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Optimized Design and Analysis of a Series-Parallel Hybrid Electric Vehicle Powertrain for a Heavy Duty Truck

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Abstract: Hybrid electric vehicles are considered as an eco-friendly alternative solution to conventional internal combustion engine driven vehicles. This paper investigates the development of a Series-Parallel hybrid electric vehicle powertrain for a heavy-duty truck based on vehicle performance requirements, and compares its performance with a Series hybrid electric configuration for the same base vehicle. The parameter matching of the vehicle powertrains was followed by optimization in terms of maximizing fuel economy for an Indian highway drive cycle using the software ADVISOR. The simulation results quantified the potential benefits of the optimized series-parallel hybrid electric configuration for a highway drive cycle with respect to the series hybrid electric configuration.

Keywords: Hybrid Electric Vehicles, Powertrain Optimization, Vehicle Performance.

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1. INTRODUCTION

Electric and hybrid electric vehicles (HEVs) have been recognized as promising technologies to replace conventional internal combustion engine (ICE) driven road vehicles, improving fuel economy and reducing harmful tail pipe emissions. The main hybrid electric powertrains available are series HEVs (SHEVs), parallel HEVs (PHEVs) and series-parallel HEVs (SPHEVs) (Ehsani, 2005). This study focused on a SPHEV as it can provide the advantages of both SHEV and PHEV, and depending on the control strategy, the most efficient configuration can be selected based on the driving conditions.

The most common form of SPHEV powertrain uses a planetary gear unit for power split whereas a few studies can be found for a SPHEV that uses a combination of two concentrically arranged electric machines for power split (Chen, 2009). A few papers have discussed the design, modeling and simulation of a SPHEV powertrain based on drive cycle demand (Niasar, 2005 and Li, 2015). SPHEV powertrain currently dominates the passenger cars market (Chen, 2011) with various studies made in terms of performance and fuel economy (Cheng, 2015 and Jingping, 2011). This paper investigates the performance of a SPHEV powertrain for a heavy commercial road vehicle (HCV). In (Liang, 2009, Cao, 2009 and Piboonrujananon, 2011), the authors had evaluated the use of a SHEV powertrain for a city bus under urban drive conditions. Since most trucks are predominantly operated on highways, a comparative analysis has been done in this paper between a SPHEV powertrain and a SHEV powertrain for a heavy-duty truck in terms of vehicle performance and fuel economy under highway operation. With increasing emphasis on electrification of road vehicles in India (Department of Heavy Industry, 2016), this paper evaluates the performance of these HEV powertrains under an Indian highway drive cycle followed by their optimization to maximize fuel economy subject to a set of vehicle performance constraints.

The vehicle powertrain design starts with initial parameter matching and sizing of its components, based on the equations of vehicle dynamics (Skugor, 2012). The next step involves the optimization of the parameterized powertrain, using different optimization algorithms (Gao, 2007). Gradient-based algorithms (Gao, 2007) use the derivative to find the local minima whereas, derivative free algorithms work well for objective functions that do not rely on derivatives. This paper used the divided rectangles (DIRECT) algorithm for optimization. Based on literature review (Niasar, 2005 and Skugor, 2012), a rule based control strategy has been used for the HEV powertrains.

In summary, the work presented in this paper can be divided into two main categories:

- initial parameter matching and design of the components for HEV powertrains to meet the vehicle performance; and
- optimization of the HEV powertrains to minimize fuel consumption subject to a specific set of constraints for the given highway drive cycle.

2. DESIGN OF A SPHEV

A SPHEV powertrain (Fig. 1) consists of a downsized internal combustion engine (ICE), a generator, a traction motor, an energy storage device and mechanical coupling devices such as a speed coupler and a torque coupler. This arrangement provides more flexibility in operating the engine in its optimized torque-speed region.

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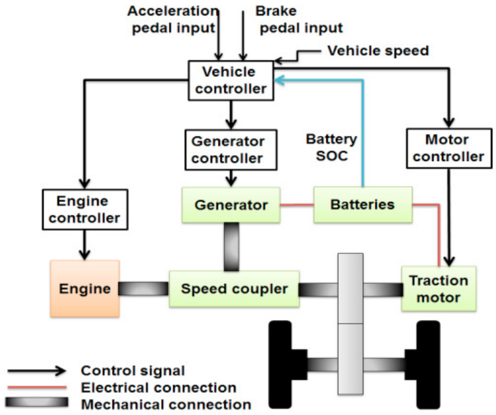

Fig. 1. Layout of a SPHEV Powertrain.

The ICE is used to supply the steady state power requirements, whereas the motor power is designed to meet the initial acceleration and gradeability at low speed (Ehsani, 2005). Mechanical coupling consists of torque coupling and speed coupling (Ehsani, 2005). A typical speed-coupling device is a planetary gear unit (Fig. 2), consisting of a sun gear, a ring gear, several planet gears and a carrier that is hinged to the centres of the planet gears. In the drivetrain considered here, an ICE and an electric generator are connected to the planet carrier and the sun gear respectively (speed coupling). The ring gear of the planetary unit is the output port that is connected to the drive wheels through a fixed gear (torque coupling). A traction motor is also connected to the drive wheels through the fixed gear, which couples the output torques of the ring gear and the traction motor together.

