

ANALYSIS OF THE PRINCIPLE OF A HYBRID PROPULSION SYSTEM INTEGRATION WITHIN RAILWAY VEHICLES

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Abstract: *Hybrid electric vehicles (HEVs) have attracted a lot of attention due to environmental and efficiency reasons. Typically, an HEV combines two power trains, a conventional power source such as a gasoline engine, a diesel engine, or a fuel cell stack, and an electric drive system (involving a motor and a generator) to produce driving power with a potential of higher fuel economy than conventional vehicles.*

This paper has presented an overview of the principle of hybrid propulsion system integration within railway vehicles. It summarizes continuing efforts in this subject area for the Railway College of Vocational Studies in Belgrade. The principle of hybrid propulsion systems are a key component of hybrid railway vehicles. There are considerable challenges in the selection of the device and the determination of suitable control strategies. The optimization potential of hybrids for particular routes and missions mean that redeployment of vehicles onto alternative routes may lead to suboptimal results, and for example, poor fuel economy and problems with energy storage device management. Practical implementation of hybrid systems introduces new challenges in terms of control and system architecture. The design philosophy for such systems should therefore embrace a modular nature which will be adaptable should sub-systems be upgraded, or different control strategies implemented.

INTRODUCTION

Hybrid vehicles can be classified in many different categories depending on the definition, like; mild hybrid, power hybrid etc. However, there is more prominent classification of the hybrid vehicle that are used today and those are: Series Hybrid Electric Vehicle; Parallel Hybrid Electric Vehicle; and a combination of those, Series-Parallel Hybrid Electric Vehicle [1].

The principle of a hybrid propulsion system is to use more than one power source for vehicle propulsion. Choices of hybrid architecture and system configuration depend on the vehicle duty cycle, and also depend on issues such as whole life cycle costs and maintainability. For systems with two power sources, the prime mover is usually an internal combustion engine, and this is supported by another power source, such as a battery system during periods of high power demand. The path of power from prime mover to the wheels of the vehicle also have many technically feasible options. Railway vehicles have a number of systems in use currently, including diesel electric transmission which is common in many

locomotives, and increasingly a feasible option for multiple units. In principle, only minor propulsion system modifications are required to convert an existing electric transmission system into one which can accommodate electrical energy storage between the traction drives and the prime mover.

Energy savings from a system containing energy storage can be realized through the downsizing and optimization of the prime mover, and through the capture and release of braking energy. Railway operations also have further potential options for energy savings by optimizing the driving style to maximize the use of regenerated energy, and by careful management of the energy storage device.

The selection of an energy storage medium is a complex process, and devices may have fundamentally different characteristics, meaning the resulting final systems differ considerably. Electric storage medium include supercapacitors, batteries, and magnetic field storage. Each of these technologies have different operating constraints and will potentially each have niche applications. Mechanical storage includes compressed storage systems, and flywheel systems.

This paper presents a broad analysis of hybrid railway vehicle configurations as shown in Fig. 1, with emphasis on the energy analysis and consideration of the methods of system optimization and implementation.

