Parameter Match and Simulation Analysis of a Parallel Hybrid Electric Vehicle

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***Abstract*- Design and simulation method for parallel hybrid powertrain used in 4WD vehicle was proposed. Computation models of main components in hybrid powertrain were established and simulated with the help of the modified ADVISOR, in which control strategy was improved to enhance regenerative efficiency. Simulation results were verified by field experiment results of the developed hybrid electric off-road vehicle. Experiment and simulation results show that the developed vehicle is practicable and match of different power sources is vey important to hybrid powertrain.**

Keywords*- *Parallel Hybrid Electric Vehicle; Powertrain Configuration; Performance Computation and Simulation; Control Strategy

I. INTRODUCTION

In a battery electric vehicle (BEV), the vehicle runs exclusively on electricity which eliminates combustion on-board the vehicle. At present, the barriers to wide acceptance of electric vehicles include their higher purchase cost, the lack of charging infrastructure, limited range and long charging time. Hybrid electric vehicles (HEVs), which use both an internal combustion engine (ICE) and an electric motor to drive vehicle and utilize the benefits of each system to enhance efficiency, can overcome range and charging time issues of a BEV. The batteries used in hybrid electric vehicles are recharged during operation, eliminating the need for an external charger. At the same time, the reason for developing hybrid electric vehicles is that it is possible to make them, in some aspects, better than conventional vehicles, for example less environmental impact, lower emissions and lower fuel consumption. Moreover, hybrid electric vehicles are as easy to handle as conventional vehicles and don't require a whole new infrastructure for fuel distribution. Unfortunately, the HEV still operates on gasoline/diesel fuel and is low emission vehicle.

The major hybrid powertrain configurations are series, parallel, series-parallel and complex hybrid configurations in [1]. Parallel hybrid powertrains have the flexibility to propel a vehicle with an ICE-alone, an electric motor-alone, or a combination of both an ICE and an electric motor simultaneously, which depends on the control strategy.

In this paper, the off-road prototype vehicle driven by a diesel engine was altered to be a parallel hybrid electric vehicle. The engine in the parallel hybrid powertrain is used to be the primary motivator and is connected to the wheels at all times, while the electric motor is typically small and designed to assist the engine when the vehicle needs extra power, such as in acceleration and inclines. Besides, determination methods of different power sources and simulation analysis of the determined powertrain are discussed in this paper.

II. LAYOUT OF THE DEVELOPED OFF-ROAD VEHICLE

The parallel hybrid powertrain, shown in Fig. 1, is used in the developed off-road vehicle, which is a four-wheel-drive. It is obvious that it is a single-axle parallel hybrid powertrain, because the motor uses the same output axle as the engine and torque is coupled by this axle. The powertrain is composed of the ICE, electric motor, clutches, transmission system and battery pack.

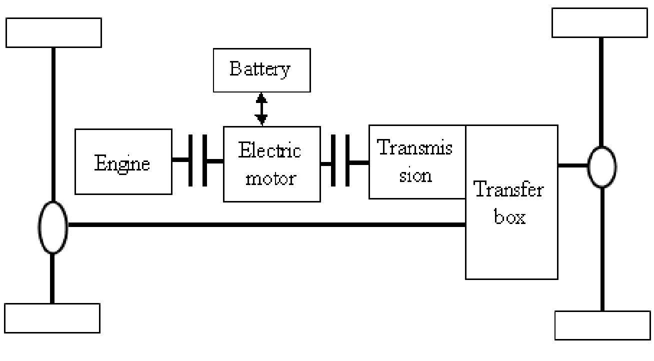

Fig. 1 Parallel hybrid powertrain in the off-road vehicle

Parameters of the prototype off-road vehicle are listed in Table I.

