Applied Energy 121 (2014) 196–206

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Performance and emissions of a small scale generator powered by a spark ignition engine with adaptive fuel injection control

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HIGHLIGHTS

- Analysis of a cost competitive injection system with adaptive control strategy for stationary spark ignition engines.
- Good running characteristics and power quality for the proposed control system.
- Efficiency and emissions analysis during multi-fuel operation of a small scale generation unit.
- Brief financial analysis of payback periods for the proposed injection system compared to carburetor fueling.

ARTICLE INFO

Article history:
Received 16 July 2013
Received in revised form 29 October 2013
Accepted 25 January 2014
Available online 28 February 2014

Keywords:
Distributed generation
Spark ignition engines
Alternative fuels
Iso-butanol
Natural gas
Regulated emissions

ABSTRACT

Distributed generation of electricity is more and more viewed as a solution for reducing transmission losses and provide better catering for the needs of end users. Small-scale generation is therefore likely to increase its share in the energy sector, as it ensures high degree of flexibility, quick start-up and good performance in combination with intermittent power sources such as solar or wind. One drawback of small scale generators driven by internal combustion engines is, however, low fuel conversion efficiency and high specific emissions compared to medium or high scale power units. A new control strategy for fuel injection and emissions reduction is proposed to mitigate both aspects, while ensuring flexibility in the choice of fuels for a spark ignition engine powered generator. Performance and emissions are compared for carburetor and fuel injection combined with the use of a three way catalytic converter, with the latter solution proving to be more efficient and environmentally friendly. Significant improvements in fuel conversion efficiency and reductions of carbon monoxide and unburned hydrocarbons emissions were obtained by employing the proposed setup and control strategy. Flexibility in the use of different fuel types was evaluated by performing measurements with gasoline, iso-butanol and combined use of alcohol and natural gas. Financial aspects are also covered through a brief analysis of initial capital costs and payback time in order to offer a more detailed view of both fuel systems.

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1. Introduction

Electric power production units are changing their characteristics, as more and more renewable sources are added to the grid. Within this context, when aging capacity needs to be replaced on an extensive scale in order to ensure stability in combination with intermittent wind and solar [1], distributed generation could provide a solution that is easier to implement from the financial perspective, and provide an optimum choice for more environmentally conscious, sustainable and renewable energy based cities [2]. Even in extremely harsh conditions, such systems can provide the required electric energy, as well as heating [3]. Small scale generators can be brought online with reduced capital cost and much quicker than large utilities. One drawback of such power units driven by internal combustion engines is that they usually feature relatively low conversion efficiency and longer downtime. Another issue that needs to be considered is fuel availability. Natural gas is set to increase its share in energy production as more and more shale gas projects develop, providing a cost competitive and low carbon dioxide emissions choice. Therefore, extensive research into distributed generation, grid stability, multi-fuel operation and emissions reduction needs to be performed.

In order to provide a somewhat comprehensive picture of the problems associated with the operation of small scale generators driven by internal combustion engines, a literature review pertaining to fundamental aspects, multi-fuel operation and

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http://dx.doi.org/10.1016/j.apenergy.2014.01.078
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Nomenclature

k	constant (–)
K	smoke opacity (1/m)
t	time (s)
U	voltage (V)
P	power (W)
η	efficiency (–)
$\dot{m}$	mass flow (kg/s)
Subscripts	
inj	injection
e	electric
f	fuel
Abbreviations	
COV	coefficient of variation
LHV	lower heating value
MAP	manifold absolute pressure
PRP	prime power
UEGO	unheated exhaust gas oxygen (sensor)
SI	spark ignition

environmental impact was performed. While the addition of hydrogen to biogas was found to increase efficiency [4] and combined with the use of exhaust gas recirculation, to significantly reduce NO_x emissions [5], large variations in the Wobbe index and stoichiometric air–fuel ratio are not beneficial for most gas fired generators [6]. As the majority of these power units do not feature closed loop control, significant mixture leaning can occur and thus result in very different performance and emissions when the fuel changes its composition. Even severe damage to the engine can occur if abnormal combustion phenomena are present [7]. Running a SI engine powered unit on pure hydrogen was found to deliver improved conversion efficiency [8], mainly due to the ability of running with lean mixtures. This strategy is however limited by increasing NO_x emissions when operating below an excess air ratio of ~2 [9]. Lean operation is possible even with fuels that feature more narrow flammability ranges than hydrogen, by using two stage combustion [10]. One drawback is that such concepts usually feature increased heat losses and require complex combustion chamber geometry. Other combustion development processes such as so called homogenous charge compression ignition can provide increased efficiency and low raw emissions, but are notoriously difficult to control, even with spark assistance [11].