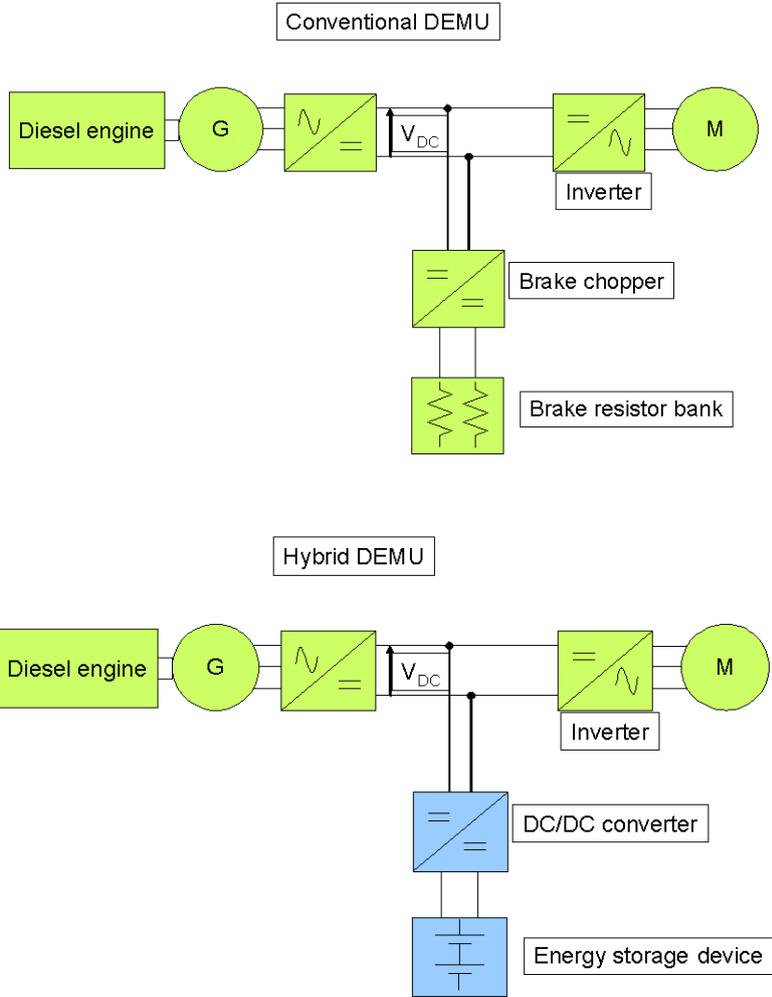


Fig. 1. DEMU (diesel electric multiple unit) ctypical traction drive schematic: upper figure - conventional DEMU system, lower figure - hybrid configuration with energy storage

The modular approach where the super capacitor and the battery and genset unit are of the same physical size could be a solution to some of the issues. In this way if the locomotive is going to be used as a switcher a more suitable design would be with higher battery power/energy rating and lower rating of the genset units. However, if the locomotive is going to perform more as a main line freight locomotive covering larger distance with relatively constant power requirement would require several more genset units and less batteries and super capacitors. A modular approach would also benefit from the use of more standardized combustion engines used e.g. in heavy trucks.

Genset units have already shown good results and are available on the market today. However, these locomotives are primarily used as a switcher units with lot of idling and it is not evident how they would perform as more profiled freight locomotives with more constant power demand.

In this case, within frame for a modular approach, a couple of smaller genset units could be replaced by a bigger one.

Concerning the maximum speed of the freight train there is a desire to increase the speed from typically 120 km/h to 140 km/h. One of the reasons is to harmonize the freight traffic with the passenger traffic which usually operate at higher speeds. This would be of a great benefit to the line operators as they could utilize the track more effectively. Yet another benefit is of course an increase in capacity of the freight traffic, thus making the railway freight more competitive compared to other solutions, especially compared to the roads.