TABLE I PARAMETERS OF THE OFF-ROAD PROTOTYPE VEHICLE

Parameter	Value
Vehicle mass [kg]	2850
Frontal area [m^2]	3.2186
Aerodynamic drag coefficient	0.35
Rolling radius of wheels [m]	0.385
Wheelbase [m]	2.6
Ratio of 5-speed transmission	4.313, 2.330, 1.436, 1.000, 0.838
Maximum hill ability	60%@10km/h
Hill ability only driven by engine	30%@30km/h
Maximum speed on 5% slope angle flat road [km/h]	≥120
Maximum speed only driven by engine [km/h]	≥70
Fuel consumption [L/100km]	12
All-electric range [km]	10

III. PARAMETERS OF POWERTRAIN CONFIGURATION

A. Power of Engine and Motor in Hybrid Powertrain

The ultimate design procedure of the parallel hybrid electric vehicle would involve the solution of the optimal design (component sizing) and optimal control problems simultaneously. Even though there are currently a considerable number of optimization strategies in [2, 3, 4, 5, 6] for energy management systems, the selection of the components will be only discussed in this paper, in which all the optimal control is thought of as no problem.

In the longitudinal direction, the tractive efforts should be involved in grade resistance, rolling resistance of the tires, the aerodynamic resistance and inertia force from acceleration. In different operating cases power consumption is combination of power resulting from the tractive efforts.

Based on power requirement, cost and mass of the developed hybrid off-road vehicle, combination of a large power engine and a small power motor with related battery packs are used as power source. Control strategy consists of the following aspects: when running at low speeds or less power requirements the vehicle is driven only by motor in order to keep the engine to run away from low load operations that generally produce high hydrocarbon (HC) and carbon monoxide (CO) emissions and inefficient fuel use; during hill climbing and maximum speed power requirements of the vehicle are jointly provided by the motor and engine. So, the engine in the parallel hybrid electric vehicle should supply power requirement running at speed u_c on flat road within 6% slop angle and at maximum speed u_{emax} only driven by the engine. In this way, the power P_e of the engine is expressed in [7, 8] by

$$P_{ec} = \frac{\beta}{3600\eta_T}(mg\cos\alpha f u_c + \frac{C_D A u_c^3}{21.15} + mgu_c \sin\alpha) \tag{1}$$

$$P_{e\max} = \frac{\beta}{3600\eta_T}(mgfu_{e\max} + \frac{C_D A u_{e\max}^3}{21.15}) \tag{2}$$

$$P_e = \max\{P_{e\max}, P_{ec}\} \tag{3}$$

Where, *m*– vehicle mass in kilogram, *g*– acceleration due to gravity, g=9.8 m/s^2, u_{emax} – maximum speed only driven by the engine in kilometer per hour, and u_c – the speed running on the flat road within slope angle α, normally α=6%. *f*– coefficient of rolling resistance, C_D– coefficient of aerodynamic drag, *A*– frontal area in square meters, η_T– efficiency of the powertrain, β – a factor for allowing for engine to recharge battery pack and to supply power to auxiliary units, and β=*1.2*.

Similarly, the motor should provide insufficient power requirements of the vehicle supplied by the engine when the vehicle is climbing maximum hill or running at maximum speed. So, the power of the motor should satisfy Eq. (4).

$$P_m = \max\{P_{h\alpha} - P_e, P_{h\max} - P_e\} \tag{4}$$

Where $P_{h\alpha}$ – the required hybrid power running at the desired speed on the maximum slope angle hill, and P_{hmax} – hybrid power required by vehicle at maximum speed.

Based on the abovementioned methods and necessary power reserve, power of the motor and engine are 14 kW and 87 kW, respectively.

B. Parameter Determination of the Battery Pack in Hybrid Powertrain

Battery packs supply energy to the motor, so the power of battery pack should not be less than the power of the motor at any required cases. Of course, the more the number of batteries is, the heavier weight of the batteries are, which would result in adverse effect on vehicle power consumption. The voltage of the battery pack in [9] should satisfy rated voltage of the motor and energy and capacity of battery pack can be determined in Eq. (5) and (6).

$$E_b \geq \left[\frac{u}{3.6\eta_T} \left(mgf + \frac{C_D A u^2}{21.15} \right) + P_{acc} \right] \frac{3600S}{v\eta_b \Delta SOC} \tag{5}$$

$$C_b = \frac{E_b}{U_b} \tag{6}$$

Where E_b and C_b are the energy and capacity of the battery pack, respectively. η_b – battery efficiency, u – the speed when the vehicle is driven only by motor, or 30 km/h in this paper. S – all-electric range and 10 km in this paper. $\triangle SOC$ is the SOC variation range, which is equal to 0.1 in this paper. U_b – total voltage of the battery pack.

