Design of Series-parallel Hybrid Electric Propulsion Systems and Application in City Transit Bus

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Abstract: - The design approaches and a design case of the series-parallel hybrid electric propulsion system for ground vehicles are presented in this paper. Based on the analysis of the base units and the combination types of the series-parallel propulsion systems, a novel manual transmission is proposed to switch the propulsion system configuration in a low-cost manual-shifted hybrid propulsion system. This propulsion system type has been used in a hybrid transit bus. The sizes of propulsion system components, including engine, electric motors, battery and gear ratios, are designed to satisfy the bus's drive ability requirements. Moreover, some features, including down-sized engine, idling elimination, regenerative brake, low-speed electric propulsion and proper control strategy, etc., are introduced to improve its fuel economy. The fuel economy of the hybrid bus was evaluated under the city transit bus driving cycle. The result shows that the fuel consumption is on average reduced by 21.3% of that of the conventional baseline bus under city driving conditions, which identifies the approach's technical and economical feasibility.

Key-Words: - series-parallel, hybrid electric propulsion system, transit bus, design, fuel economy

1 Introduction

As a new-generation technology to reduce the fuel consumption and emission pollutions, hybrid electric vehicles (HEV) arrest the manufactures and researchers' attentions recently [1-3]. With the features of public transportation and high-load capability, the hybrid electric buses (HEB) develop rapidly in some areas. For example, the New York City Transit (NYCT) has launched pilot fleets of HEBs since 1998. The experiences from NYCT show that the HEBs brought out advantages in fuel economy and maintenance cost [4-5].

Based on propulsion system's configuration, like the common HEVs, the HEBs in market can also be classified into three types: series type, parallel type and series-parallel type [6,7]. The series hybrid electric vehicle is solely propelled by an electric motor (EM), whereas both the engine and the motor of the parallel hybrid system can drive the wheels. Since the series hybrid system requires a big-size battery pack to provide adequate electric power to drive the vehicle by the traction motor alone, it is mainly adopted in the heavy-duty vehicles [5,8-10]. Parallel hybrid electric system is the simplest. It was applied in variable vehicle classes [11-13].

It is known that a series propulsion system is more suitable for low-speed driving cycle conditions, but during highway driving conditions parallel hybrid behaviour is desired. In order to extract the benefits from both propulsion systems, the series-parallel hybrid electric propulsion system (SPHEPS) combines a series hybrid propulsion system with a parallel hybrid propulsion system. It involves an additional mechanical link compared with the series hybrid and also an additional generator compared with the parallel hybrid system [14]. It is then more suitable for the complex driving cycles.

Since the developments of series and parallel hybrid systems have been accelerated over the past decade, the focus of R&D efforts has shifted to series-parallel hybrid system recently. The SPHEPS includes two types: Electric Continuously Variable Transmission (eCVT) type and series-parallel configuration switched type. The representative eCVT types are the Toyota-THS, Ford-FHS and GM-Allison-AHS [15-20]. These systems employ the 2-degrees of freedom planetary gears as power splitters, by which the power can flow in both series and parallel simultaneously. A heavy-duty eCVT system, like AHS, is costly and hard to be controlled. Nissan-Tino is a representative series-parallel configuration switched type light-duty hybrid car [21,22]. For this type, a certain device, for example the electromagnetic clutch in Tino, is used to switch the propulsion system configuration between series type and parallel type. The power in this propulsion system can flow in either series or parallel.

Table 1 shows some representative hybrid bus propulsion system in market. There are different trends in different areas. In USA, the series hybrid electric bus (SHEB), such as HybriDrive from BAE and ThunderVolt from ISE, is the major solution adopted by the manufactures [5]. In China, many auto producers have developed their hybrid bus systems [23]. They focused on the parallel hybrid systems for the bus applications, including post-transmission and pre-transmission coupled types, such as Dong-Feng Hybrid Electric Bus System (DFHEBS) and Eaton Hybrid Power System (EHPS) adopted by Fu-Tian, reprehensively. Different from the bus systems above, the research emphasis of this paper is put on the design of a low-cost series-parallel hybrid electric propulsion system for heavy-duty buses.

This paper is organized as following. In Section 2, the base architectures of SPHEPS are described, and the proposed novel manual-shifted architecture for buses is also schematically presented. Section 3 describes the design of the hybrid propulsion system components' sizes for the application in the bus. Section 4 presents the features used to improve the fuel economy in this system. The experimental results are provided in Section 5, which validates its technical accessibility and economical feasibility. Lastly, a brief conclusion is presented.

2 Series-parallel Architecture Design

The aim of this paper is not to design an eCVT type, but to design a series-parallel switched type SPHEPS which can be easily applied in the conventional bus chassis systems. In this section, based on the analysis of base units, in order to obtain a manual-shifted SPHEPS, a novel approach is proposed and applied in the SWB6116HEV, which is a hybrid electric city transit bus (HECTB) jointly developed by Shanghai Jiao Tong University (SJTU) and Shanghai Automotive Industry Co. Ltd (SAIC).

2.1 Base Architecture Analysis

The internal combustion engine (ICE) is often used as the fuel converter in the ground vehicles. To combine a series system with a parallel system for a series-parallel propulsion system, shown in Fig. 1, two base power units which are ICE-generator (ICE-G) unit and the transmission-electric motor (T-EM) unit should be included in the system.

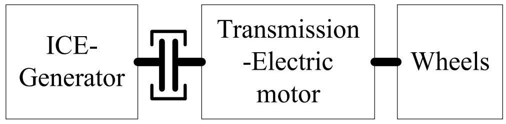


Fig.1 Top level configuration of series-parallel hybrid electric vehicles

2.1.1 Base ICE-G units

Based on the generator mounting styles, shown in Fig. 2, there are two base ICE-G types [24,25]:

(1) Belt-driven starter/generator (BSG) type.

In this type, a BSG is pre-ICE coupled via a belt system. It is often located at the place where the conventional generator is removed. The belt can be a separate belt or the existing belt system.

