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Review

High voltage electrification of tractor and agricultural machinery – A review

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ABSTRACT

Reduction of both pollutant emissions and fossil fuel dependency is an objective of energy policies worldwide. In many countries, governments promote the use of efficient vehicles like the hybrid electric vehicle. Incorporation of electric drives in tractor and agricultural machinery presents advantages in terms of increased energy efficiency and expanded functionalities. Higher efficiency means reduction in fuel consumption and subsequent decrease in CO_2 emission. New functionalities improve work quality and increase operator comfort. Tractor electrification takes advantage of decoupling loads and drives from the engine, which allows operating the latter at its highest efficiency point. Major advantages of machinery electrification are torque and speed control, noise reduction, and a more flexible design. In this paper, a review of the state-of-the-art of agricultural machinery high voltage electrification is presented.

Contents

1. Introduction

The automotive industry is devoting considerable research efforts to reduce emissions and fossil fuels dependency without sacrificing drivability [1,2]. Likewise, many researchers and manufacturers have worked on reducing the energy consumption of agricultural machines without compromising their functionality and performance [3].

The European Union first introduced mandatory CO_2 standards for new passenger cars in 2009 [4]. This regulation set a 2020-onwards target of 95 g CO_2/km as average emissions for the new car fleet. Emission of NO_x and diesel particulate matter has been regulated since the early 1990 s for passenger cars [5], and since the mid-1990 s for off-road vehicles [6], with emission limits becoming increasingly tighter [7].

To reduce NO_x and particulate matter emissions of diesel engines, manufacturers have developed technologies like selective catalytic reduction, diesel oxidation catalyst, cooled exhaust gas recirculation, and exhaust particulate matter filter [8]. Reitz and Duraisamy [9] stated that innovative in-cylinder combustion strategies and exhaust emission after-treatment systems are required to meet stringent emissions regulations. Du et al. [10] reported on a compound combustion mode featuring lower NO_x

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Nomenclature

Abbreviations

AC	alternating current
A/C	air-conditioning
AEF	Agricultural Industry Electronics Foundation
BEV	battery electric vehicle
CNG	compressed natural gas
CVT	continuously variable transmission
DC	direct current
EDV	electric-drive vehicle
FCV	fuel cell vehicle
HEV	hybrid electric vehicle
HF	hybridization factor
HHV	hybrid hydraulic vehicle
ICE	internal combustion engine
M/G	motor/generator
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PTO	power take-off
PVEV	photovoltaic electric vehicle
RESS	rechargeable energy storage system
SAE	Society of Automotive Engineers
TTW	tank-to-wheel

Symbols

M	torque
P	power
P/W	power/weight (power-to-weight ratio)
r/min	revolutions per minute
1∼	single-phase
3∼	three-phase

and particulate matter emissions than the conventional diesel engine, and higher efficiency than the typical spark-ignition engine. Their system was based on cooperative control of exhaust gas recirculation and combustion phasing of gasoline/diesel blended fuels.

To reduce net CO_2 emission, partial substitution of biodiesel and pure plant oil fuel for fossil diesel-fuel is an appealing option [11,12]. According to Flórez-Orrego et al. [13], the addition of 5–7% v/v of biodiesel to fossil diesel fuel is compulsory in the Brazilian transportation sector since 2012.

Common-rail fuel injection has led to higher efficiency diesel engines [14,15]. More recently, hybrid electric vehicles (HEVs) have gained popularity because they have reduced the fuel consumption and the exhaust gas emission of automobiles [16–18]. Ao et al. [19] proposed a weighted cost function of fuel economy and NO_x emissions for a HEV. Compared with the strategy of maximizing only fuel economy, the combined fuel economy-NO_x optimization strategy yielded a 15.2% reduction in NO_x emission at the cost of increasing fuel consumption by 5.5%. This result is in agreement with Clark [8], who stated that NO_x and particulate matter emissions requirements are not fully aligned with efficiency requirements. Yet analogously Janulevičius et al. [20] reported a NO_x distribution between effective ploughing and headlands maneuvering of 69.4% and 30.6%, respectively; while the CO_2 share was of 84.6% and 15.4%, respectively.

Prior to 1955, automobiles used 6 V batteries [21]. Thereafter, impelled by the ever-increasing demand of electric power, the 12 V battery charged by a 14 V alternator took over.[1] This change was motivated by practical reasons: transmitting high power at low voltage entails high current and subsequent large conductor cross-sectional area. This is expensive, adds weight to the vehicle and occupies more space.

Apart from the conventional safety-extra-low-voltage 12 V direct current (DC) system, HEVs include a higher voltage battery (e.g. 201.6 V in Toyota Prius Hybrid 2010-3rd generation) for vehicle propulsion. Hereinafter the term *high voltage* is used for any wiring system which contains one or more circuits operating above 60 V DC or alternating current (AC) root-mean-squared, as defined by the Society of Automotive Engineers (SAE, [22]). The terms *high voltage battery* and *traction battery* are regarded as synonymous. Analogously, *traction alternator* means a high voltage generator devoted to power propulsion motors.

Demirdöven and Deutch [23] forecasted a swifter pace of adoption for HEV technology compared to fuel cell vehicle (FCV). Since 2004 their previsions have been confirmed, and today most automobile manufacturers offer at least one HEV model in their product palette. Simpson [24], taking the conventional internal combustion engine (ICE)-vehicle as the baseline, reported a fuel economy of 45% for the plug-in hybrid electric vehicle (PHEV), higher than HEV's 30%. Worldwide, there is general agreement in that the following natural step in vehicle electrification is the PHEV.

Walkowicz et al. [25] reported results of 13-month comparative field study between five conventional diesel tractors and five parallel-HEV tractors of the Coca-Cola Refreshments delivery trucks fleet. The five diesels and the five hybrids drove similar cycles with similar kinetic intensity, average speed and stops per mile. The HEV group yielded a 13.7% fuel economy improvement over the diesel group. Barnitt [26] compared in-use performance of hybrid-electric, compressed natural gas (CNG) and diesel buses at New York City Transit. He concluded that second generation hybrids exhibited 43% and 22% better fuel economy than the CNG and diesel buses, respectively. Although on-road vehicles are second to none as to electrification, a bunch of remarkable high voltage applications can be found in the fields of mining, earthmoving, construction, forestry, and agricultural machinery.

In 1974, Terex started marketing their *Titan*, a diesel-electric mining haul dump truck [27]. The term *diesel-electric* is used for those vehicles that have an electrified powertrain but lack high voltage batteries. In 2014 BELAZ started marketing their *75710*, the largest dump truck manufactured to date, with a payload capacity of 450 t. This truck has two *traction alternators*, each one of 1704 kW, and four traction motors, each of 1200 kW. According to Chadwick [28], diesel-electric mining dump trucks outperform their mechanical-drive counterparts, especially on steep grades.

Earthmoving machinery manufacturers have developed some diesel-electric or even hybrid-electric model. Johnson et al. [29] compared emissions of Caterpillar *D7E* diesel-electric bulldozer with its conventional counterpart. They obtained that CO_2 emission of the diesel-electric bulldozer ranged from a 28% lesser to a 2% higher than the conventional, depending on push-distance and push effort. However, NO_x emissions of the diesel-electric were 7–21% higher than the conventional bulldozer. The latter

[1] Some trucks use a 24 V DC electrical system, powered either by a 24 V off-the-shelf battery or by two batteries of 12 V connected in series. On the other side, the possibility of using a 36 V battery charged by a 42 V alternator on luxury automobiles has been a recurrent topic during the last decades.