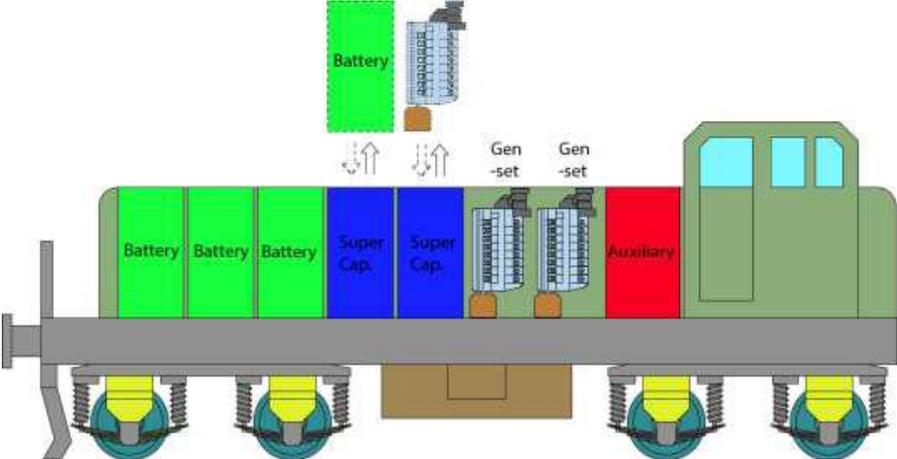


Fig. 2. Schematic view of a locomotive in a modular design approach

VEHICLE SIMULATION AND ENERGY ANALYSIS

The potential of hybrid railway vehicles to save energy over conventional autonomous vehicles is dependent on the duty cycle. The ratio of peak traction power demand to mean traction power demand can influence the relative power capabilities of the prime mover and energy storage device. For instance, for shunting railway operations, the locomotive may require large peak power for a short time, and this is followed by an extended period of idling. This type of duty cycle could permit engine downsizing, and the use of a powerful energy storage device. The prime mover therefore operates continuously at an efficient operating point, and delivers a modest continuous charge to the energy storage device.

Fig. 3 shows a flow chart of hybrid railway vehicles. For more realistic layout, the model of a hybrid railway vehicle is divided into the following sub-systems: electric, internal combustion engine, energy control, planetary gear and vehicle dynamics.

