on the battery pack–as well as the cells within. It generates heat while charging and discharging. This necessitates a cooling system–whether by air or liquid. Lithium-ion batteries are currently used in HEVs, compared to other energy storage systems, mainly because of their higher specific energy i.e. energy per unit mass. They also have the advantages of good high-temperature performance, low self-discharge, high power-to-weight ratio, and high levels of energy efficiency.

4.4.2 Ultra-capacitors

The ultra-capacitor is characterised by higher specific power, but much lower specific energy compared to batteries. Ultra-capacitors can provide the vehicles additional power, during acceleration. The load levelling effect of the ultra-capacitor helps in reducing the high discharge current from the batteries. This effect also minimises the high charging current while charging the battery during regenerative braking.

4.4.3 Battery Management System

Battery management system (BMS) is a key element in the overall HEV architecture. It is a controller based system which protects the battery from damage. The battery's lifetime and the range of the vehicle in fully electric drive mode can be considerably extended by an intelligent implementation of BMS. Various sub modules of the battery system are identified and placed in various positions in the vehicle. All these modules require supervision of the battery and cell-balancing features. These sub modules are connected through CAN bus to ensure that system delivers as much energy to the application as possible. Built-in temperature management plays an important role in ensuring safety and in extending the system lifetime.

4.5 Hybrid Control System

The control objectives of the hybrid electric vehicles are to meet the power requirement of the vehicle, operation of each component of the vehicle at optimal efficiency, recovering energy through regenerative braking as much as possible and maintenance of the state-of-charge of the battery. The Intelligent Power management Algorithm chooses the appropriate mode of operation based on the tractive effort and drive cycle to ensure that the HEV energy components - Engine, generator, battery and motor operate at their instantaneous equilibrium points to assure maximum efficiency of the entire HEV at each instant of time. The state-of-the-art power management control algorithms available in literature are rule-based control, fuzzy logic/artificial neural networks (ANNs), dynamic programming (deterministic and stochastic formulation), model predictive control, etc.

5. CONFIGURATION SPECIFICATION OF SERIES HYBRID ELECTRIC POWERPACK ARCHITECTURE FOR ICV

5.1 Characteristics, Power Torque Requirements of ICV

The ICV, BMP-II is a 14 t fully tracked, armoured, amphibious, highly mobile combat vehicle with high mobility, fire power and protection of infantry troops operating in the battle field. The vehicle is originally powered by six cylinders, V type (120°) compression ignition high speed, diesel, 4 stroke and water cooled UTD-20 engine with manual transmission and skid steering capability. The engine develops 300 hp at 2600 rev/min and is capable of high temperature operation Table 3.

The ICV equipped with the Hybrid electric power pack needs to have a similar vehicle performance as shown Figure 2. But in order to propose the Motor and generator power for the Hybrid vehicle for the given performance, the vehicle traction power needs to be calculated. In order to calculate the vehicle tractive power, first the vehicle performance needs to be finalised and the following vehicle specification is considered for calculating the vehicle performance requirement.

Table 3. Typical load spectrum of a tracked military vehicle

Gear	Engine load				
	0-10 %	10-50%	50 -80%	80-100%	Total
Neutral + Pivot	21.7	3.1	2	3.4	30.2
F1 and R1	11.3	2.7	3.5	4.2	21.7
F2 and R2	2.1	3.3	12	21.3	38.7
F3	0.2	0.4	1.8	6.4	8.8
F4	0	0	0.1	0.5	0.6
Total	35.3	9.5	19.4	35.8	100

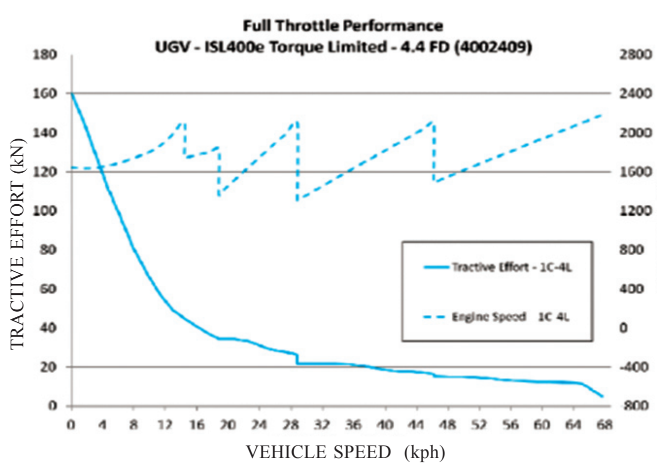

Figure 2. Tractive effort diagram.

