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A new hybrid pneumatic combustion engine to improve fuel consumption of wind–Diesel power system for non-interconnected areas

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ABSTRACT

This paper presents an evaluation of an optimized Hybrid Pneumatic-Combustion Engine (HPCE) concept that permits reducing fuel consumption for electricity production in non-interconnected remote areas, originally equipped with hybrid Wind–Diesel System (WDS). Up to now, most of the studies on the pneumatic hybridization of Internal Combustion Engines (ICE) have dealt with two-stroke pure pneumatic mode. The few studies that have dealt with hybrid pneumatic-combustion four-stroke mode require adding a supplementary valve to charge compressed air in the combustion chamber. This modification means that a new cylinder head should be fabricated. Moreover, those studies focus on spark ignition engines and are not yet validated for Diesel engines. Present HPCE is capable of making a Diesel engine operate under two-stroke pneumatic motor mode, two-stroke pneumatic pump mode and four-stroke hybrid mode, without needing an additional valve in the combustion chamber. This fact constitutes this study's strength and innovation. The evaluation of the concept is based on ideal thermodynamic cycle modeling. The optimized valve actuation timings for all modes lead to generic maps that are independent of the engine size. The fuel economy is calculated for a known site during a whole year, function of the air storage volume and the wind power penetration rate.

1. Introduction

1.1. Power generation in remote areas

Most of the remote and isolated communities or technical installations (communication relays, meteorological systems, tourist facilities, farms, etc.) which are not connected to national electric distribution grids rely on Diesel engines to generate electricity [1]. Diesel-generated electricity is more expensive in itself than large electric production plants (gas, hydro, nuclear, wind) and, on top of that, should be added the transport and environmental cost associated with this type of energy.

In Canada, approximately 200,000 people live in more than 300 remote communities (Yukon, TNO, Nunavut, islands) and are using Diesel-generated electricity, responsible for the emission of 1.2 million tons of greenhouse gases (GHG) annually [2]. In Quebec province, there are over 14,000 subscribers distributed in about 40 communities not connected to the main grid. Each community constitutes an autonomous network that uses Diesel generators. The total production of Diesel power generating units in Quebec is approximately 300 GW h per year. In the mean time, the exploitation of the Diesel generators is extremely expensive due to the oil price increase and transportation costs. Indeed, as the fuel should be delivered to remote locations, some of them reachable only during summer periods by barge, the cost of electricity produced by Diesel generators reached in 2007 more than 50 cent/kW h in some communities, while the price for selling the electricity is established, as in the rest of Quebec, at approximately 6 cent/kW h [3]. The deficit is spread among all Quebec population as the total consumption of the autonomous grids is far from being negligible. In 2004, the autonomous networks represented 144 MW of installed power, and the consumption was established at 300 GW h. Hydro-Quebec, the provincial utility, estimated at approximately 133 millions CAD$ the annual loss, resulting from the difference between the Diesel electricity production cost and the uniform selling price of electricity [3]. Moreover, the electricity production by the Diesel is ineffective, presents significant environmental risks (spilling), contaminates the local air and largely contributes to GHG emission. In all, we estimate at 140,000 tons annual GHG emission resulting from the use of Diesel generators for the subscribers of the autonomous networks in Quebec. This is equivalent to GHG emitted by 35,000 cars during one year.

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Nomenclature

A	area [m^2]
cp	specific heat at constant pressure [J K^{-1} kg^{-1}]
cv	specific heat at constant volume [J K^{-1} kg^{-1}]
D	displacement [l]
h	specific enthalpy [J kg^{-1}]
H	enthalpy [J]
m	mass [kg]
n	number [–]
N	engine speed [r min^{-1}]
P	pressure [Pa]
Pw	power [kW]
Qa	specific air consumption or compression [kg kW^{-1} h^{-1}]
Qf	specific fuel consumption [g kW^{-1} h^{-1}]
Qm	air consumption rate during motor mode [kg h^{-1}]
Qp	air compression rate during pump mode [kg h^{-1}]
r	gas constant [J K^{-1} kg^{-1}]
T	temperature [K]
Tp	compressed air temperature at the engine's outlet during pump mode [K]
Tq	torque [N m]
Tqs	specific torque [N m/l]
u	specific internal energy [J kg^{-1}]
V	volume [m^3]
ws	wind speed [m s^{-1}]
γ	specific heat ratio [–]
αv	isochoric burned fuel proportion [–]
αp	isobaric burned fuel proportion [–]
Γ	compression ratio [–]