In this way, rated voltage of the battery pack is 336 V and capacity is 8 Ah.

C. Simulation Model

In order to be used for simulation of 4WD vehicle, ADVISOR was modified in MATLAB environment. The control strategy for regenerative brake was altered to fully utilize kinetic energy for electric braking. The flow chart of the modified control strategy is sketched in Fig. 2. Main model in the modified ADVISOR is shown in Fig. 3, and SOC variation is shown in Fig. 4 when original and modified control strategies were used in simulation, respectively. It is concluded that the modified control strategy is more effective.

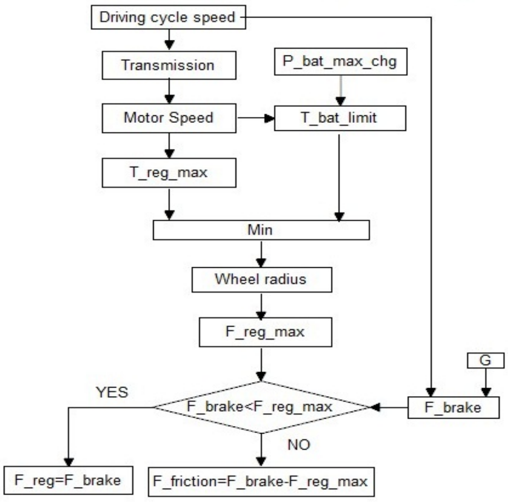

Fig. 2 The modified control strategy

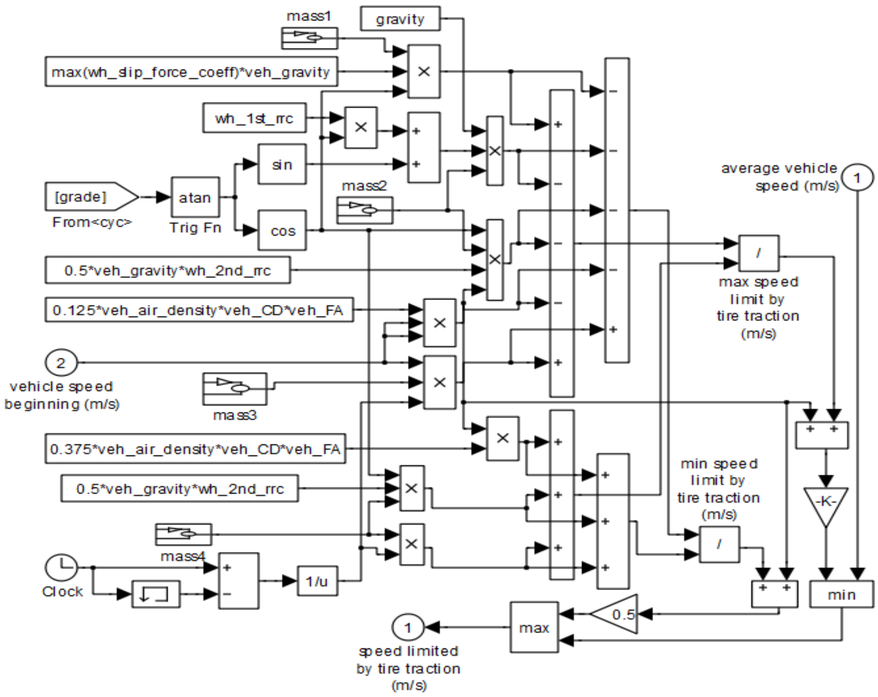

Fig. 3 The simulation model for the off-road vehicle

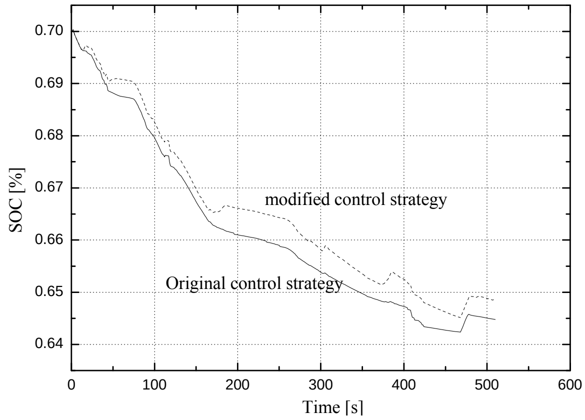

Fig. 4 SOC variation of different control strategies

IV. EXPERIMENT AND SIMULATION ANALYSIS

A. Experiment Results

