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Application of Micro Gas Turbine in Range-Extended Electric Vehicles

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ABSTRACT

The increasing number of passenger cars worldwide and the consequent increasing rate of global oil consumption have raised the attention on fuel prices and have caused serious problems to the environment. Nowadays, the demand for reducing fuel consumption and pollutant emissions has paved the way to the development of more efficient power generation systems for the transportation sector. The lower fuel burning and pollutant emissions of hybrid electric vehicles give a strong motivation and encourage further investigations in this field. This research aims to investigate novel configurations, which could achieve further performance benefits for vehicle powertrain. Automakers claim that the employment of a gas turbine operating as range extender in a series hybrid configuration is the most efficiency solution in the coming years. In particular, a Micro Gas Turbine (MGT) can be considered as an alternative to the internal combustion engine (ICE) as a range extender for electric vehicles. The MGT produces less raw exhaust gaseous emissions such as HC and CO and static applications compared to the ICE. In addition, the MGT weight is lower than an equivalent ICE and potentially can reduce the level of CO_2 especially in a vehicle application. This study presents a parametric study of MGT applications for Range-Extended Electric Vehicle (REEV). The main objective is to examine the MGT performance to meet the requirements for a REEV that could become competitive, in terms of fuel consumption and pollutant emissions, to equivalent diesel or gasoline hybrid propulsion units or to conventional diesel vehicle.

1. Introduction

The reduction of fuel consumption of passenger cars is a challenging goal. Many approaches that promise to reduce the fuel consumption and the emissions of passenger cars have been presented so far, and new ideas emerge on a regular basis [1,2]. One technology currently available is the electric vehicle, but their mass production is inhibited by a source of barriers. Range-Extended Electric Vehicle (REEV) is a solution to the limited range and exorbitant cost of Battery Electric Vehicles (BEVs). They operate essentially as a BEV until their batteries become depleted; at this point they utilize an Auxiliary Power Unit (APU) that draws energy from liquid or gaseous fuel and provides electricity, allowing the vehicle to continue operating [3–8]. The APU generally only provides the average power demanded by the vehicle, so it can be downsized compared to the power unit of a conventional vehicle. In addition, because the APU is decoupled from the road load, its operation can be optimized to produce high efficiency and low exhaust emissions [9–14]. Furthermore the main requirements of APU are compactness, lightweight to minimize the vehicle efficiency penalty of carrying dead weight, low noise and vibration, inexpensive and little maintenance. So the Micro Gas Turbines have the potential source to be an alternative APU in the REEVs [15–21].

This work presents an assessment of a novel hybrid configuration comprising a MGT, a battery pack, and a traction electric motor, focusing on its potential contribution to the reduction in fuel burn and pollutant emissions. The main purpose of this study is to evaluate the MGT performance through appropriate software to meet the requirements for a REEV that becomes competitive in

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terms of performance to equivalent diesel or gasoline hybrid propulsion units or to conventional diesel vehicle. The power required for the propulsion of the vehicle is provided by the electric motor. The electric power is stored by the batteries, which are charged by a periodic function of the MGT. The MGT starts up when the battery state of charge becomes lower than 20%, and its function continues until the battery reaches a state of charge of 80%. The performance of the vehicle is investigated using a specific REEV model built in MATLAB® software. The simulations are carried out using a quasi-static approach. The calculated performances, in terms of fuel consumption and pollutant emissions, are compared with those of an equivalent hybrid vehicle having a diesel engine (at the same power of the MGT) as APU, and with the performances of a conventional diesel vehicle. The simulations are carried out also for different fuels supplying the MGT and at different ambient temperatures, to show the MGT's operation limits at high ambient temperatures. The sensitivity of the results to the variation in the vehicle parameters such as mass, and battery type is calculated to identify the conditions under which the application of this hybrid technology offers potential benefits.