Replacing gasoline with alcohols (ethanol and more recently methanol and butanol) is a fueling strategy intensely researched, as it reduces dependency on finite energy sources and can offer a reduction of green house gas emissions. The use of methanol presents significant advantages compared to gasoline in terms of efficiency and emissions due to specific properties of this fuel [12]. Several studies have investigated the influence of blending butanol with gasoline on raw emissions [13] and experimental combined with simulation investigations revealed that the alcohol containing mix resulted in improved full load performance even at high engine speed [14]. One important issue that needs to be addressed when using alcohol fuels is the control strategy employed for compensating large variations in relative air–fuel ratio such as is the case for so called 'flex-fuel' engines [15]. Essentially, fuel metering is controlled through two main mechanisms, a feed forward component that relies on estimation of air flow into the engine and a feedback loop that is required for precise air–fuel ratio control in order to ensure optimum operation of the exhaust gas treatment system [16]. Lean burn SI engines feature additional complications due to much wider range of air–fuel ratios during normal operation, thus making closed loop control for lean NO_x trap regeneration a good opportunity for ethanol content estimation in the fuel blend [17].

Dual fuel operation is usually employed for diesel power units and is relatively rare for SI engines. Studies pertaining to injection of gasoline and butanol separately, obtained reduced knock tendency and unburned hydrocarbon emissions as compared to using the two fuel types blended [18]. Injection phasing was also found to have an influence on emissions during stoichiometric operation and to a lesser degree when using lean mixtures [19]. Similar results were obtained for the use of gasoline with ethanol and dimethylfuran [20,21]. Given that, as mentioned before, natural gas is likely to increase its share in the energy mix, dual fueling by using combined gaseous and liquid combustibles may be a strategy that can offer great flexibility, with increased performance and reduced emissions [22]. In addition to the reduction in carbon dioxide emissions when using natural gas instead of gasoline, methane enriched biogas can offer close to 'carbon neutral' operation (given that it is obtained from biomass) without major differences in performance as compared to the fossil fuel [23].

Following the literature review pertaining to fundamental aspects of internal combustion engines operation, the use of alcohols and dual fuelling of SI power units, this study investigated the implementation of a cost competitive solution for ensuring increased efficiency and low emissions for a small scale generator powered by a spark ignition (SI) engine. The ability of the proposed injection system to operate within the same power quality range as the original equipment that features carburetor fueling was studied for gasoline, iso-butanol, as well as dual fueling, by using natural gas combined with the four carbon atoms alcohol. Electric efficiency and emissions for all investigated conditions were compared and a brief economic assessment was also performed to provide a more detailed view of issues associated with small scale distributed generation using multi-fuel SI engines.

2. Experimental setup and injection control

The generator used in the experimental trials was powered by a single cylinder SI engine (Fig. 1). Table 1 shows the main engine and generator characteristics. No modifications were made to the original ignition system (that featured fixed spark advance) and mechanical speed governor; the carburetor was kept as well.

Given that cost is an important issue for small scale generators, a simplified injection system was developed in order to reduce the number of sensors and help mitigate this financial aspect. The proposed control system relies on the readings from an absolute manifold pressure sensor for feed-forward control and the use of a narrow band exhaust gas oxygen sensor for closed loop operation. In this way, close to stoichiometric air–fuel mixtures can be delivered to the engine so that high efficiency can be ensured for a three way catalytic converter. One Hall type sensor mounted near the engine's flywheel was used for triggering the injection control and synchronize it to the rotational velocity. Rather than relying on so called 'injection maps' that contain predetermined injection time values for specific engine speed and load settings, the

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