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Modeling, analysis and feasibility study of new drivetrain architectures for off-highway vehicles

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A B S T R A C T

Electrified powertrains/propulsion systems have gained a significant interest in transport industry to develop energy-efficient vehicular systems. In these powertrains, rechargeable energy storage systems (such as High Energy Batteries, Electrochemical Double-Layer Capacitors or High Power Batteries), electric motors, energy management strategies and advanced power electronics converters play an important role in the development of new generations of clean vehicles. Therefore, this paper proposes new drivetrain architectures for Straddle Truck Carriers, as one of off-highway vehicles, which are used in harbors to move containers, in order to improve the Straddle Truck Carriers drivetrain efficiency and to reduce the greenhouse emissions as well as the energy bills. The proposed drivetrains are: (1) series hybrid Straddle Truck Carrier based on a small rechargeable energy storage system (option A), (2) series hybrid based on a reduced internal combustion engine (option B), (3) full electric drivetrain, and (4) new full electric drivetrain based on dynamic wireless-power transfer system.

In this paper, an accurate quasi-static model of the conventional Straddle Truck Carrier drivetrain is developed and described in detail. Then, the proposed drivetrain architectures are designed and modeled using Matlab/Simulink. This article also presents the optimal design of rechargeable energy storage systems that can be utilized in those drivetrains. Based on the rechargeable energy storage system type, a thorough comparative study of new Straddle Truck Carrier drivetrains is described in detail. Finally, the developed model and simulation results have been validated with real measurements of the drivetrain.
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1. Introduction

Owing to rising global concerns about the environmental issues (i.e. climate change, global warming, urban pollution…), fossil fuels depletion, health issues and energy issues, alternative vehicles powertrains have been investigated and compared in the recent years. From an energy point of view, Max Ahman in Ref. [1] has presented a comparative study between different drivetrains, where the energy-efficiency could be doubled by using electric powertrains compared to the conventional vehicles. From the environmental and economic point of views, Palencia et al. (2015) in Ref. [2] developed a dynamic energy-economic model to investigate the impact of using alternative vehicles powertrains on the emissions and energy consumption that can be significantly reduced.

In response to these issues, automobile manufacturers are being forced to shift their attention towards more advanced and electrified energy-efficient powertrains that can include novel topologies (the base ones being the series, parallel and combined topologies) like the hybrid topologies described by Ref. [3]. At this topology level, in Ref. [4], advanced and integrated power converters have been developed and proposed to optimize the powertrain design and performance.

The increased complexity of hybrid and electric vehicles powertrains has led to the development of vehicle models and simulation tools that can help design and evaluate the performance of a specific topology and to develop dedicated power flow management strategies like the ones presented for plug in-hybrid and

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diesel hybrid vehicles in Ref. [5], while Hegazy et al. (2013) proposed new drivetrains for FCEVs (fuel cell hybrid electric vehicles) and their EMCS (energy management control strategies) [6].

With the large improvements given in the electric powertrain in the last decades, extensive research work is currently being conducted to assess the overall benefits of incorporating the latest technologies of RESSs (rechargeable energy-storage systems) (i.e. batteries, supercapacitors and flywheels) into vehicular applications (such as passenger cars, buses and trucks) [7]. The integration of the RESSs into the vehicular powertrains yields several technologies such as HEVs (hybrid electric vehicles), PHEVs (plug-in hybrid electric vehicles) and FEVs (full electric vehicles).

As is clear from the literature, the hybrid topology has a proven potential of reducing the fuel consumption around 30% depending on the vehicle use and the type of the rechargeable energy-storage systems. This is particularly marked in urban driving scenarios [8]. Higher values of fuel economy are reported in applications where the vehicle engine and RESS are designed for an expected driving cycle [7].

It should be point out that the hybridization options not only significantly improve the fuel economy of the vehicular applications, but also reduce the greenhouse emissions in transport sector. Consequently, with future developments, the hybrid and electric technologies have a strong potential to achieve the long-term European goal of 80% CO_2 − reduction by 2050 [10].

The electrification of powertrains is being considered for large urban transit vehicles. Kühne presents the advantages of trolleybuses and electric buses with a special focus in Germany [11], while Zhou et al. (2016) in Ref. [12] presented the advantages of electric buses vs. diesel buses in a life cycle perspective in terms of energy, fossil fuels and CO_2 emissions reduction.

The progressive electrification of the vehicles powertrain, is leading to research on the influence of electric vehicles in the future power grid, which is a current research trend, as shown in Ref. [13] where the possibility to use the vehicles energy storage system to help renewables energies integration is assessed.