Field experiment was carried out to verify simulation results. Fig. 5 and Fig. 6 show running speed and variation of voltage and current during experiment, in which maximum speed of the vehicle is 124.5 km/h.

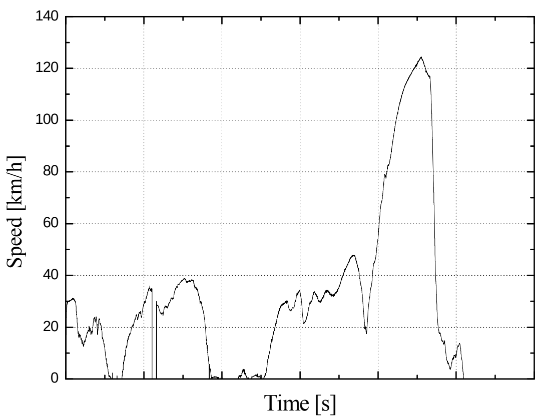

Fig. 5 Running speed in field experiment

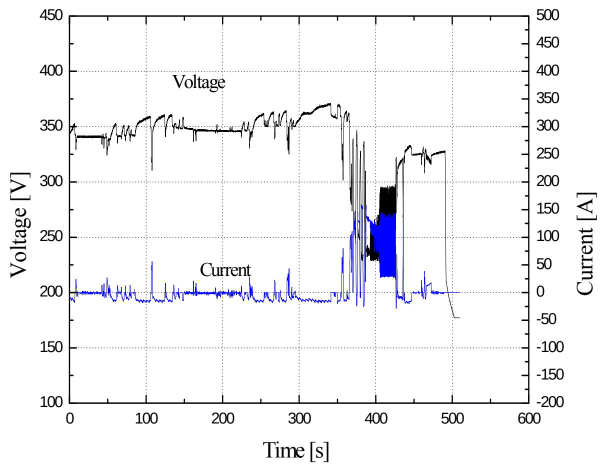

Fig. 6 Experiment results of voltage and current variation

B. Simulation Results

Simulation results are shown in Fig. 7 according to the speed in Fig. 5, which is consistent with results in field experiment. Errors between experiment and simulation results originate from different engine and motor models in two cases. It can be noted that simulation and experiment results are acceptable.

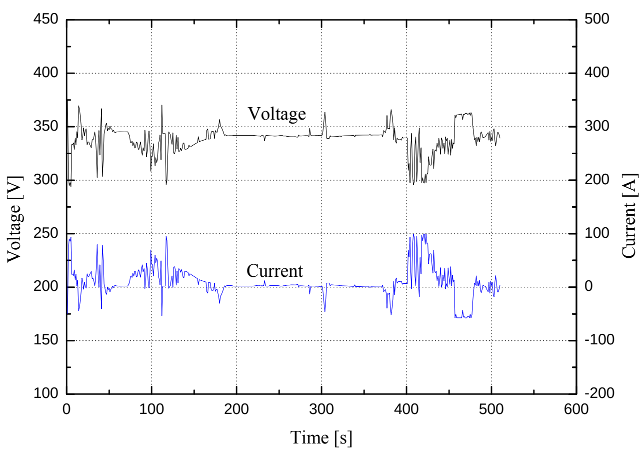

Fig. 7 Simulation results of voltage and current at the experimental speed

Simulation analysis of the developed vehicle is performed and simulation results are listed in Table II. It is noted that performance of the developed vehicle can achieve the desired performance.

