Applied Energy 169 (2016) 748–756

Contents lists available at ScienceDirect

Applied Energy

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

An optimal power management system for a regenerative auxiliary power system for delivery refrigerator trucks

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HIGHLIGHTS

- A new anti-idling system for refrigerator trucks is proposed.
- This system enables regenerative braking.
- An innovative two-level controller is proposed for the power management system.
- A fast dynamic programming technique to find real-time SOC trajectory is proposed.
- In addition to idling elimination, this system reduces fuel consumption.

ARTICLE INFO

Article history:
Received 25 November 2015
Received in revised form 12 February 2016
Accepted 14 February 2016
Available online 27 February 2016

Keywords:
Anti-idling systems
Power management
Refrigerator delivery trucks
A-ECMS
Fast dynamic programming

ABSTRACT

Engine idling of refrigerator trucks during loading and unloading contributes to greenhouse gas emissions due to their increased fuel consumption. This paper proposes a new anti-idling system that uses two sources of power, battery and engine-driven generator, to run the compressor of the refrigeration system. Therefore, idling can be eliminated because the engine is turned OFF and the battery supplies auxiliary power when the vehicle is stopped for loading or unloading. This system also takes advantage of regenerative braking for increased fuel savings. The power management of this system needs to satisfy two requirements: it must minimize fuel consumption in the whole cycle and must ensure that the battery has enough energy for powering the refrigeration system when the engine is OFF. To meet these objectives, a two-level controller is proposed. In the higher level of this controller, a fast dynamic programming technique that utilizes extracted statistical features of drive and duty cycles of a refrigerator truck is used to find suboptimal values of the initial and final SOC of any two consecutive loading/unloading stops. The lower level of the controller employs an adaptive equivalent fuel consumption minimization (A-ECMS) to determine the split ratio of auxiliary power between the generator and battery for each segment with initial and final SOC obtained by the high-level controller. The simulation results confirm that this new system can eliminate idling of refrigerator trucks and reduce their fuel consumption noticeably such that the cost of replacing components is recouped in a short period of time.

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1. Introduction

The refrigeration system of delivery trucks must have either mechanical or electrical power source. In the former option, the power generated by the engine is transmitted to an engine-driven compressor by a belt and pulley mechanism. In the latter option, the electrical power generated by an engine-driven generator is consumed by an electric compressor. One major issue regarding these configurations is a significant increase in idling time. Delivery vehicles have frequent stops for loading or unloading, so the engine is required to run constantly in order to supply the power required by auxiliary devices. Idling of vehicles contributes to greenhouse gas emissions due to their increased fuel consumption. In addition, diesel engines have a very low efficiency during idling (1–11%) [1]. These negative environmental consequences are the reason that anti-idling provisions have existed in Canada and other countries for at least three decades. To decrease or eliminate idling, many strategies and technologies such as automatic shutdown/turn-on systems, truck stop electrification (TSE), and auxiliary power units (APU), have been employed [2]. The main drawback of these technologies is that they are either unable to supply auxiliary power for the refrigeration system when the main engine is OFF, or they utilize a small auxiliary engine to

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http://dx.doi.org/10.1016/j.apenergy.2016.02.078
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constantly power the refrigeration system, and consequently the issue of engine idling is not resolved.

Auxiliary battery powered system (ABPS) is a technology that addresses the aforementioned issues of anti-idling systems. The ABPS utilizes two sources of power for auxiliary devices: electrical power generated by an engine-driven generator and a battery bank (see Fig. 1). The battery can be charged by the generator or an external electrical outlet. The ABPS has many advantages over former technologies. In this system, idling can be eliminated because the engine is turned OFF and the battery supplies auxiliary power when the vehicle is stopped for loading or unloading. Furthermore, unlike the engine-driven compressors, the compressor in the ABPS can operate at a constant speed (or desired variable speed independent from engine speed), thereby improving its performance and efficiency.

This study proposes a new system to improve the performance of the current ABPS. This system enables regenerative braking, which lowers fuel consumption and reduces wear on friction braking components. We call it the Regenerative Auxiliary Power System (RAPS). Although the main objective of all the current ABPS is to eliminate idling, the RAPS, in addition to this goal, reduces fuel consumption by utilizing a well-designed power management system. Therefore, the cost of energy can be noticeably reduced, and consequently, the cost of replacing old components is recouped in a short period of time.