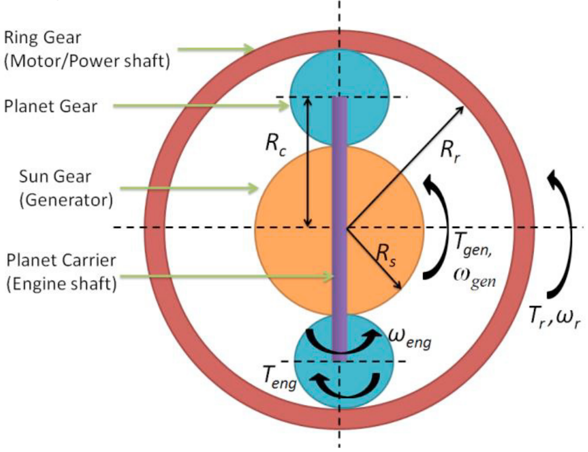

Fig. 2. Planetary gear unit.

The maximum power output from the engine for a constant speed of v_{max} is given

$$P_{eng(\max)} = \frac{1}{\eta_t}(Mgf_r + \frac{1}{2}\rho C_d A v_{\max}^2) v_{\max}, \tag{1}$$

where M is the mass of the vehicle, f_r is the rolling resistance coefficient, C_d is the coefficient of drag, A is the frontal area and η_t is the transmission efficiency. The electric motor power rating, P_m, designed to meet the vehicle acceleration performance is given by (Ehsani, 2005)

$$P_m = \frac{\gamma M}{2t_a\eta_t}(v_f^2 + v_b^2), \tag{2}$$

where γ is the rotational inertia factor (Nandakumar, 2015), t_a is the acceleration time, v_f is the vehicle rated speed (km/h) and v_b is the vehicle speed corresponding to the motor base speed. The rotational speeds of the ring gear, the generator (sun gear) and the engine (carrier) satisfy

$$\omega_r = \frac{1+k}{k}\omega_{eng} - \frac{\omega_{gen}}{k}, \tag{3}$$

where k is the planetary gear ratio defined as the ratio of the radius of the ring, R_r, to the radius of the sun, R_s. As the ring gear is connected to the drive wheels through a fixed reduction gear,

$$v = \omega_w r_e (1-s) = \frac{\omega_r r_e (1-s)}{i_g}, \tag{4}$$

where ω_w is the rotational speed of the wheels, v is the vehicle longitudinal speed and s is the wheel longitudinal slip ratio, which is considered to be 10%. From (3), it can be concluded that for a desired engine speed, the vehicle longitudinal speed can be varied by controlling the generator speed. The torques transferred from the ICE, T_{eng}, to the ring gear, T_r, and to the generator, T_{gen}, are given by (5) and (6) respectively:

$$T_r = \frac{k}{k+1}T_{eng}, \text{ and} \tag{5}$$

$$T_{gen} = \frac{1}{1+k}T_{eng}. \tag{6}$$

The drive shaft is connected to the ring gear through a final reduction gear with a gear ratio, i_g. Hence, the total drive torque at the wheels is

$$T_{wheels} = \frac{1}{i_g\eta_t}(T_m + T_r) = \frac{1}{i_g\eta_t}\left(T_m + \frac{k}{1+k}T_{eng}\right). \tag{7}$$

3. CONTROL STRATEGY OF SPHEV POWERTRAIN

The various operation modes available are engine alone traction mode, motor alone traction mode, engine and motor hybrid traction mode, battery charging and regenerative braking (Ehsani, 2005). Depending on the driving conditions, the vehicle controller chooses one of these operating modes (Fig. 3).

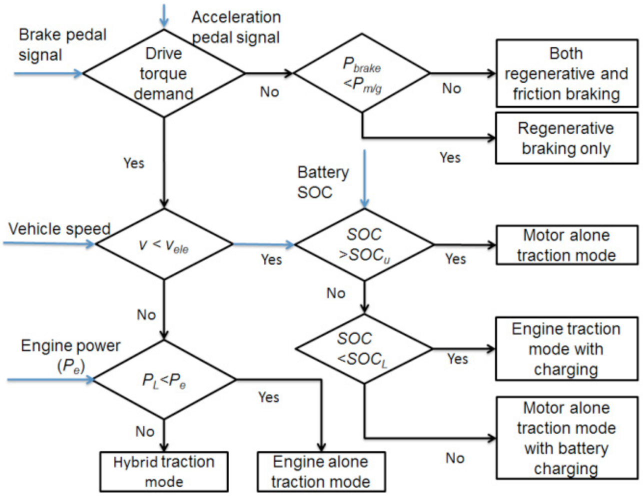

Fig. 3. Flowchart of the control logic.

4. COMPONENT SIZING OF SPHEV POWERTRAIN

The vehicle parameters considered in this study are given in Table 1 (Ashok Leyland Ecomet 1214 Strong truck, 2016) and the performance specifications in Table 2. The same vehicle was used as a base vehicle to change the drivetrain from conventional to a SPHEV powertrain. The coefficient of drag (C_d) and the coefficient of rolling resistance (f_r) for the heavy duty truck was taken from (Wong, 2011).