2. Modeling approach

2.1. Vehicle and powertrain modeling

A generic in-house vehicle model was developed in this study, based on MATLAB®, to predict the performance characteristics of various powertrain types of passenger vehicles. The theoretical background of this model has been presented in previous studies [1,12,14]. Briefly, the simulated vehicle is discretized on a number of sub-models (components) including vehicle (body), electric motor/generator, battery, gearbox and thermal engine. Proper selection of the components can result in the simulation of a conventional vehicle or a REEV. Inputs of the model are the geometrical characteristics of the components as well as the driving conditions, such as velocity and road slope angle versus time. At each time step, calculations of the vehicle energy flow are performed on both ways, forward and backwards. Initially, calculations are performed at a forward flow from wheel to tank, to calculate the required energy, while backward calculations are performed to ensure that each component would never require higher torque or power than that being able to be delivered by the respective component placed upstream. The comparison between the conventional diesel vehicle and the MGT REEV is performed by utilizing New European Driving Cycle (NEDC).

2.1.1. Powertrain modeling

The first step to model vehicle performance is to calculate the tractive forces of the vehicle for a given velocity and slope of angle driving profile. The forces which are applied on the vehicle are rooted on rolling resistance, aerodynamic drag, road inclination and vehicle's acceleration, when velocity is changed. The sum of rolling resistance force (Eq. (1)), aerodynamic drag force (Eq. (2)), gradeability driving force (Eq. (3)), the acceleration force (Eq. (4)) and the angular acceleration force results the tractive effort at each time step (Eq. (5)) [22–25].

$$F_{rr} = \mu_{rr} \cdot m \cdot g \tag{1}$$

$$F_{ad} = (1/2) \cdot \rho \cdot A \cdot C_d \cdot v^2 \tag{2}$$

$$F_{hc} = m \cdot g \cdot \sin(\psi) \tag{3}$$

$$F_{la} = m \cdot a \tag{4}$$

$$F_{te} = F_{rr} + F_{ad} + F_{hc} + F_{la} + F_{\omega a} \tag{5}$$

The angular acceleration force $F_{\omega a}$ is considered in this study as a 5% increase of the acceleration force F_{la} value. Fig. 1 schematically presents the forces acting on vehicle's motion.

The tractive effort power as well as the required power and angular speed (ω) of the motor or engine are described in equations Eqs. (6)–(8) respectively. Finally, the mean brake effective torque is calculated by Eq. (9):

$$P_{te} = F_{te} \cdot v(t) \tag{6}$$

$$\omega = G \cdot \frac{v(t)}{r} \tag{7}$$

$$P_{mot\_out} = \frac{P_{te}}{\eta_G} \tag{8}$$

$$T = \frac{P_{mot\_out}}{\omega} \tag{9}$$

The electric motor that has been assumed in this study is a DC electric motor with 200 N m maximum torque between 200 and 2500 rpm while its maximum power is 60 kW at 4000 rpm. The efficiency of the DC electric motor in this study has been simply simulated by using Eq. (10), as a function of torque and rotational speed [26,27]. The efficiency of its controller is also assumed in this formula. The coefficients for copper, iron, windage and other constant losses are described in Table 1.

$$\eta_m = \frac{T \cdot \omega}{T \cdot \omega + k_c \cdot T^2 + k_i \cdot \omega + k_w \cdot \omega^3 + C} \tag{10}$$

During acceleration or breaking the electric machine operates either as an electric motor or a generator (in the case of regenerative breaking) respectively. At each case, the required power is described by Eqs. (11) and (12) respectively.

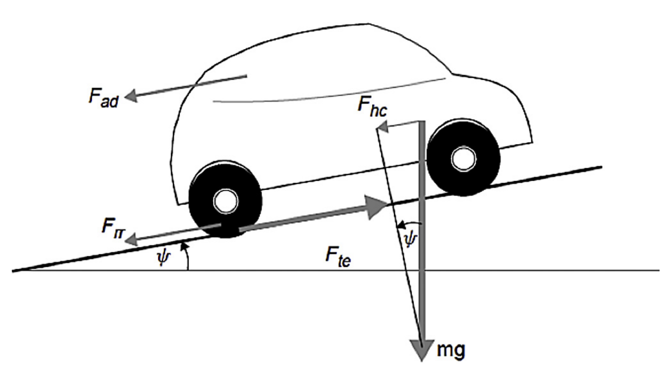

Fig. 1. Schematic representation for uphill driving [26]

Table 1
Coefficients used for electrical power of motor.

Coefficients	Names	Values
k_c	Copper loss coefficient.	0.3
k_i	Iron loss coefficient	0.01
k_w	Windage loss coefficient	$5.0 \cdot 10^{-6}$
C	Constant loss coefficient	600