RAPS can supply auxiliary power using only the battery, only the generator, or combination of these two sources. In the battery only or completely electric mode, all demanded auxiliary power is provided by the battery, and no auxiliary load is added to the engine by the generator. The system can operate in this mode until SOC of the battery reaches a predefined minimum allowable value. In the generator only mode, the auxiliary power is supplied by the engine-driven generator. In addition, extra power can be generated by the generator to charge the battery as required. Finally, in the combined mode, both battery and generator provide the demanded auxiliary power. The ideal scenario is to use the battery for the whole trip where it can be charged by the electrical grid, but the problem is that the electric mode cannot sustain most trips. To resolve this issue, one solution is to deplete the battery (charge-depleting) until it reaches the minimum allowable SOC and then to maintain the SOC at a constant level (charge-sustaining) until the end of trip. It has been shown that the results of this method

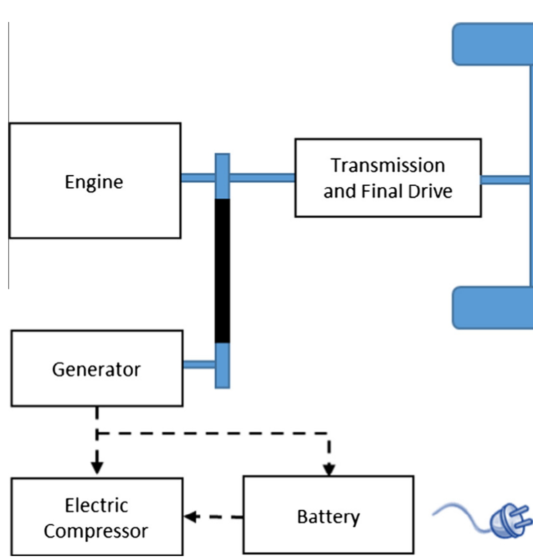

Fig. 1. Powertrain configuration of a refrigerator truck with the auxiliary battery powered system.

for plug-in hybrid electric vehicles (PHEVs) are far from the optimal solution in terms of fuel economy [3]. As a result, the power management system of RAPS should determine the split of auxiliary power demand between the generator and battery during the whole trip in order to minimize fuel consumption. In the literature, no study focuses on the power management system of the ABPS; however, reviewing control strategies of PHEVs, which have similar concept to ABPS, will gives us good insight into designing an optimal power management system.

The power management system for PHEVs can be categorized into two main groups: rule based and optimization based. In the rule-based control strategy, predefined rules are set to operate the vehicle at its highest efficiency point without any prior information about the trip. These control strategies can be classified into deterministic [4] and fuzzy [5] rule-based methods. Although rule-based control strategies are easy to implement, the resulting performance can be far from optimal as they do not use prior information to optimize the whole cycle.

Optimization-based control strategies find the optimal split ratio between sources of power in order to minimize a cost function, which is usually the cost function of fuel consumption. This type of control strategy can be further categorized into two groups: global optimization and real-time optimization. Global optimization is a non-causal method since it needs complete knowledge of future driving cycles to find the minimum fuel consumption. This method is also highly computationally demanding, and the processing power it requires cannot be facilitated by standard vehicles' on-board processors. Therefore, it cannot be implemented as a real-time controller, but it can be used to design rules for rule-based control strategies [6], and it is a good benchmark to evaluate the performance of other controllers. The most popular technique to obtain a global optimal solution is dynamic programming (DP) [7,8]. To address the problems associated with real-time implementation of DP, many research studies have been conducted recently. Gong et al. proposed a driving cycle modeling using traffic information in order to implement a DP-based power management scheme for PHEVs [9]. Also, the authors in another study proposed a two-scale dynamic programing to reduce the computational effort of this technique [10].

On the other hand, real-time optimization is a casual method as it only uses past and current information to minimize cost function. Model Predictive Control (MPC) and Equivalent Fuel Consumption Minimization Strategy (ECMS) are two widely used real-time optimization control schemes for the power management of PHEVs. MPC is a model-based method with the advantage of solving nonlinear constrained optimization problems which is performed over a moving finite horizon. Taghavipour et al. showed the effectiveness of this method on minimizing fuel consumption of PHEVs [11]. ECMS is a method that seeks to find a real-time sub-optimal solution for the power management system of hybrid vehicles [12]. In this method, the instantaneous sum of actual fuel consumption and equivalent fuel consumption of the power used by the battery is minimized. To find the equivalent fuel consumption of the electrical energy which is stored in or drawn from the battery, an equivalent factor is required. If a big value is selected for the equivalent factor, the discharging battery is penalized and more fuel is consumed. However, a small equivalent factor leads to more usage of electrical energy, thereby decreasing battery SOC [13,14]. Therefore, this parameter should be tuned such that the SOC reaches the minimum allowable value at the end of a trip. To achieve this goal, a-priori knowledge of the driving cycle is required, and the equivalent factor can be determined offline by an iterative search or optimization method. To address this problem and implement this strategy online, Adaptive Equivalent Fuel Consumption Strategy (A-ECMS), which updates the equivalent factor online was proposed [15].

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