Energy 67 (2014) 422–434

Contents lists available at ScienceDirect

Energy

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

Design strategy for improving the energy efficiency in series hydraulic/electric synergy system

R. Ramakrishnan, Somashekhar S. Hiremath*, M. Singaperumal

Precision Engineering and Instrumentation Laboratory, Indian Institute of Technology Madras, Chennai 600036, India

ARTICLE INFO

Article history:
Received 29 August 2013
Received in revised form
13 December 2013
Accepted 16 January 2014
Available online 16 February 2014

Keywords:
Series hydraulic/electric synergy system
Multi-objective design optimization
Energy efficiency
Hydro-pneumatic accumulator
Hydraulic regeneration efficiency

ABSTRACT

Battery is a vital subsystem in an electric vehicle with regenerative braking system. The energy efficiency of an electric vehicle is improved by storing the regenerated energy in an electric battery, during braking, and reusing it during subsequent acceleration. Battery possesses a relatively poor power density and slow charging of regenerated energy, when compared to hydro-pneumatic accumulators. A series hydraulic/electric synergy system – an energy efficient mechatronics system is proposed to overcome the drawbacks in the conventional electric vehicle with regenerative braking. Even though, electric battery provides higher energy density than the accumulator system, optimal sizing of the hydro-pneumatic accumulator and other process parameters in the system to provide better energy density and efficiency. However, a trade-off prevails between the system energy delivered and energy consumed. This gives rise to a multiple objective problem. The proposed multi-objective design optimization procedure based on an evolutionary strategy algorithm maximizes the energy efficiency of the system. The system simulation results after optimization show that, the optimal system parameters increase the energy efficiency by 3% and hydraulic regeneration efficiency by 17.3%. The suggested design methodology provides a basis for the design of a series hydraulic/electric synergy system as energy efficient and zero emission system.

1. Introduction

The ever-growing energy demand, high cost/shortage of crude oil and increasing pollution have created an alarm within the automotive industries to develop an energy saving, efficient and environmentally friendly power transmission system in vehicles. In recent years, electric vehicles play a major role in attaining sustainability in transportation sector. It has received renewed consideration as energy efficient and environmentally acceptable alternative for internal combustion engines. The main reasons, which made the world to look at these vehicles as an alternative technology, are advanced battery technologies with very high energy density; growing demand and shortage of imported crude oil, and concern over the environmental pollution and air quality in urban environment [1,2].

The strength of an electric vehicle is the high energy density of electric batteries, which have large storage capacity and scalability to passenger cars [3]. The new feature of advanced battery technology (lithium-ion battery) delivers long service life and environmental friendliness [4]. However, they do have their own limitations like poor regeneration energy saving due to lower rates of charging the energy into the battery, high maintenance cost of batteries and non-scalability to heavy vehicles due to enormous power requirements [5]. In spite of this, the energy efficiency of an electric battery operated vehicle is drastically limited. One such technology, which can significantly increase the energy efficiency of an electric vehicle, is a SHESS (Series Hydraulic/Electric Synergy System) that has two distinct energy sources – primary and secondary. Typically, one source is an energy storage unit (hydro-pneumatic accumulator), and the other is conversion of one form of energy in to another form (electric motor) [6,7]. Hydro-pneumatic accumulator has higher power density, which can surmount the drawback of a battery [8]. Hydraulic/electric synergy system discussed in an earlier research [9] uses three distinct power sources – gasoline engine, battery, and hydro-pneumatic accumulator for driving the vehicle. The usage of multiple energy storage sources instead of a single energy storage source in a vehicle can effectively satisfy the synergy drive vehicle's requirements for both energy density and power density. However, this system will reduce the reliability, energy efficiency, and increase initial/maintenance cost of the system due to several reasons like energy losses at each source, drivability, and controllability issues in a vehicle.

* Corresponding author. MSB 310, Precision Engineering and Instrumentation Laboratory, IIT Madras, Chennai 600036, Tamilnadu, India.
E-mail address: somashekhar@iitm.ac.in (S.S. Hiremath).

0360-5442/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2014.01.057

Series hydraulic/electric synergy technology is the current potential solution to overcome the limitations in electric vehicles. In an SHESS, the regenerated hydraulic energy is saved as potential energy by compressing nitrogen gas in hydro-pneumatic accumulators. This permits creation of a relatively higher power density storage system. Moreover, high charging rate of the regenerated energy makes the SHESS a more energy efficient system than the electric and electric hybrid system [10,11]. In this paper, a novel design procedure for SHESS in a passenger car is proposed.