(2) Integrated starter/generator (ISG) type.

In this type, the conventional generator and starter as well as flywheel are eliminated and their functions are replaced by the ISG. The ISG is connected to the ICE crankshaft directly that helps to start the ICE rapidly and quietly.

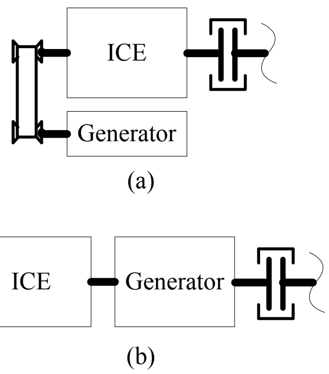


Fig. 2 ICE-G base types: (a) BSG type; (b) ISG type

The comparisons of these two types are listed in Table 2. A BSG system often only provides start-stop function which marks the low end of hybridization. Since it drives the engine via a belt with lower energy transfer efficiency, it can not

Table 1 Representative hybrid bus propulsion system

Propulsion system	Type	Supplier	Country	Feature
HybriDrive	S[1]	BAE	USA	Diesel; Battery
ThunderVolt	S	ISE	USA	Diesel/gasoline; Ultra-capacitor
E^P40/50	SP[2]	Allision	USA	Dual-mode
EHPS	P[3]	Eaton	USA	AMT; Pre-transmission coupled
DFHBS[5]	P	DFM	China	Post-transmission coupled

[1] S: Series; [2] P: SP: Series-parallel; [3] Parallel.

provide hybrid propulsion behaviours. The ICE-ISG is a common completed mid hybrid propulsion system, it has the base functions of a HEV.

Table 2 Comparisons of two base ICE-G units

Type	BSG	ISG
Start-stop	√	√
Regeneration	√[1]	√
Hybrid propulsion	-	√
Hybridization ratio	Low	Low-mid

[1] Sometimes the BSG is not used to regenerate brake energies.

2.1.2 Base T-EM Units

Shown in Fig. 3, there are three base T-EM units [26, 27]:

(1) Type A: Pre-transmission coupled type

The EM is mounted on the input gear shift of the transmission directly or via a torque coupler. The speed of the EM is the same as the ICE when the clutch is engaged.

(2) Type B: Post-transmission coupled type

The EM is mounted on the output gear shaft of the transmission directly or via a torque coupler. The angular speed of the EM is decided by the wheel's rotational speed.

(3) Type C: 4-wheels driven (4-WD) type

Koprubasi presented a 4-WD propulsion system in literature [27]. As to this configuration, the EM is separated from a conventional propulsion system to powers a separated axle and then provide "through the road" ability.

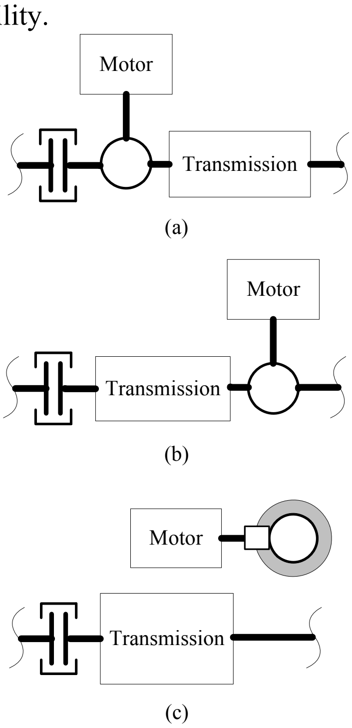


Fig. 3 T-EM base types

Table 3 presents the characteristics of these units. The drive ability of a 4-WD propulsion system is better than others, but the conventional axle system should be modified to be powered by the separated EM. Since the EM is linked with the wheels all the time, the post-transmission propulsion system is considered favorable to capture the kinetic power with less energy transfer loss during brake.

Table 3 Comparisons of three base ICE-G units

Type	A	B	C
Regeneration	√	√	√
Electric propulsion	√	√	√
Hybrid propulsion	√	√	√
Through the road	-	-	√
Modify axle system	-	-	√
Hybridization ratio	Mid-strong		

A feature of HEVs to improve fuel economy is the electric propulsion at low-speed [20]. To provide the pure electric propulsion behaviors, the driveline before the EM should be disconnected at a certain point through actuating some devices to obtain a series configuration. For some applications, the automated clutch is often such a device used to disconnect and connect the driveline through disengaging and engaging operations.

Of course, the driveline can be disconnected at neutral gear in transmission. But two intentions are involved in the neutral gear for this application: (1) pure electric propulsion; (2) the transition stage of the gear-shift operations. In order to autonomously distinguish the drive intentions, an automatic transmission system, but not a manual system, is also required in such an application.

In summary, Table 4 lists the feasible devices that can be used to switch the hybrid propulsion system configuration.

Table 4 Propulsion system configuration switcher

Type	A	B	C
Automated neutral gear	-	√	√
Automated clutch	√	√	√
Manual neutral gear/clutch	-	-	-

2.2 Novel Manual-shifted SPHEPS

The authors took efforts to develop both automatic-shift and manual-shift hybrid electric propulsion systems. Considering the availability of heavy-duty automatic transmission and the cost of the system, in this case, a precondition that to retain the conventional manual clutch/transmission system is promoted. Base on this principle, a novel approach to combine an ICE-G unit with a manual-shifted T-EM unit for a SPHEPS in heavy-duty vehicles is introduced as follows.

(1) Selection of ICE-G type

To provide adequate power to electric drive the bus, a high-voltage battery pack should be employed. As a result, a high-power ISG is then favorable to be used to cold start a big-size engine. In this case, the ISG type ICE-G is selected.