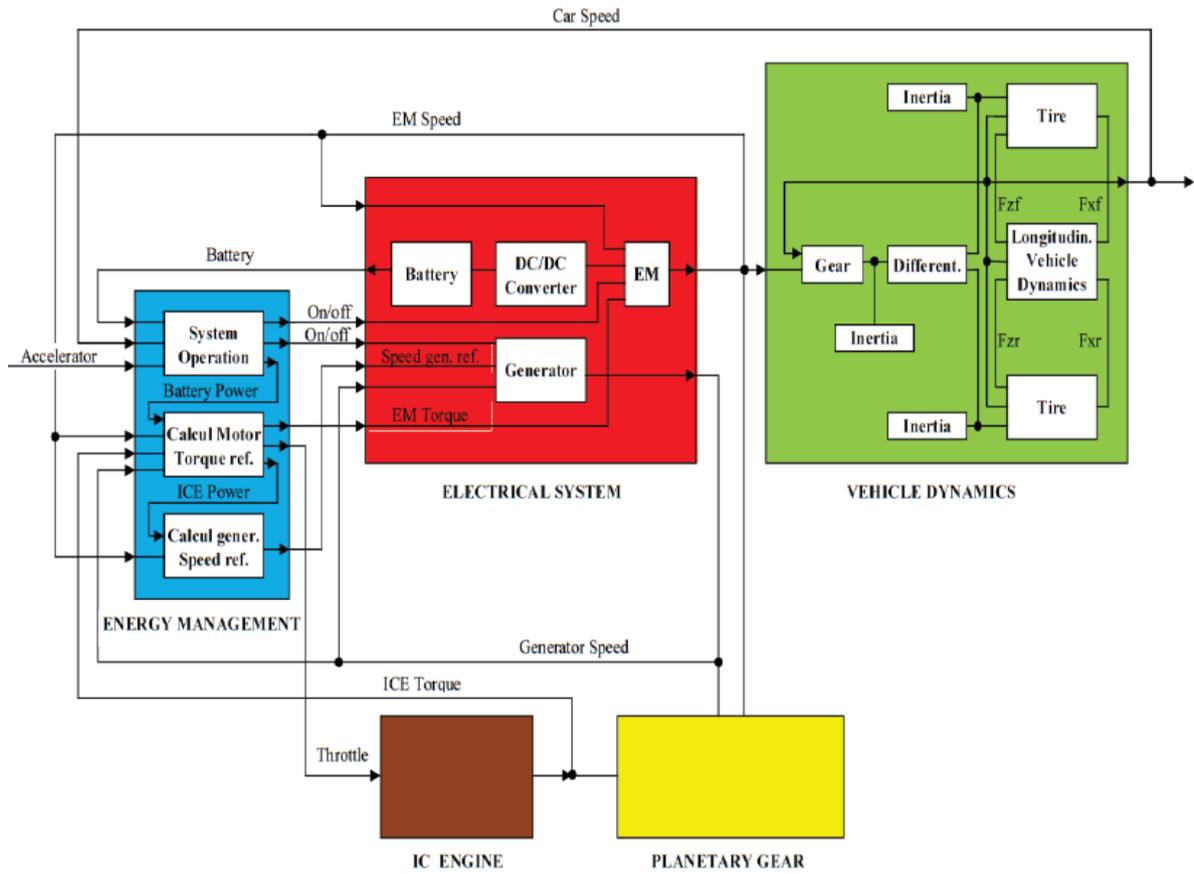


Fig. 3. Flow chart of hybrid railway vehicles

In passenger applications, the duty cycle is also potentially suited to hybridization, but in this case the dominate energy savings do not originate from the engine downsizing (although in certain applications this may be possible) rather the energy savings arise due to the ability to capture braking energy and to redeploy this during the acceleration phases. This potential of this type of energy saving has been investigate by performing numerous vehicle simulations using an established single train vehicle simulator in which the total braking energy is normalized with respect to the traction energy [2, 3].

The results are shown in Fig. 4 for a simple journey, based on a conventional passenger train.

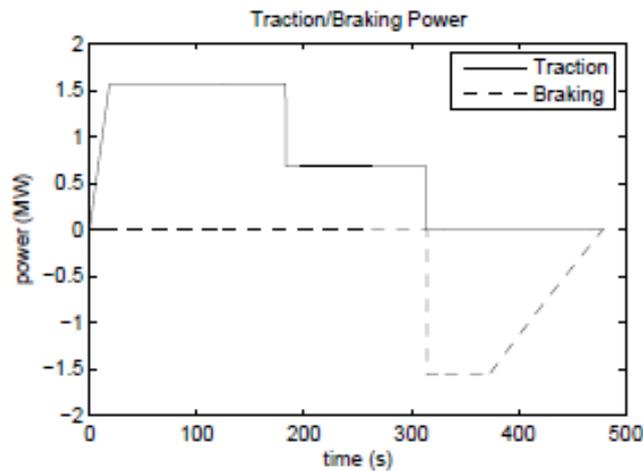


Fig. 4. Example traction and braking power requirements for a simple journey

In Fig. 5 the results of several simulations are plotted. The resultant surface represents the degree to which hybridization can offer energy saving benefits. Consideration of the form of the surface reveals that the benefits of hybridization are greatest for short inter-station journeys, and there is also a second order benefit of having high line speeds for these journeys.

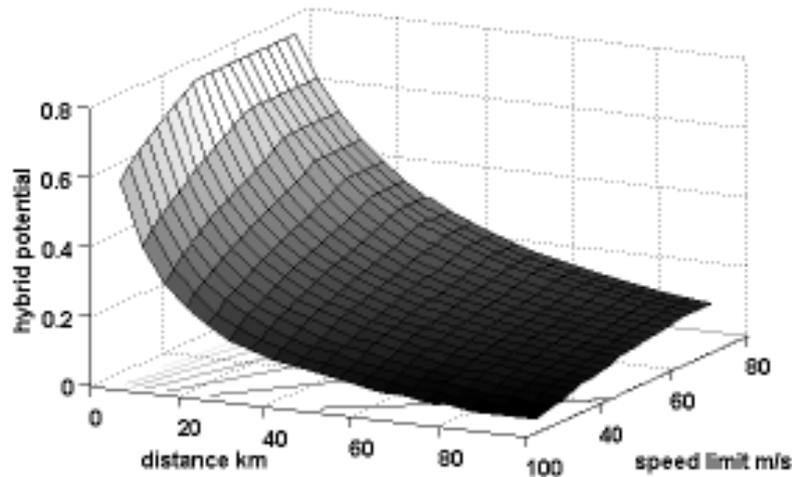


Fig. 5. 3D surface plot of hybridity potential as a function of line speed and inter-station distance.