An SHESS is a multi-domain, non-linear mechatronics system, which consists of a hydrostatic transmission drive system, an electric motor, an electric battery, hydro-pneumatic accumulator and a hydraulic brake energy recovery sub-system [12]. This system does not require a conventional drive shaft, which facilitates better engine management, energy efficiency during stop, and go driving, greater energy savings and zero emission unlike its parallel counterparts powered by gasoline engines [13,14]. Authors, in their earlier work [15] have presented a parametric simulation study of SHESS. The study indicated that the change in several system parameters such as pre-charge pressure of accumulator, nominal size of the accumulator, volumetric displacement of master hydraulic pump, hydraulic regeneration pump and hydraulic traction motor, combinedly has an effect on system energy efficiency and hydraulic regeneration efficiency. The selection of these parameters for an SHESS is a complex process. Moreover, the sizing or designing the key components in a passenger car is more cumbersome process when compared to a heavy vehicle because of its space constraint, mass and fuel efficiency. Hence, a structural procedure has to be adopted in order to decide the system parameters. In such synergy systems, a conflict exists between the input energy supplied and the output energy delivered. This trade-off situation, losing one aspect in turn for gaining another aspect, gives rise to a conflicting multiple objective function such as maximizing regeneration energy, maximizing vehicle driving energy and minimizing energy consumption [16]. Essentially, a multiple objective optimization procedure is required to optimize these system parameters. A multi-objective design optimization based on MMES (Multi-membered Multi-criteria Evolutionary Strategy) algorithm is presented. This methodology has not been attempted for an SHESS in a passenger car. With maximum energy efficiency as a convergence criterion for multiple objectives, this procedure decides the component sizes and process parameters of the system.

2. Configuration of the series hydraulic/electric synergy system (SHESS)

Fig. 1 shows the configuration of the proposed SHESS. The subsystems such as an electric motor powered by a battery, a MHP (Master Hydraulic Pump), a hydraulic TM (Traction Motor), a variable displacement hydraulic RP (Regeneration Pump) and a hydro-pneumatic accumulator are arranged in a series configuration. The PM (Prime Mover) or electric motor is mechanically coupled to an MHP, which converts the mechanical energy into hydraulic energy. According to the operating mode and SoC (State of Charge) of hydro-pneumatic accumulator, the hydraulic TM is driven by the hydraulic energy from the master hydraulic pump as well as hydro-pneumatic accumulator. The hydraulic regeneration pump and hydraulic traction motor are coupled through a GB (Gear-Box) to the wheel via a differential.

Fig. 2 shows the control block diagram of the SHESS. The virtual driver in the control logic generates acceleration and deceleration signals based on current vehicle speed and the reference driving cycle. These signals are sent as inputs to the fuzzy logic control algorithm. The controller decides the power source (prime mover or hydro-pneumatic accumulator) based on SoC of hydro-pneumatic accumulator. The working principle of the system is divided into three operating modes namely acceleration mode, cruising mode and braking mode in a vehicle.

When the vehicle is in an acceleration mode, the power requirement or demand by the vehicle is large. To provide for this high demand, the power is delivered by combining the power from both the prime-mover and the hydro-pneumatic accumulator. The acceleration signal generated by the fuzzy controller switches on the input power to drive the prime-mover and a signal to operate the PFCV (Proportional Flow Control Valve) to control the discharge of hydraulic energy from the hydro-pneumatic accumulator. PFCV controls the accumulator dynamics. The combined flow from the master hydraulic pump ($q_{\rm m}$) and the flow from the accumulator ($q_{\rm d}$) drives the traction hydraulic motor, providing for the required power during acceleration. In the cruising mode, the power demand is constant and hence, the controller sends a signal to run the master hydraulic pump driven by the prime-mover to maintain a constant speed of the vehicle.

During the braking mode of the vehicle, an energy recovery method called hydraulic regenerative braking is adopted to recover

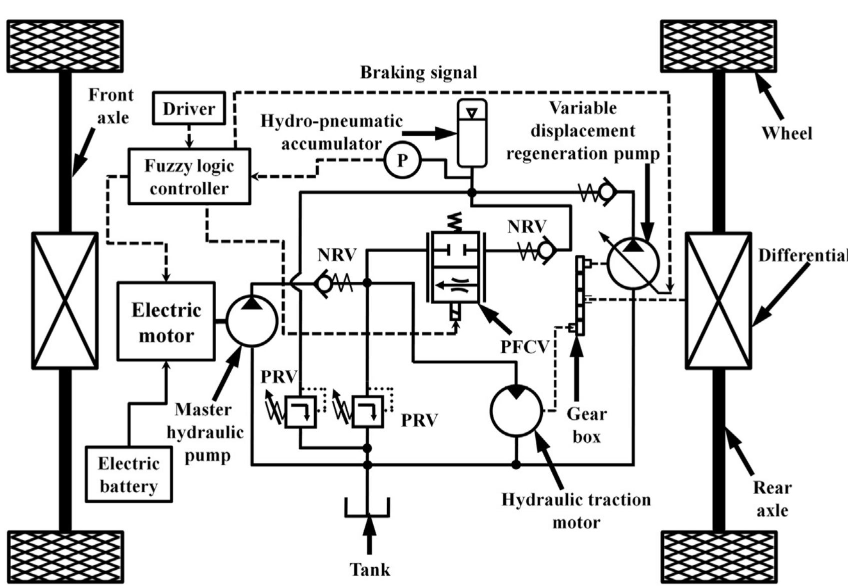

Fig. 1. Configuration of the proposed series hydraulic/electric synergy system [15].