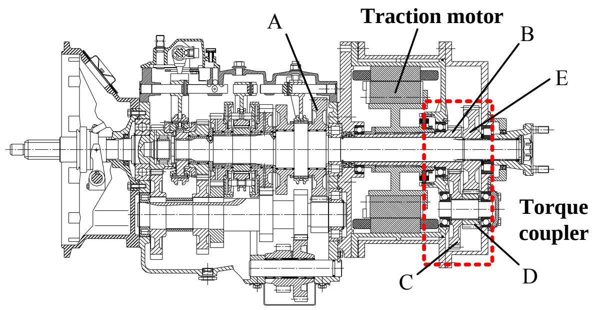
(2) Selection of T-EM type

Based on the considerations below, the authors focus on the post-transmission coupled T-EM:

▪ The complex 4-WD propulsion system is hard to be applied in a baseline duty-heavy bus.

▪ For a pre-transmission coupled T-EM shown as Fig. 2(a), an automated clutch located before the EM is necessary to disconnect the driveline for the pure electric propulsion behaviour.

For a manual clutch equipped post-transmission coupled SPHEPS, it is unfeasible to disconnect the driveline through disengaging the clutch by the driver when the vehicle is moving. In this paper, a concept inspired from but distinguished with neutral gear is applied in the original first gear of a manual mechanical transmission shown in Fig. 4. In this transmission, the first gear “A” is replaced by a smooth disk-shaped metal block, which has the original moments of inertia of gear “A” and can’t couple any other gears. Therefore, if the transmission is manually set in the original first gear position, the transmission’s counter shaft can not couple the second shaft, and then the power path from the engine is cut off at gear “A” and the bus consequently runs as a series hybrid electric vehicle (SHEV). To keep the driver’s feelings on shifting, the first synchronizing ring and sleeve are also retained.



A: First gear of transmission B: First gear of TC
C: Second gear of TC D: Third gear of TC
E: Fourth gear of TC

Fig. 4 Configuration of the T-EM

A traction electric-motor (TM) is linked to the output gear shaft of the transmission via a torque coupler (TC). The TM and the TC are housed in the same case. This TC is a reduction gear set including four gears indicated with letters “B”, “C”, “D” and “E” in Fig. 4, which enlarges the torque transmitted through it and as a result the TM can be reduced in size.

2.3 Application in SWB6116HEV

The baseline bus of SWB6116HEV, shown in Fig. 5, is SWB6116 provide by SAIC. It is a 12-meter, low-floor city transit bus. The parameters of SWB6116HEV are listed in Table 5. The load capacity of SWB6116HEV is 5 tons.

Fig. 5 Photography of SWB6116HEV

Table 5 Parameter of SPHETB

Parameters	Specification
Curb weight (kg)	12,000
Frontal area (m^2)	7.5
Aerodynamic coefficient	0.62
Wheel radius (m)	0.508
Wheel base (m)	5.8

Shown in Fig. 6, the manual-shifted series-parallel propulsion system mentioned before was retrofitted to the baseline bus. In order to modify the conventional system at least for a low-cost series-parallel propulsion system in the rear-wheels driven duty-heavy bus, many electric components are integrated into an ICE-driven propulsion system, and a majority of conventional components are also retained in the system.

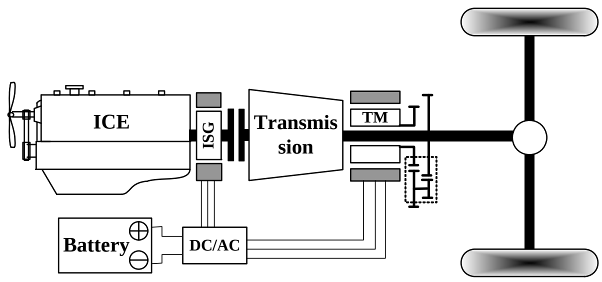
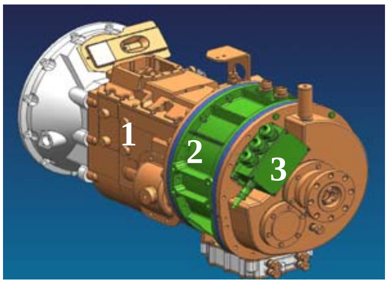


Fig. 6 Propulsion system of SWB6116HEV

A conventional manual clutch is also mounted between an ISG typed ICE-G unit and a post-transmission coupled T-EM unit, which are all located in the place where the conventional ICE system are mounted. Fig. 7 shows the 3-D profile of the T-EM unit used in SWB6116HEV. The T-EM couples with the propeller shaft via gimbals, then to the final drive and rear wheels. The conventional transmit systems after the T-EM are also preserved in the bus. The ISG and the TM are all AC type. A DC/AC converter is used to convert the direct current from the battery pack to the alternating current flowing into the ISG and TM.



1: Transmission; 2: TM (TC housed);
3: 3-phase voltage inputs

Fig. 7 3-D profile of the T-EM unit

As the researches done by others, the Control Area Network (CAN) is also adopted to configure a real-time control system for this propulsion system. Shown in Fig. 8, besides the Vehicle Control Unit (VCU), four local controllers which are Engine Management System (EMS), ISG Control Unit (ISGCU), TM Control Unit (TMCU) and Battery Control Unit (BCU) are also included in the network. The VCU acquires the signals from the sensor, like the clutch sensor, pedal stroke sensor and pressure sensor, etc., packs the data and sends the messengers through the CAN network. The VCU also control the relay ***A*** indicated in Fig. 8 to power a motor to charge the air tank when the air pressure is insufficient. This tank provides power for friction braking and operating the clutch in the heavy-duty vehicles.

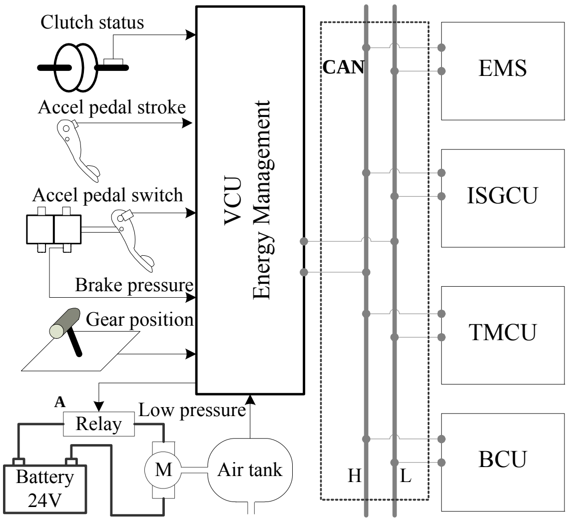


Fig. 8 Control network of SWB6116HEV

3. Propulsion System Size Design

For a hybrid electric propulsion system, besides the propulsion machines, including the electric motors and the ICE, the power storage is also another important electric component. The power storages are often connected with the electric motors via inverter/converters. They are used to power the electric motors for traction, and storage the energies for generation.