The results from these simulations illustrate the potential energy savings that may be gained from hybridization given 100% turnaround efficiency of the energy storage device. The properties of real storage devices therefore affect the potential energy savings. Issues such as management of the state of charge (SoC), state of health, charge and discharge rates all have a bearing on the whole system performance. Additionally, the complexity of drive systems will increase and have further maintenance requirements whilst maintaining reliability and availability requirements.

PORTABLE ENERGY STORAGE DEVICES

Various systems of energy storage have been implemented within the railway environment.

One of the most mature chemical storage device is the lead-acid battery. Notwithstanding the improvements in alternative battery technologies, the lead-acid battery has an important position within the high power battery market for both mobile and stationary applications.

In conventional lead-acid batteries, overcharging can lead to corrosion of surrounding metallic parts, and discharge of material from the battery. To address these problems, valve regulated lead acid (VRLA) batteries, otherwise known as sealed lead-acid battery have been developed. The VRLA battery is a kind of ‘recombinant’ battery in which the oxygen evolved at the positive plates will recombine with the hydrogen present on the negative plates, creating water. Therefore water loss is prevented.

The valve on a VRLA battery also provides a safety feature to mitigate against battery failure when the rate of chem

Another kind of battery which is gaining popularity in many sectors is the Lithium-ion battery. The most attractive feature of Li-ion battery for railway systems is that it has a higher energy density than other batteries. Also it can be shaped flexibly and has a lower rate of self-

discharge of 5% per month. Li-ion batteries do not suffer from memory effects, and energy densities exceed 100Whr/kg and 200Whr/L. The operating temperature of these batteries ranges from -20°C to 60°C .

In a lithium ion battery, the ions are not oxidized, but are transported to and from the cathode or anode.

Flywheel energy storage is a suitable method to store energy in mechanical systems. Flywheels in reciprocating engines for example will store a release energy during each rotation of the engine crank shaft which results in a smooth total torque output. Flywheel storage is also suitable for longer term energy storage, and therefore is suited to railway applications. The fundamental limitations of flywheel energy storage is the strength of the flywheel material. Additionally, in order to reduce energy loss from the system, flywheels are usually suspended on magnetic bearings in a vacuum. There are also specific difficulties in charging and discharging the flywheel particularly when high rotational speed flywheels are use.

Ultracapacitors have the same principle with a normal capacitor in which energy is stored in an electric field between two plates carrying a charge, but it has a significantly higher energy density. In comparison to batteries, they have higher cycle life and are able to sustain rapid deep discharge and recharging cycles. Unlike batteries, the terminal voltage of ultracapacitors is only affected by the amount of energy that stored, and they have low internal resistance and are therefore energy efficient.

Commercial ultracapacitors have an energy density range around 0.5 to 10 Wh/kg. For comparison, a conventional lead-acid battery is typically 30 to 40 Wh/kg, modern lithium-ion batteries are about 100Wh/kg. This compares with a net energy density of automotive fuels of over 10,000 Wh/kg.

DRIVE SYSTEM CONFIGURATION AND OPTIMIZATION PROCEDURES

Configuring an optimum a hybrid propulsion system for a particular duty cycle will limit its applicability to significantly different duty cycles, and lead to sub-optimal performance. For example, a hybrid railway vehicle which is optimized for short interstation commuter routes could have a downsized prime mover. Deploying this vehicle on a mission which involves significant continuous operation at high speed could lead to SoC management issues, and possibly would require stationary periods for engine charging of the energy storage device.

