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Control strategy of hydraulic/electric synergy system in heavy hybrid vehicles

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A B S T R A C T

Energy consumption and exhaust emissions of hybrid vehicles strongly depend on the energy storage source and the applied control strategy. Heavy vehicles have the characteristics of frequent starts/stops and significant amounts of braking energy, which needs to find a more efficient way to store and use the high power flow. A novel parallel hybrid vehicles configuration consisting of hydraulic/electric synergy system is proposed to overcome the existing drawbacks of single energy storage source in heavy hybrid vehicles. A control strategy combining a logic threshold approach and key parameters optimization algorithm is developed to achieve acceptable vehicle performance while simultaneously maximizing engine fuel economy and maintaining the battery state of charge in its rational operation range at all times. The experimental and simulation results illustrate the potential of the proposed control strategy in terms of fuel economy and in keeping the deviations of SOC at high efficiency range.

1. Introduction

With the rising concern in a global scale environmental issue, energy saving in automobiles is a very important subject. The search for improving fuel economy, reducing emissions, and affordable vehicles, without sacrificing vehicle performance, safety, reliability, and other conventional vehicle attributes has made the hybrid technology one of the challenges for the automotive industry [1]. Heavy vehicles such as city bus have the characteristics of frequent starts/stops and significant amounts of braking energy which needs to find a more efficient way to store and reuse the high power flow in the hybrid configurations [2]. Battery technology and fuel battery technology have the advantage of high energy density, but the relatively lower power density makes them only marginally recovery the brake energy. supercapacitors has higher power density and lifetime than battery, but the large challenges of supercapacitors are the expensive price and relatively lower application reliability [3]. Another hybridization option, hydraulic hybrid application recently has increasingly aroused the attention of the research institutions and automotive manufacturers all over the world [2,4,5]. Hydraulic accumulators have relatively higher power density and energy conversion efficiency than batteries and supercapacitors, which is well suited for heavy vehicles [5]. However, the lower energy density of the hydraulic accumulator makes it difficult to design the energy control strategy for realization the fuel economy fullest [2], It is widely accepted that a single energy storage source cannot satisfy both the peak power and energy density requirements the heavy vehicles [6]. Recently, the simultaneous use of multiple energy storage sources with different characters is a promising solution for hybrid vehicles because both the high energy density and the high power density can be exploited [7–9]. There is a wealth of literature focused on hybrid energy system in electric form such as battery/supercapacitors, fuel cell/supercapacitors, battery/fuel cell/supercapacitors, but the publications devoted to hydraulic accumulator/battery are relatively scarce [10–15].

Some of energy control strategies for hybrid energy system in electric form deal with heuristic control techniques such as logic threshold, fuzzy logic and others devoted to global optimization for power split between the hybrid energy sources [8–11]. Realistic vehicle operating conditions vary over in a very wide range, heuristic control is different to coordinate all the powertrain components in an optimal manner while satisfying performance constraints. Global optimization techniques are not implemented in real-time control because of requiring a prior known driving cycle [16]. Contrary to the energy control methods mentioned above, the heuristic control based on key parameters optimization approach is a feasible method to real-time control the torque distributions among hybrid energy sources [13]. In this paper, a novel hydraulic accumulator/battery hybrid energy system, called hydraulic/electric synergy system (HESS), is designed to overcome the existing drawbacks of single energy storage source used in heavy hybrid vehicles. The torque control strategy based on logic threshold incorporating key parameters optimization approach is proposed to achieve acceptable vehicle performance and drivability requirements while simultaneously minimizing engine fuel consumption and maintaining the battery state of charge (SOC) within

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its operation range at all times. Finally, the feasibility of applying the HESS with proposed control strategy in the heavy vehicles is researched and discussed.

2. Hybrid vehicles with HESS

2.1. System architecture

System structure of heavy hybrid vehicles with HESS is shown in Fig. 1. Hybrid vehicles consists primarily of an engine, a high pressure accumulator, a reservoir, a variable displacement hydraulic pump/motor, NiMH battery, electric motor (EM), DC/DC converter and transmission. HESS includes electric regenerative system and hydraulic regenerative system. Electric regenerative system is consisted of battery, electric motor and converter. Battery is linked to the electric motor through a DC/DC converter which delivers a directional current. Similarly, hydraulic regenerative system, including a hydraulic pump/motor, hydraulic accumulator, hydraulic reservoir and hydraulic relief valve, is coupled to the drive shaft through a torque coupler at a constant gear ratio. The torque coupler increases the speed of hydraulic pump/motor and allows it to rotate in its optimum efficiency range corresponding to a normal vehicle speed range over city driving cycle.