3.1 Propulsion Machines Size Design

To satisfy the drive ability requirements shown in Table 6, the propulsion machines are selected.

Table 6 Drive performances required

Maximum speed (km/h)	>80
Maximum slope (%)	20
0~50km/h acceleration time(s)	25

The vehicle can be considered like a moving mass subjected to the traction force $F_{TR}(t)$. The road load $F_{RL}(t)$ includes the aerodynamic drag force $F_A(t)$, the rolling resistance $F_R(t)$ of the tires and the gravitational force $F_G(t)$ [28]. These forces can be described as follows:

$$F_A(t) = 0.5\rho_A v(t)^2 C_D S \quad (1)$$

$$F_R(t) = mg\cos(\alpha(t)) f \quad (2)$$

$$F_G(t) = mg\sin(\alpha(t)) \quad (3)$$

where f is the tire rolling resistance coefficient; m is the vehicle mass; g is the gravitational acceleration constant; C_D is aerodynamic drag coefficient; S is the vehicle frontal area; v is the vehicle speed; α is the road slope; ρ_A is the air density.

The vehicle speed $v(t)$ is evaluated using the equation of motion, given by:

$$F_{TR}(t) - F_{RL}(t) = m\delta \frac{dv(t)}{dt} \quad (4)$$

where δ is the rotational inertia coefficient to compensate for the apparent increase in the vehicle's mass due to the onboard rotating mass.

The traction force F_{TR} at wheels can be described as following for a post-transmission coupled series-parallel hybrid electric vehicle.

$$F_{TR} = \frac{(T_{TRAN} + T_{TM}\eta_{TC})\eta_{FD}}{r} \quad (5)$$

$$T_{TRAN} = \begin{cases} (T_{ICE} + T_{ISG})\eta_{TRAN} & series \\ 0 & parallel \end{cases} \quad (6)$$

where, T_{TRAN} is the torque passed through the transmission; T_{ICE}, T_{TM} and T_{ISG} are the output torques of the ICE, TM and ISG, respectively; η_{TRAN}, η_{TC} and η_{FD} are the efficiencies of the transmission, TC and final driver, respectively; r is the wheel radius.

The dynamic factor D, a non-dimensional quantity, is a major dynamic characteristic index [29]. It is the reserve of driving force per unit of weight. As that of a conventional vehicle, the dynamic factor of a hybrid electric vehicle can also be defined as:

$$D = \frac{F_{TR} - F_{A}}{mg} \tag{7}$$

The dynamic factors in the maximum ratio gear and direct gear are used to evaluate the maximum road slope and maximum speed, respectively. For the minor grades, an approximate formula is used to evaluate the maximum gradient angle a_{MAX}:

$$\alpha_{MAX} \approx \sin(\alpha_{MAX}) \approx D_{2MAX} - f \tag{8}$$

where D_{2MAX} is the maximum dynamic factor at the maximum gear ratio, second gear in this bus.

Not counting the gear-shift times, the minimum 0~50km/h acceleration time can be evaluated by:

$$\frac{125}{9} = \int_0^{t_A} \frac{F_{TR,MAX}(t) - F_{RL}(t)}{m\delta} dt \tag{9}$$

where $F_{TR,MAX}$ is the maximum traction force, t_A is the acceleration time.

Electric motor play an important role in the success of HEVs. Three types of electric motors that are suitable for HEV applications: (1) permanent magnet (PM) synchronous or PM brushless motors; (2) induction motors; and (3) switched reluctance (SR) motors. The comparisons of these motor types are given in Table 7 [30]. The guideline prices of the 863 Program in the Ministry of Science and Technology of the People's Republic of China, for the electric motors applied in the electric vehicles, is presented in Table 8.

In this case, incorporating with a 135kW generic diesel engine (Fig. 16), a 30kW PM synchronous ISG and a 80kW PM synchronous TM are selected to power the bus. The efficiency Maps of the electric motors are given in Fig. 9 and 10.

The dynamic factors at each gear of this system are presented in Fig. 11. The dot lines indicate the dynamic factors at each gear when the bus is driven by engine alone, and the real lines are the dynamic factors when the TM assists at 60kW (the half of the sum of the continuous power and the peak power). Different from the conventional vehicles, in order to operate the engine and motors in the economic regions, governed by the control rules, sometimes the power sources can not output their peak power at peak requirements. Therefore, some extra power, which provides the freedoms to tune the operation points to economy areas during acceleration, should be considered to the power sources in some cases.