5.2 Vehicle Data and Performance Specification for Hybrid Variant

Vehicle Data

Gross vehicle weight : 14 t ± 10%

Vehicle dimensions:

Track width : 300 mm

Length of track contact on ground : 3600 mm

Track centre distance : 2550 mm

Sprocket radius : 0.3125 mm

Vehicle performance requirement

Driving:

Maximum speed on plain road : 65 kmph

Cross country speed maximum : 30 kmph

Maximum speed at 35° gradient : 5 kmph

Acceleration performance : 0 to 32 kmph in 8 s

For the above performance requirement for Hybrid variant, the required propulsive power has been estimated as 185 kW at the sprockets to meet the vehicle performance requirements. Taking drive line efficiency and motor efficiency into account, the traction motor power is estimated to be around 220 kW. With regenerative steering system, that allows power flow from inner sprocket to outer sprocket, the required steering power is the difference between driving and braking power of outer and inner sprockets respectively. The steering motor power is estimated to be around 103kW. The chosen series hybrid electric drive configuration for ICV is shown in Fig. 3. To arrive at a suitable HEV Architecture for the chosen vehicle, various hybrid configurations are explored based on vehicle performance requirement, vehicle load cycle, Power range, Power train operating mode, volume, weight and Environmental conditions, efficiency, drivability, system complexity, weight, functionality and possibility of local sourcing. The hybrid electric drive control architecture for series configuration is as shown in Fig. 4. The traction motor is powered by a battery pack and an engine-generator unit. The engine generator unit drives the traction motor and also charges the batteries. The motor controller controls the traction motor to produce the power required by the vehicle. The hybrid ECU is responsible for the system wide energy management. The amount of torque and power required for the motor is commanded by the hybrid ECU. It also commands the amount and timing of power generation to charge battery. The engine ECU determines the amount of fuel to be injected given the accelerator input and controls various parameters of the engine[5]. Transmission ECU provides the correct gear ratio to control the torques and angular speeds of the EM. The battery management system (BMS) monitors and measures battery temperature and ensures that cooling is adequate. Vehicle performance viz. acceleration, grade-ability and maximum speed is completely determined by the size and characteristics of the traction motor drive.

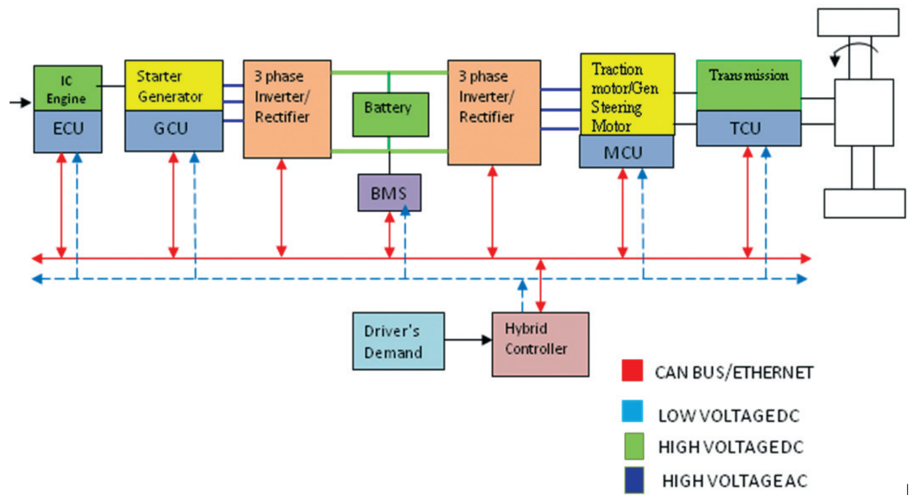

Figure 4. Control system architecture for series HEV.

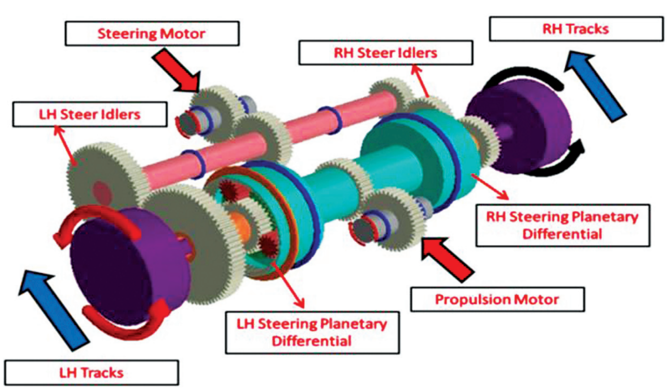

Figure 3. Configuration of series hybrid electric drive for tracked vehicle.

6. CONCLUSIONS

Hybrid electric powerpack technology for military vehicle application offers significant payoffs that cannot be overlooked. The fielding of full hybrid vehicles however depends on the availability of some critical technologies such as silicon carbide power electronics, energy efficient batteries and other high temperature components. While these enabling technologies are being developed and matured, the integrated starter generator is becoming more attractive for applications in combat and tactical vehicles to meet the electric power demand.

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His contribution in the current study is overall guidance during the work and conclusion through results.

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He has contributed towards the estimation of vehicle performance requirement, overall traction power and driveline configuration aspect of the hybrid tracked vehicle.

Mr Hari Viswanath completed MTech (IC Engines) from IITM, Chennai, in 2001 and currently working as Scientist `E’ at Combat Vehicles Research & Development Establishment, Chennai. His research areas include diesel engines for armoured fighting vehicles (AFVs), development of intake port, study of air motion and combustion process of diesel engines, advanced fuel injection system for diesel engines, development of in cylinder diesel engine components like piston, liner and piston rings and tribology studies and diesel hybrid power train for AFVs.
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She has contributed towards the electrical machine topologies and power converters.