In the HESS, hydraulic accumulator is used to absorb the higher power from the regenerative braking, provide the auxiliary power during the vehicle startups and emergency acceleration conditions. When the vehicle brake is applied, the hydraulic pump/motor uses the braking energy to charge the hydraulic fluid from a reservoir into a high pressure accumulator, increasing the pressure of the nitrogen gas in the high pressure accumulator. The high pressure hydraulic fluid is used by the hydraulic pump/motor unit to generate torque during the next vehicle start and acceleration [17,18]. It is designed and sized to capture braking energy from normal, moderate braking events and is supplemented by friction brakes for aggressive braking. With the help of accumulator, electric battery can be restricted to work in a pre-defined range of SOC characterized by higher efficiency region which avoids overheating and destruction. Electric battery is invoked only in vehicle's cruise or high power demand situations. The existing of HESS obviously reduces the application frequency and intensity of engine. Once the engine starts, engine is maintained in the high efficiency range by load regulation through active charging battery and HESS assist. The vehicle parameters used in this paper are listed in Table 1.

2.2. Operation modes of hybrid vehicle with HESS

Based on the scheme of hybrid vehicle with HESS shown in Fig. 1, all the operating modes transitions are illustrated in Fig. 2.

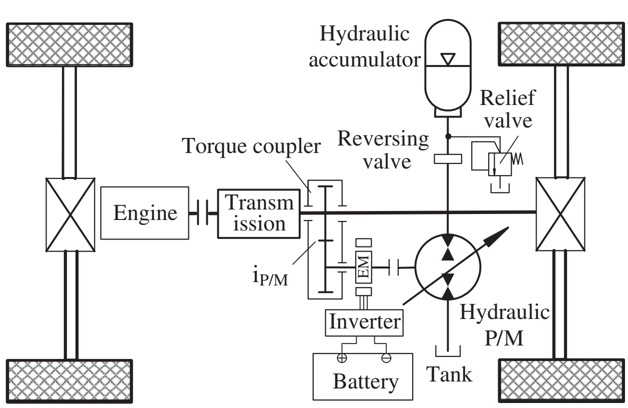

Fig. 1. After-transmission parallel configuration of hybrid vehicle with HESS.

Table 1
Key components parameters of hybrid vehicle with HESS.

Parameter	Value
Total vehicle mass (kg)	14,310
Front area (m^2)	6.5
Wheel diameter (m)	0.5
Rolling resistance coefficient	0.02
Drag coefficient	0.65
Gear ratio	6.62, 3.99, 2.47, 1.55, 1
Main gear ratio	4.875
Engine power (kW)	180
Transmission ratio of torque coupler	3.3
Displacement of hydraulic P/M (mL/r)	125
Hydraulic accumulator volume (L)	63
Power of electric motor (kW)	73
Ni–MH battery rated voltage (V)	300
Ni–MH battery rated capacity (Ah)	93

During the actual operating process, the operating modes are determined by control strategy according to conditions such as the driving torque, the work status of engine, HESS state of charge [13].

2.3. Hydraulic-propelling mode

Hydraulic-propelling mode occurs when the SOC_{acc} is higher than the minimum value SOC_{min}. In this mode, the engine and the EM are cut off, and hydraulic pump/motor engages to propel the vehicle with the power from the accumulator. The torque can be expressed as follow:

$$T_d = i_{P/M} T_{P/M} \eta_{P/M} \tag{1}$$

where $i_{P/M}$ is the ratio of torque coupler, $T_{P/M}$ is the torque of hydraulic pump/motor, $\eta_{P/M}$ is the efficiency of hydraulic pump/motor.

2.3.1. Electric-propelling mode

Electric-propelling mode involves only in vehicle's cruise situations. In this case, the battery is kept in satisfy the total torque demand as long as available energy exists. The torque relationship is shown as follow:

$$T_d = i_{P/M} T_{EM} \eta_{EM} \tag{2}$$

where T_{EM} is the torque of electric motor, η_{EM} is the efficiency of electric motor.

2.3.2. Engine propelling mode with charging

Once the engine starts and the required torque is relatively smaller, engine can be maintained in the high efficiency range by load regulation through active charging. Considering the complex cooperation and energy density of HESS, only batteries are used to absorb the engine redundant power. In order to improve the efficiency and security of battery charging and discharging performance, set high SOC_b limits (SOC_{bH}) and low SOC_b limits (SOC_{bL}), and control battery SOC_b within the high efficiency operational range. Whenever the value of battery SOC_b is less than SOC_{bL}, the battery is actively charged by the engine, and when it is greater than SOC_{bH}, the hybrid system stops active charging. The torque relationship is shown as follow:

$$T_d = (T_{eng} - T_c) i_g i_0 \eta_e \tag{3}$$

where T_c is the torque for active charging battery, η_e is the efficiency of engine, i_g is the transmission gear, T_{eng} is the torque of engine.

2.3.3. Hybrid propelling mode

Hybrid propelling mode involves only in vehicle's accelerating/climbing conditions. In order to enable the engine runs in a certain