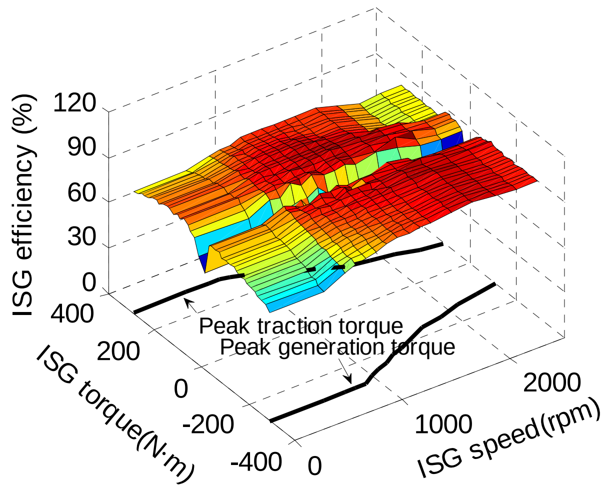


Fig. 9 ISG efficiency Map

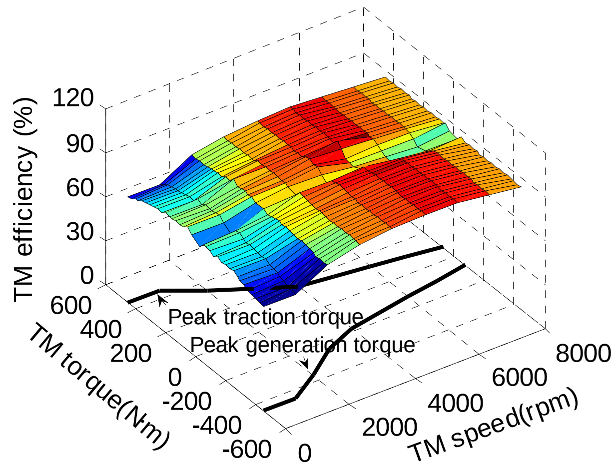


Fig. 10 TM efficiency Map

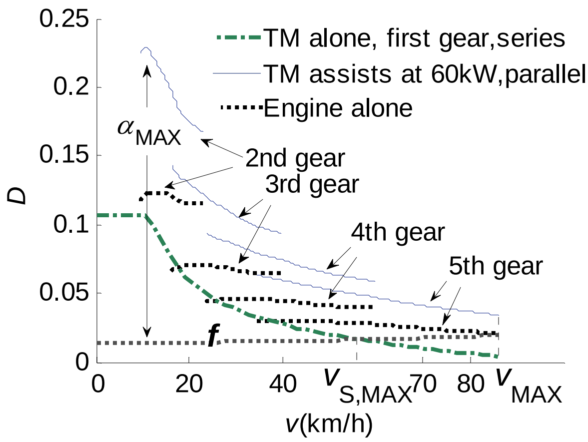


Fig. 11 Dynamic factors of SWB6116HEV

Since this propulsion system outputs the peak torque with hybrid behaviours at second gear, but not first gear. The acceleration time launching at second gear is the shortest. Fig. 12 shows a case of the simulation and actual acceleration processes of

Table 7 Comparisons of the electric motors

Type	Advantage	Disadvantage
Induction	▪ Simplicity; ▪ Robustness; ▪ Wide speed range;	▪ Low efficiency; ▪ Big size;
PM	▪ High efficiency; ▪ High torque; ▪ High power density;	▪ Limited field weakening capability; ▪ Back electromotive force at high speed;
SR	▪ Simple and rugged construction; ▪ Simple control; ▪ Extremely high speed operation; ▪ Hazard-free operation;	▪ Higher cost; ▪ Not a widely produced standard motor;

Table 8 Guideline prices of electric motors in electric vehicles in 2008

Application	HEV			PEV[1] and FCEV[2]	
Duty (Hybridization)	Light (mid)	Light (strong)	Heavy	Light	Heavy
Peak power (kW)	10~20	30~50	60~90	50~90	120~240
Guideline price[3] ($)	1,765~2,647	3,676~5,147	5,882~ 7,353	4,412~ 5,882	10,294~1 4,706
Maximum efficiency	>90%	>90%	>90%	>93%	>90%
Life (10,000 km)	≥30	≥30	≥50	≥30	≥50

[1] Pure Electric Vehicle; [2] Fuel Cell Electric Vehicle;
[3] The exchange ratio of 6.8:1 is considerate for RMB against USD

the hybrid electric bus. The result identifies that the acceleration requirement is satisfied.

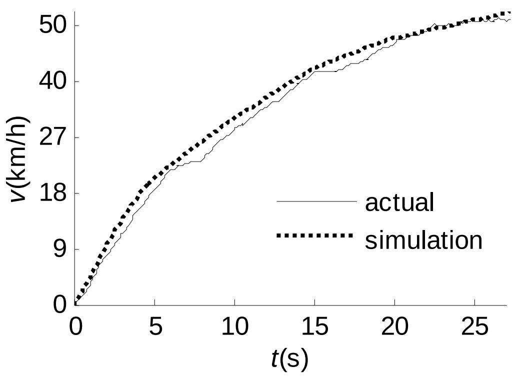


Fig. 12 Evaluation of acceleration

3.2 Power Storage

Many power storage types have been estimated for the applications in the electric vehicles by some researches [7]. The major types are the electro-chemical storage systems (batteries) and the ultra-capacitors.

Batteries generally have high energy density but less power density compared with ultra-capacitors. Ultra-capacitors have very high power density but hold very little energy. In the last decade, the research and development of new batteries have been accelerated. In order to meet the extremely varying technical and economical requirements in fast growing vehicular applications, the lithium and nickel are replacing lead in batteries.

Table 9 Major power storage types used in hybrid vehicles

Battery type	Specific Energy (wh/kg)	Specific Power (W/kg)	Energy Effi. (%)	Cycle life (#)	Specific cost[3] ($/kWh)
Lead-acid	35-40[1]	150-400	>80	500-1000	120-150
	30[2]	>450	-	>3000	<150
NiCd	40-60	80-150	65	1500-2000	200-400
NiMH	70-90[1]	200-300	<50	>1200	300
	35-40[2]	650	-	100000	400-450
Ni-Zn	55-75	170-260	70	750-1200	200-350
Li-ion	80-130[1]	200-300	>95	>1000	200
	90[2]	1400	-	300000	500
Ultra-capacitor	3-5	300-500	90-95	100000+	500,000

[1]High energy type; [2] High power type; [3] Battery cost projections for production volume of 100,000 packs per year.

Ultra-capacitors are presently being proposed by various vehicle manufacturers for HEVs to load level energy demand and shave peak power of used batteries in order to solve some of the problems involved with their use: capacity limitation, life and thermal management [31]. But the use of ultra-capacitors is limited because of its highly cost. The characteristics of the batteries and ultra-capacitor are summarized in Table 9 [7,31,32].