The optimization of power management in Hybrid Electric Vehicles can however be realized by applying different control strategies. In work by Salmasi [4], a classification of control strategies for hybrid electric vehicles defined two main categories. These are rule based strategies including fuzzy and deterministic methods, and optimization based strategies including global and real-time approaches. The issue of optimization for hybrid vehicles address both initial component sizing issues, in addition to real time optimization while the vehicle is in operation.

RULE-BASED CONTROL STRATEGIES

In a rule-based system, a set of rules specify how to act on the assertion set which collectively form the 'working memory'. Rule-based systems consist of several sets of if-then statements and are integrated with expert systems [5]. A number of possible strategies may be employed for energy storage device control, these include; thermostat, power follower and a fuzzy rule based control.

The thermostat control strategy, which is comparatively primitive, works by maintaining the SoC of the battery between preset regions with full power prime mover charging when the low SoC level is reached. This strategy may not always be able to meet the

power demand during different operational conditions. However, it is stated that for a series or dual-mode HEV, this control strategy appears to have significant potential benefits, however problematic emissions and thermal-cycle issues may be introduced for some hybrid power unit technologies [6].

In the Power Follower Control Strategy, the rules encode the ‘expert systems’ to operate the primary power source at its most efficient operating points and to follow the power demand simultaneously whilst using battery as an additional power source. Under this rule-based power split strategy, the power requirement will be distributed between the primary power source and battery given the instantaneous conditions, which include the SoC status, power demand from wheels, and other sensory data. The rule based controller determines how much power is needed to drive the wheels and how much is needed to charge or discharge the battery according to the current conditions. To identify the optimal points, the efficiency maps of components need to be determined in advance [7].

Fuzzy logic control strategies are suitable for control of inexact, imprecise and approximate realworld system. This type of strategy is supposed to be much closer in spirit to human thinking than traditional control strategies and presents an advantage in control of nonlinear, multi-domain and time varying plant with multiple uncertainties. It is an extension of conventional rule based control strategies with more complex rules related by the dual concepts of fuzzy implication and the compositional rule of inference [8]. Fuzzy logic rule based control strategies are regarded as more robust and adaptive [9]. Rule based control strategies are suitable for online implementation. However, they are suboptimal and setting up of the rules is subjective.

OPTIMIZATION BASED STRATEGIES

These strategies are generally implemented by applying optimization algorithms. If a driving cycle has been determined, the optimization procedure could be performed statically. The global optimum solution can be found by minimizing the a predefined cost function. The cost functions definitions may include energy consumption, noxious emissions, journey time or any other key output parameter. However, availability of future driving information limits online implementation of these strategies [4].

Dynamic programming is amongst the optimization based strategies. It is not a specific algorithm but a technique. Dynamic programming is based on the theory of Bellman’s principle which asserts that for every sub-problem an optimal solution must contribute to the overall policy to find an overall optimal solution. If the power requirement from the wheels is discretized in time and is distributed between prime mover and the energy storage device, then the incremental solution for the power split must also result in an optimal continuous driving strategy. Dynamic programming suffers from the ‘curse of dimensionality’ since the number of states often grows exponentially with the number of state variables. Optimization based control strategies can provide a basis for designing rules for online implementation or evaluating the quality of other control strategies. Being able to determine global optimality is their main advantage.

PRACTICAL IMPLEMENTATION

In order to successfully implement and validate advanced control strategies, a suitable engine control unit architecture must be chosen. An ideal controller must be robust and reliable enough to control all aspects of the Hybrid Power Unit (HPU) while being flexible enough to accommodate different control strategies without excessive changes to the system hardware and minimal alterations to the control software.