TABLE II SIMULATION RESULTS

Parameters	Simulation results
Maximum hill ability	61.8%@10km/h
Hill ability only driven by engine	35.4%@30km/h
Maximum speed on 5% slop angle flat road [km/h]	130.8
Maximum hill ability [%]	61.8@10km/h
Maximum speed only driven by engine [km/h]	73.4
All-electric range [km]	11.1

C. Simulation Results in NEDC Driving Cycle

The New European Driving Cycle (NEDC), shown in Fig. 8, is a driving cycle consisting of four repeated ECE-15 driving cycles and an Extra-Urban driving cycles (EUDC).

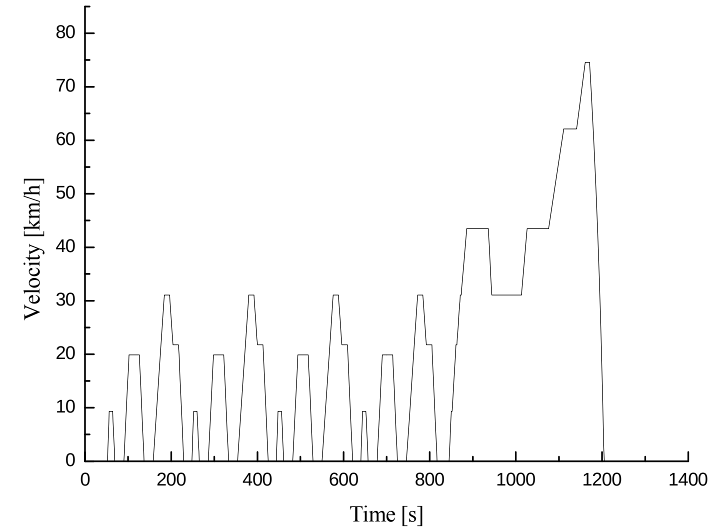

Fig. 8 NEDC driving cycle

The developed hybrid off-road vehicle is simulated with NEDC as a driving cycle to compare simulation results, in which fuel consumption is 9.01 L and less than 12 L consumed by the prototype vehicle. SOC varies in the case of NEDC driving cycle in Fig. 9.

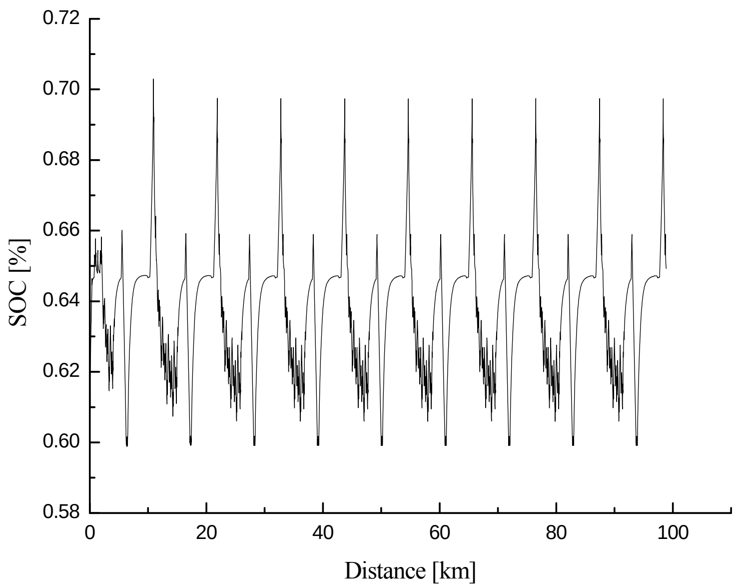

Fig. 9 SOC variation with distance

Fuel consumption relates to SOC desired variation range. In this paper, SOC desired variation range is between 0.6 and 0.7. If different SOC variation ranges are used to simulate, fuel consumption will definitely vary.

V. MATCH OF THE ENGINE AND MOTOR IN THE POWERTRAIN

Parameter match of the engine and motor in the powertrain is very important to performance of the vehicle. According to Table 2, the vehicle can run on the 60% slope at the speed of 10 km/h when the powertrain uses 87 kW engine and 14 kW motor. However, the vehicle can run the same slope at the speed of near 20 km/h as shown in Fig. 10, which means that maximum hill ability does not locate in minimum speed. It can be found that maximum power point of the engine is not able to match that of the motor.