Two necessary conditions should be considered for the power storage applied in HEVs [33]:

(1) Available energy capacity

The available energy of the batteries should be sufficient for discharge and charge requirements. Correspondingly, the peak requirements often occur at continuous pure electric propulsion and long-time regenerative brake operations. Shown graphically in Fig. 13, for an idealized charge un-depletion battery, the available energy is, indeed, roughly 50% of the rated capacity.

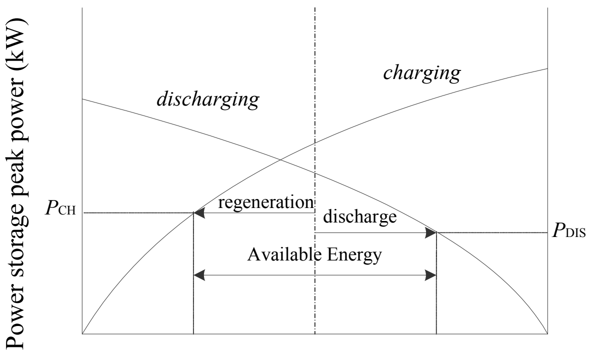


Fig. 13 Power capacity vs. SOC

(2) Power ability

Within the available SOC range, the battery should be capable of output and storage energy at the peak discharge power requirements (P_{DIS}) and the charge power requirements (P_{CH}), respectively.

Table 10 shows a case of propulsion system size for the hybrid bus. Considering the availability, safety and energy density, a high-power 336V, 60Ah Nickel Metal Hydride (NiMH) battery pack from Chunlan which embodies 280 cells connected in series is used as power storage. This battery can discharge at 4 times rated current with the SOC of 75% and charge at 5 times rated current with the SOC of 40% for 1 minute periods. The specific power is more than 500W/kg. The batteries can operate at -20^{o}C to +55^{o}C. To supply adequate thermal management, the battery pack is air cooled with motor fans. The characteristic parameters of the battery cells are presented in Fig. 14.

Table 10 Propulsion system parameters

Parameters	Specification/ cost
Engine	-
▪ Peak power (kW)	135
▪ Peak torque (N·m)	550
▪ Speed range (rpm)	0~2,500
TM	\$5,882[1]
▪ Peak power (kW)	80
▪ Continuous power (kW)	40
▪ Peak torque (N·m)	450
▪ Speed range (rpm)	0~10,000
ISG	\$2,941[1]
▪ Peak Power (kW)	30
▪ Continuous Power (kW)	20
▪ Peak torque (N·m)	290
▪ Speed range (rpm)	0~3,000
Battery	\$14,706[2]
▪ Type	NiMH
▪ Power capability (Ah)	60
▪ Rated voltage (V)	336

[1] The controllers of electric motors and the converters/inverters are integrated in one unit, their costs are included.
[2] The BCU is included.
[1,2] These bulk prices are provided in RMB by certain manufactures in China, the RMB:USD exchange ratio is considered as 6.8:1.

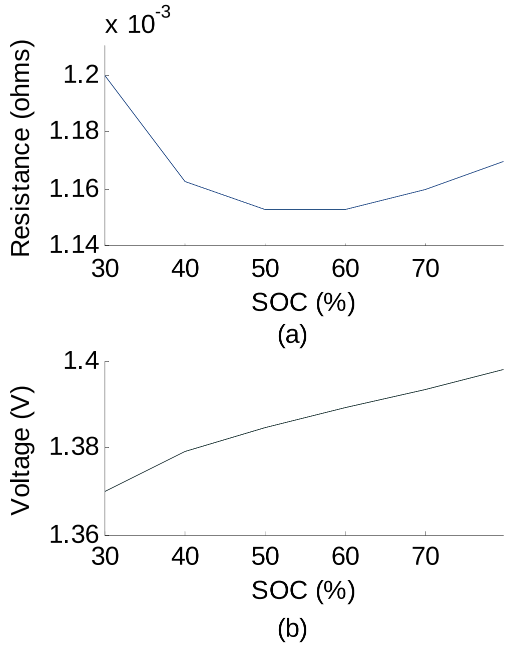


Fig. 14 Characteristic parameters of battery cells: (a) resistance; (b) open circuit voltage.

4 Features for Improving Fuel Economy

As to a series-parallel propulsion system, some features inherited from both the series and the parallel configurations can be used to improve its fuel economy or reduce the emission pollutions. The major technical features of the SPHEPS proposed in the paper are introduced as follows.

4.1 Downsized Engine

It is well known that it is possible to achieve a reduction in fuel consumption by downsizing the engine and it is reasonable to select the compression ignition diesel engine as the ICE power since it is the most efficient energy conversion of fossil fuels for vehicle propulsion. Therefore, considering the engine has to operate efficiently at a multitude of speed and loads, a 4-cylinder generic direct injection, compression ignition diesel engine with the rated power of 135kW at 2500rpm and the peak torque of 550N·m at 1200~1700rpm, which is downsized compared with the original 6-cylinder engine, is used in this bus.

4.2 Elimination of Idling

Like a series hybrid electric propulsion system, the following measures have been incorporated in the bus to eliminate engine idling.

(1) Start the ICE with the ISG;

(2) Operate accessories, including the electric air conditioner, electric motor for air tanks and electro-hydraulic steering system, by electric power.

(3) Using a DC-DC converter to supply 24V power from the batteries.

The engine idling will be automatically shut off if one of the conditions below is satisfied:

(1) Stop the vehicle at a traffic light in neutral gear.

(2) Set the transmission in first gear without battery charge requirement.

4.3 Regenerative Braking

This system recovers deceleration energies. For a motor-driven vehicle, the brakes can be applied by means of regeneration to convert the deceleration energy to electric energy charging the batteries. Pure electric propulsion condition should be the most favorite case for regeneration because the engine friction is not produced, which increases the amount of energy regenerated at low-speed. For this powertrain configuration type, the traction motor is mechanically linked to the wheels directly, which is beneficial for capturing kinetic energies.