System Architecture

Fig. 6 outlines the basic structure of such a control unit. To ensure a flexible system architecture the Control Strategy Evaluator (CSE) and Hybrid Engine Controller (HEC) have been separated. This approach lends itself to separate development of the CSE and HEC subsystems thus allowing advancements to the system stability and performance to be made with the least amount of impact to the rest of the subsystems.

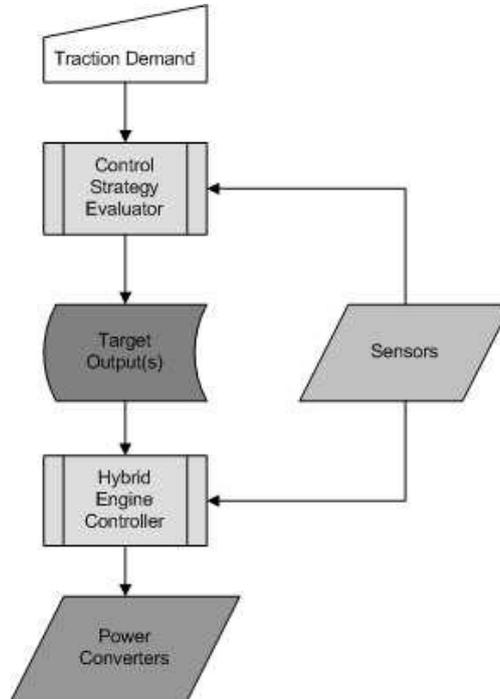


Fig. 6. Control flow diagram for a typical hybrid power unit controller

Control Strategy Evaluator

The underlining control strategy is implemented in this sub-system. The objective of the module is to monitor traction demand, driving strategy, speed, hybrid power unit status and health and compute key control variables based on the implemented energy management strategy for the Hybrid Engine Controller.

Hybrid Engine Controller

The objective of this module is to maintain the smooth running of the hybrid power unit. The primary goals of the controller are to:

- Update control variables determined by the CSE.
- Monitor underlying health of the HPU.
- Ensure the HPU does not exceed preset operating limits.

It should be noted that while the HEC does not make decisions regarding the energy control strategy, it does perform the task of an engine supervisory controller and therefore does have control logic similar to that of the CSE to allow local optimization.

HARDWARE ARCHITECTURE

This section describes a decomposition of the system hardware into the following broad subsystems: Control interface; Engine management system; Communication bus; and Hardware (Fig. 7).

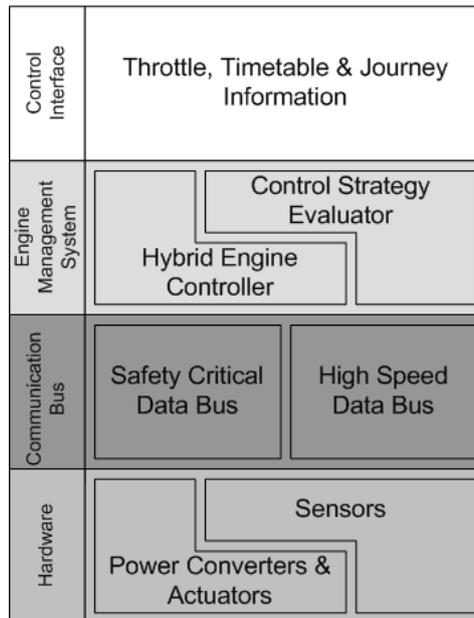


Fig. 7. HPU Engine Management System Hardware architecture

Control Interface

This subsystem primarily consists of the driver controls (throttle and brake control) and provides feedback on vehicle speed and other driving parameters to the driver.

Engine Management System

The subsystem comprises of the CSE and HEC. Linked directly to a communication bus, the Engine Management System will be capable of directly controlling and managing the HPU.

Communication Bus

A communication bus working in this environment will carry two fundamental types of data - primarily safety and time critical hardware control commands. These will typically be power converter and traction inverter output values, brake control and other actuators values. For this purpose the bus will need to efficiently deliver the data to its recipient while having a high level of fault tolerance and error control to ensure the correct control of the overall power unit.