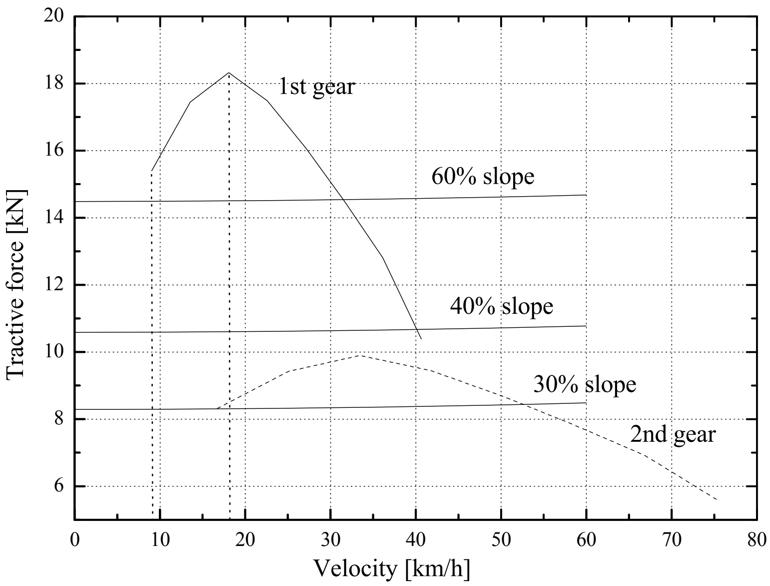

Fig. 10 Dynamic performance of 100kW hybrid powertrain

In order to enhance performance of the HEV and compare operating region of the engine in the powertrain, 100 kW engine and 70 kW motor are used in the powertrain in the developed vehicle and dynamic performance was analysed. The tractive forces at different speed are shown in Fig. 11. At this time, hill ability is maximum at the lower speeds responding to range between minimum and base speed of the motor. Furthermore, 170 kW hybrid powertrain can negotiate 40% slope road in second gear. Of course, fuel consumption of 170 kW hybrid powertrain is definitely more than 100 kW hybrid powertrain's fuel consumption.

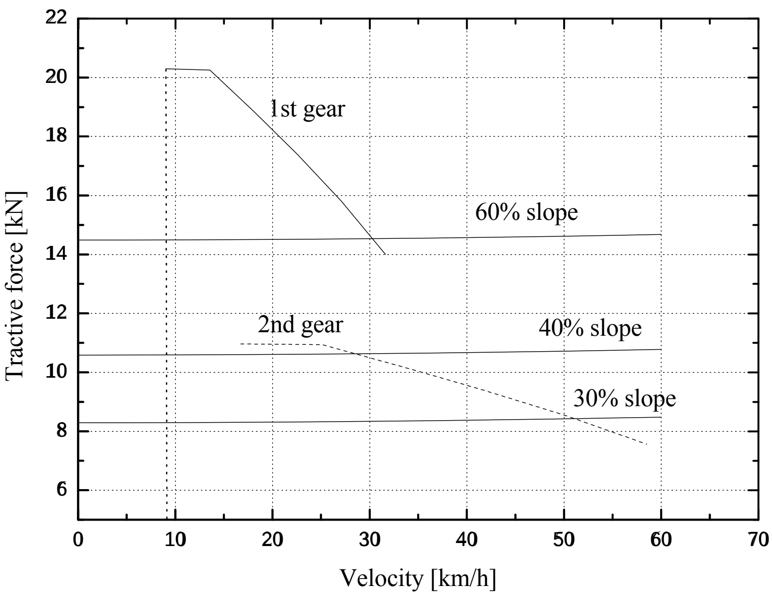

Fig. 11 Dynamic performance of 170kW hybrid powertrain

It is noticed that it is very important for a hybrid powertrain to match different power sources.

VI. CONCLUSIONS

The developed hybrid off-road vehicle used parallel hybrid powertrain to improve dynamic performance and lower emissions. Power of engine and electric motor in the powertrain was determined according to power distribution to them. Field experiment was carried out and experimental results showed that the vehicle performance was achieved. The modified control strategy can enhance efficiency of regenerative energy. Power match of different power sources in hybrid powertrain is very important to dynamic performance. Results in this paper will be references for researches to design and develop hybrid vehicles.

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