Nowadays, emissions and fuel consumption of off-highway vehicles is subject of study, as presented by Van Linden in an agriculture context [14]. In an attempt to increase the energy efficiency and reduce emissions, there is a strong trend to incorporate more hybrid and electric technologies in off-highway vehicles applications (i.e. STCs (straddle truck carriers), lift trucks, military vehicles, etc.). A model of a hybrid military vehicle as one of heavy-duty vehicles is developed to investigate the impact of using energy storage systems in this application [15]. Furthermore, in Ref. [16], a typical powertrain model of a hybrid heavy-duty off-highway vehicle is proposed to study the dynamic performance of the drivetrain. The energy-storage systems are one of the key powertrain components that play a significant role in the development of those hybrid and electric propulsion systems in terms of energy savings, low emissions and integrated design. However, introducing energy storage systems (ESSs) in heavy-duty drivetrains will lead to a high integration level as well as high dynamics, facing major challenges such as dynamic ESS modeling, power-flow control, dynamic performance, energy consumption, stability, drivetrain cost, robustness and efficiency as well as reliability. Moreover, the system complexity makes the design and sizing of the energy sources more challenging. In the literature, a limited work has been conducted on the hybridization technologies in off-highway vehicles, especially the straddle truck carriers (STCs) in order to provide the proper solutions for their challenges. In Ref. [17], Liukkonen et al. (2013) proposed a fuel cell hybrid powertrains for non-road mobile machineries, in particularly straddle carriers in order to enhance the system performance. However, there is a lack of ESSs modeling as well as sizing, control strategy, STC modeling, powertrain design and component sizing approaches. Additional challenge is that the FC powertrain is still very expensive, and there is a lack of safety regulations as well as standards. In Ref. [18], Halme et al. (2010) presented a dual energy-storage power system for heavy duty hybrid vehicles/off-highway vehicles. However, the used models showed a number of limitations due to their dependency on a simplified modeling approach. It means that there is still a lack of ESSs modeling and powertrain modeling as well as optimal design. As is clear from previous studies, the aforementioned challenges of the STC drivetrains have not been fully addressed yet in the literature.

Due to the current advances in energy storage systems, there is a crucial need for investigating the different hybridization options as well as full electric solutions that can be used to develop the future off-highway vehicles, especially STC drivetrains and can achieve further reductions in the fuel consumption as well as emissions. It is important to highlight that the proper selection, accurate models and design of those ESSs and propulsion systems cannot only improve the performance of the STC powertrains, but also can reduce the greenhouse gas emissions as well as a reduction in the capital and operating costs, resulting in minimum TCO (Total Cost of Ownership).

The main contributions of this paper are to critically assess the energy-storage technologies in new STC drivetrains, to develop new STC drivetrain architectures, and to develop accurate ESS models and powertrain models in order to achieve the optimal design and integration as well as accurate energy estimation for those drivetrains. In this paper, an accurate quasi-static model of the CSTC is developed and experimentally validated. Then, to optimize the STC performance, this paper has proposed a series hybrid STC based a small RESS (Option A), a series hybrid STC based a reduced ICE (internal combustion engine) (Option B), full electric STC drivetrain, and new full electric STC based on DWPT (dynamic wireless-power transfer). These new drivetrain architectures are optimally designed and accurately modeled using Matlab/Simulink. Additionally, dedicated ESS sizing methodologies for these drivetrains are described in this paper. The simulation and experimental results are provided to validate the performance of the proposed STC powertrains and their models.

2. Energy storage systems for STC drivetrains

There are many types of energy-storage technologies (i.e. batteries, EDLCs, flywheels, etc.) available at present [9]. Among the different rechargeable energy-storage technologies utilized for transport applications, the most common ones are batteries, EDLCs and flywheels. While the energy is stored in EDLCs by means of charge separation, batteries convert electric energy to chemical energy and flywheels store the energy in kinetic form in a rotatory mass.

Recently, significant development is going on in the battery technologies. Different kinds of batteries are being developed of which some are available commercially, while other types are still in the experimental stage. In the literature, different battery technologies i.e. Lithium-Ion, Ni-Cd, Ni-MH, Lead-Acid, Lithium-polymer, Sodium sulfur, and flow batteries (i.e. Vanadium Redox, (VRB)) are reported in details [20]. One-way to classify the different energy storage technologies, and particularly interesting for portable applications, is to compare their power and energy densities, as shown by the Ragone plot in Fig. 1, where EDLCs (also known as Supercaps or Ultracaps) are positioned against batteries and flywheels. It is observed that EDLCs have a high power and low energy density in comparison to that of Flywheels and batteries [21]. As can be seen from Fig. 1, the difference among flywheels and EDLCS is that flywheels have higher energy density while EDLCs

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