4.4 Low-speed Electric Propulsion

Electric propulsion is beneficial for the frequent start-stop, low-speed, rapidly accelerating and decelerating conditions for a transit bus to reduce the fuel economy and emission pollutions. With the pure electric propulsion capability, the first gear is recommended when the vehicle is moving at a low-speed.

4.5 Operate ICE in Economic Regions

Notice that the gear status is passively resulted in by the driver for a manual transmission. It means that the speed of the ICE can not be actively optimized when the bus runs as a parallel hybrid electric vehicle, but the output torque of the ICE at a rotational speed can be tuned to an economic range. A real-time optimal control strategy is then adopted to operate the ICE in the economic regions in both the series and the parallel configuration.

Meanwhile, as is shown in Fig. 15, the charge-sustaining rules are also included in the control strategy to prevent the depletion and overcharge of the battery, which should deteriorate the batteries' life and performances. If the battery state of charge (SOC) is low, an additional power will be commanded to the engine to power the electric motors charging the batteries.

The power flow paths are classified into three types when the transmission is set in non-first gears (parallel configuration):

(1) Engine alone (EA).

If the required torque is economic for the ICE or the battery/motor is insufficient to assists the ICE, the vehicle should be drive by engine alone. It often occurs when the vehicle cruises at a high speed or runs at higher load with low battery charge state.

(2) Motor assist (MA).

If the vehicle is suddenly accelerated, climbing hill or over charged, the traction motor must provide assist torque to power the vehicle and then to satisfy the driver's attention or prevent battery overcharge.

(3) Parallel charge (PC)

This mode often occurs when the battery state charge is low or the vehicle load is low at normal SOC range. A charging torque is commanded from the engine to generate electricity in this mode.

Besides these modes, three other modes are also included in the operations of the system, they are:

(1) Regenerative brake (RB).

(2) Motor alone (MAL, series configuration).

If the battery/motor is sufficient in first gear, the vehicle is then powered by the TM alone, and the ICE-ISG is shut down.

(3) Series charge (SC, series configuration).

In series configuration, if the battery/motors are incapable of satisfying the driver's requirement or the battery need charging to prevent depletion, the ISG will start the ICE and combines it as an on-board generator set to charge the battery and power the electric motors. Since the driveline is cut off at

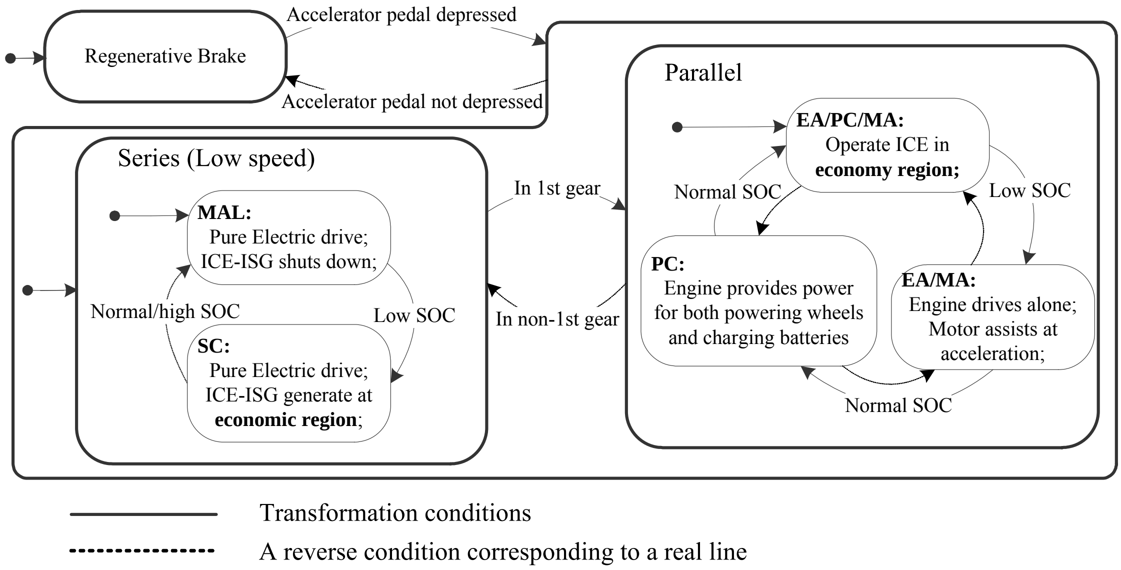


Fig. 15 Control strategy of the HECTB

first gear, the vehicle is also propelled by the TM alone.

The ICE operation regions in both series and parallel configurations for a city driving cycle are shown in Fig. 16. In this figure, the Brake Specific Fuel Consumption (BSFC) contours are given in grams per kilo Watt hrs. The left bottom section gives the ICE-ISG operation points in the ICE-ISG generator set efficiency Map in series charge mode. At each configuration, the ICE is controlled to operate in the pre-set economic regions.

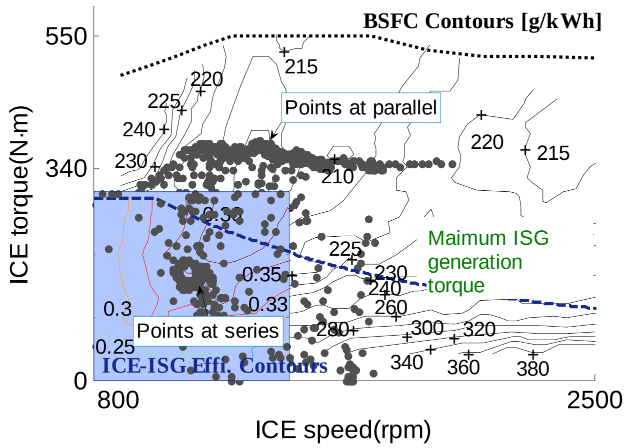


Fig. 16 ICE operation regions

In summary, the features can be presented as a representative real operation shown in Fig. 17:

(1) A~B: electric launch and propel the bus at low speed;

(2) B: the ISG starts the ICE;

(3) B~C: operate the ICE at economic regions in the parallel configuration;

(4) C~D: Regenerative brake.