Subscripts

air	refers to air consumed or compressed
Diesel	refers to Diesel engine
fuel	refers to injected fuel
tank	refers to tank condition
int	refers to intake conditions
ref	refers to reference conditions
WindT	refers to Wind turbine
Load	refers to consumption demand

Acronyms

BDC	Bottom Dead Center
CAES	Compressed Air Energy Storage
EVC	Exhaust Valve Close
EVO	Exhaust Valve Open
FIS	Fuel Injection Start
HPCE	Hybrid Pneumatic Combustion Engine
ICE	Internal Combustion Engine
IVC	Intake Valve Close
IVO	Intake Valve Open
TDC	Top Dead Center
WDS	Wind Diesel System
WPPR	Wind Power Penetration Rate

1.2. Hybrid Wind–Diesel systems for remote areas

The Diesel power generating units, while requiring relatively little investment, are generally expensive to exploit and maintain, particularly when are functioning regularly at partial load [4]. The use of Diesel power generators under weak operating factors accelerates wear and increases fuel consumption [5]. Therefore, the use of hybrid systems, which combine renewable sources and Diesel generators, allows reducing the total Diesel consumption, improving the operation cost and environmental benefits.

Among all renewable energies, the wind energy experiences the fastest growing rate, at more than 30% annually for the last 5 years [6,7]. Presently, wind energy offers cost effective solutions for isolated grids when coupled with Diesel generators. The Wind–Diesel System (WDS) represents a technique of generation of electrical energy by using in parallel one or several wind turbines with one or several Diesel groups. This approach is at present used in Nordic communities in Yukon [8], Nunavut [9] and in Alaska [10]. The "penetration rate" is used in reference to the rated capacity of the installed wind turbines compared to the maximum and minimum loads. A strict definition of a "low-penetration" system is one when the maximum rated capacity of the wind component of the system does not exceed the minimum load of the community. In practical terms however, a low-penetration system is one where the wind turbines are sized so as not to interfere with the Diesel generators' ability to set the voltage and frequency on the grid. In effect, the wind-generated electricity is "seen" by the Diesel plant as a negative load to the overall system. It is important to note however that, because such a system needs to be designed for the peak capacity of the wind generator, it will typically operate with an average annual output of 20–35% of its rated power, such that while low-penetration systems will have noticeable fuel and emissions savings they will be fairly minor [11,2]. In many cases it is likely that similar savings could be achieved through energy efficiency upgrades for similar capital costs. A "high-penetration" system without storage [12] is one where the output from the wind generators frequently exceeds the maximum load for extended periods of time (10 min to several hours), such that the Diesel generators can be shut off completely when there is significant wind. The Diesel generators therefore are required only during periods of low winds and/or to meet peak demands. The advantage of such systems are that very significant fuel savings can be achieved reducing import and storage costs, but also will extend the life and servicing frequency of the Diesel generators as they will log less hours. Such systems can also benefit from economies of scale for construction and maintenance, but require much more significant and expensive control systems [13,14] to regulate the grid frequency and voltage while the Diesel generators are turned off. A dispatchable or a "dump" load is required during periods when the power from the wind turbines exceeds the demand in order to maintain system frequency and voltage [10].

A medium-penetration system refers to a system in between the low- and high-penetration configurations. A medium-penetration system will have periods of time when the wind-generated electricity dominates the Diesel-generated electricity and may also be able to meet the system load for brief periods of time (30 s/min). When wind speeds are high and/or the community demand is very low, the Diesel generators may not be required at all, but are not shut off, rather they are left to idle to be able to respond quickly to load demands. A medium-penetration system is potentially subjected to both the benefits and the drawbacks of low- and high-penetration configurations. Beyond a certain penetration, the obligation to maintain idle the Diesel at any time, generally around 25–30% of its nominal output power, forces the system to function at a very inefficient regime. Indeed, for low- and medium-penetration systems, the Diesel consumes, even without load, approximately 50% of the fuel at nominal power output. These systems are easier to implant but their economic and environmental benefits are marginal [11].