The other will be sensory data. Typically sensor readings from temperature, current and voltage sensors within the HPU. While the quality and validity of the data maybe relatively less important the data bus will need to be capable of relaying sensor readings at relatively high speed to ensure important control decisions can be made as quickly as possible.

Therefore it is envisaged the above requirements will be met by two distinct communication busses within the system:

- A safety critical data bus used to convey all command data
- A high speed data bus used for retrieving sensory data

Hardware

The final subsystem will consist of energy storage devices, power converters, prime mover, sensors and actuators that make up the HPU.

CONCLUSIONS

When it comes to hybridization of a certain vehicle the obvious question is do we need to do it and what are the benefits? What are the challenges and what is the cost? There are several reasons that are pushing for the development, governmental legislations but also the competitiveness of the market just to mention some.

For a freight locomotive a higher efficiency is definitely an issue, as for other types of hybrid electric vehicles, the issue whether the efficiency can be increased or not is strongly related to the load cycle and the way the locomotive is operated.

With the advent of more stringent regulations related to emissions, fuel economy, and global warming, as well as energy resource constraints, electric, hybrid, and fuel-cell vehicles have attracted increasing attention from vehicle constructors, governments, and consumers. Research and development efforts have focused on developing advanced powertrains and efficient energy systems. This paper presents an analysis of the hybrid propulsion system integration within railway vehicles. Autonomous hybrid railway vehicles combine two power sources. The conventional diesel primemover is supplemented with power derived from an on-board energy storage device. The device is discharged during high power demand, and may be recharged through regenerative braking. The energy savings that are achievable through the adoption of such technology are also dependent on the duty cycle. It is shown that for a given vehicle there is a inter-station distance beyond which the benefits become marginal.

The performance of the energy storage device fundamentally affects the whole system performance and careful consideration is required in device selection. The constrained nature of the railway system also presents opportunities for optimization of architectures and control strategies.

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АНАЛИЗ НА ПРИНЦИПА НА ВНЕДРЯВАНЕ НА СИСТЕМА ЗА ХИБРИДНО ЗАДВИЖВАНЕ НА ПРЕВОЗНИТЕ СРЕДСТВА В ЖЕЛЕЗОПЪТНИЯ ТРАНСПОРТ

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***Ключови думи:** превозни средства в железопътния транспорт, хибридни системи за задвижване.*

***Резюме:** Хибридните електрически превозни средства са особено популярни през последните години, тъй като се считат за екологосъобразни и енергийно ефективни. Типично от тяхното наименование, тези превозни средства съчетават в себе си два източника на задвижване на влаковете – конвенционален източник, като бензинов или дизелов двигател или горивна клетка и електрическа система на задвижване (включваща мотор и генератор), която да произвежда двигателна сила с възможност за икономии на гориво при конвенционалните превозни средства.*

Настоящата статия прави преглед на принципа на интегриране на система за хибридно задвижване на превозните средства в железопътния транспорт. Тя представя обобщение на продължителни изследвания в тази област, проведени в Професионалния колеж по железопътен транспорт в Белград. Принципа на системите за хибридно задвижване е ключов компонент на хибридният подвижен състав в жп транспорт. Съществуват редица предизвикателства при избора на подходящо устройство и стратегии за контрол. Оптималното използване на потенциала на хибридните превозни средства по съответните маршрути означава, че тяхното повторно използване по алтернативни направления може да доведе до полу-оптимални резултати, като по-малки икономии на гориво и проблеми със съхранението на енергия. Практическото внедряване на хибридните системи за задвижване създава определени трудности при системната архитектура и техния контрол. Следователно дизайнът на тези системи трябва да има модулен характер, който да се адаптира при надграждане на подсистемите, или съответно да се въвеждат различни стратегии за контрол.