(5) C(D)~E: the ICE-ISG charges the batteries.

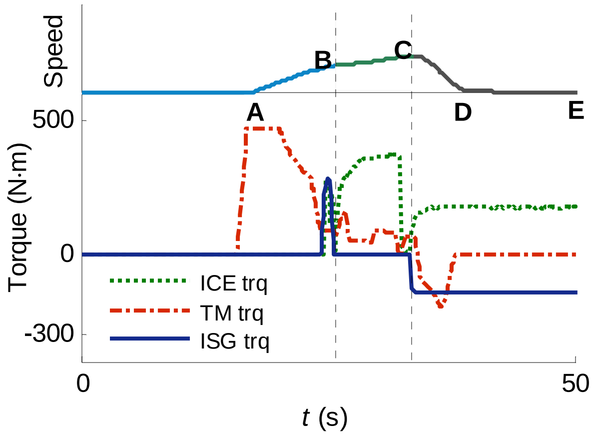


Fig. 17 Representative operation of the bus

5 Fuel Economy Evaluations

The fuel economy of the SPHETB is evaluated under the Chinese Transit Bus City Driving Cycle (CTBCDC). The cycle distance is 5.8km for 1314 secs. Fig. 18(a) shows the profile of this cycle. An experimental test case is also shown in this figure, it can be seen that the SOC is sustained within the desired range under the control strategy presented above.

Some experimental tests have been carried out to evaluate the bus's fuel economy. Since the driver's operations in transmission will deeply affect the performances of a manual-shifted propulsion system, different types of drivers have been involved in the tests. In the case that the final SOC and the initial SOC are not the same, a linear approach using a

SOC correction factor k, which represents the equivalent fuel consumption per unit of SOC, is adopted to calculate the equivalent fuel consumptions (EFC):

$$EFC = FC - k \cdot \Delta SOC \tag{10}$$

$$\Delta SOC = F_{\mathrm{SOC}} - I_{\mathrm{SOC}} \tag{11}$$

$$k = \frac{Q_{\mathrm{C}}}{\rho_{\mathrm{F}} \cdot LHV \cdot \eta_{\mathrm{CH}} \cdot S_{\mathrm{CYC}}} \tag{12}$$

where FC is the fuel consumption; F_{SOC} is the final SOC; I_{SOC} is the initial SOC; ΔSOC is the SOC interval; Q_{C} is the battery energy capacity; ρ_{F} is the fuel density; LHV is the low heat value of diesel; S_{CYC} is the cycle's distance; the overall charge efficiency, including the losses in the ICE-GEN and batteries, η_{CH} is assumed as 30% on average.

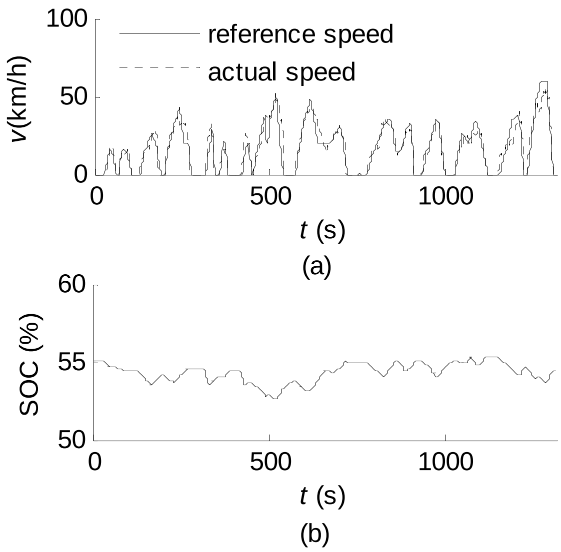


Fig. 18 Test case under CTBCDC: (a) reference and actual speed; (b) transient SOC.

Fig. 19 shows some samples of the half-load fuel consumptions in Liters per 100km vs. the SOC intervals. The EFC range is 29.0~33.9L/100km. The base fuel consumption is 31.5L/100km, which is on average reduced by 21.3% compared with the conventional diesel bus's fuel consumption of 40.0L/100km.

6 Conclusions

The design approaches for the SPHEPS are introduced in this paper. Based on the analysis of the base units, a design case of a low-cost manual-shifted SPHEPS for city transit bus is presented. The fuel economy of the hybrid bus is evaluated. The results show that the SPHEPS proposed in this paper helps to reduce the fuel economy of 21.3% to that of the conventional bus at city transit bus driving cycle while the drive performances are satisfied, which also identifies its feasibility.

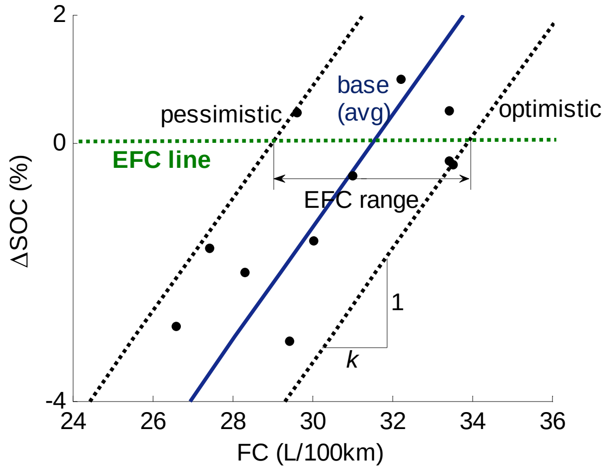


Fig. 19 Fuel consumptions vs. SOC intervals for the bus

The design approaches presented in this paper can also be applied in the automatic-shifted series-parallel hybrid electric propulsion systems. It is known that an automatic transmission will help to optimize the fuel economy and emissions globally and release the operators' labor, and our group also takes efforts on the development of the automatic system. The evaluations of performance differences between the manual and automatic system as well as the optimization of such a system need deeply future studies yet.

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