Table 1. Vehicle parameters

Glider Mass	3940 kg
Cargo Mass	9700 kg
ICE power, mass	200 kW, 545 kg
Gross Vehicle Weight (GVW)	14351 kg
A_f	6.50 m^2
C_d	0.44
f_r	0.009
r_e	0.50 m
L	4.75 m

Table 2. Vehicle performance specifications

Maximum speed	95 km/h
Gradeability	15 % at 16 km/h
Acceleration speed	0 to 50 km/h
Acceleration time	13 s

Based on the equations provided in section 2, the initial component sizing for the SPHEV powertrain was done, with the component specifications summarized in Table 3. The electric launch vehicle speed, v_{ele}, during which the motor only drives the wheel, was considered to be 30 km/h in this study. An induction motor with a maximum speed of 12000 rpm and a speed ratio of 5 was considered. Li-ion batteries were considered in this study. The planetary gear ratio was calculated for a cruising speed of 95 km/h with engine alone traction mode.

Table 3. Specifications of SPHEV components

Engine	Max. power (kW)	73
	Max. speed (rpm)	2500
Generator	Torque output (Nm)	100
	Max. speed (rpm)	7000
	Efficiency (%)	90
Traction motor	Torque output (Nm) at speed (rpm)	565 at 2400
	Max. power (kW)	135.24
	Max. speed (rpm)	12000
	Efficiency (%)	90
Batteries	Battery cells	150
	Initial capacity (Ah)	70
	Power (kW)	136
	Energy output (kWh)	90
Planetary gear ratio (k)		3.913
Final drive ratio		5.57

5. DESIGN OF A SHEV POWERTRAIN

A SHEV consists of an electric motor directly connected to the wheels through a single speed gearbox. The ICE is mechanically disconnected from the transmission system and its working mode is independent of the vehicle load conditions. The ICE along with the generator recharges the batteries when the state of charge (SOC) goes down below its lower limit and/or provides electrical power directly to the traction motor.

In a SHEV, the maximum vehicle speed is limited by the maximum motor speed, gradeability is limited by maximum motor torque and the acceleration is limited by the peak power of the motor. The fundamental vehicle equations used for the initial parameter matching of the vehicle components are well established (Ehsani, 2005). Initial parameter matching of the SHEV powertrain for the heavy duty truck was analyzed by the authors and presented in (Borthakur, 2016). Based on the analysis, the initial component sizing of the SHEV powertrain is summarized in Table 4.

The commonly used rule based control strategies for SHEV powertrains are maximum SOC of peak power source (Max. SOC-of-PPS) and the engine turn-on and turn-off (thermostat control strategy) (Ehsani, 2005). For this study, thermostat control strategy was used for the SHEV powertrain.

Table 4. Specifications of SHEV components

Engine	Max. power (kW)	49
	Max. speed (rpm)	2500
Generator	Torque output (Nm)	60
	Max. speed (rpm)	7000
	Efficiency (%)	90
Traction motor	Torque output (Nm) at speed (rpm)	635 at 2400
	Max. power (kW)	152
	Max. speed (rpm)	12000
	Efficiency (%)	90
Batteries	Battery cells	160
	Initial capacity (Ah)	72
	Power (kW)	187
	Energy output (kWh)	130
Transmission (i_g)		20.81

6. OPTIMIZATION OF THE HEV POWERTRAINS

Once the initial parameter selection of the powertrain was accomplished, its performance was evaluated using ADVISOR (National Renewable Energy Laboratory, 2015) for a Modified Indian drive cycle (MIDC) developed by the Automotive Research Association of India (ARAI) (ARAI CMVR Type approval document). It is a synthesized cycle consisting of two parts: elementary urban drive cycle and a highway drive cycle. For this simulation study, only the highway drive cycle was considered (repeated four times) (Fig. 4). To ensure the vehicle's best performance, an optimization of the parameterized SPHEV and SHEV was done using ADVISOR in Graphic User Interface (gui)-free mode with the optimization procedure in MATLAB®.

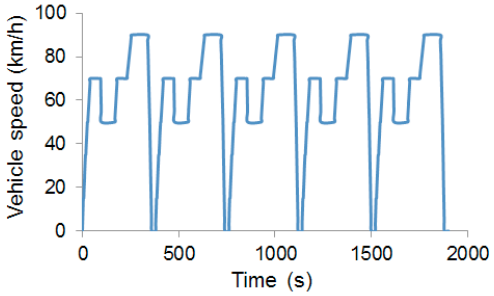

Fig. 4. MIDC considered for the study

The objective considered for optimization was maximization of fuel economy, and the fuel consumption was calculated in terms of mpgge (miles per gallon gasoline equivalent) (Chris, 2011). The design variables of the main powertrain components considered for optimization are listed in Table 5 and Table 6 for SPHEV and SHEV respectively; whereas the constraint conditions are listed in Table 7. Both the design variables and constraint conditions were defined in terms of scaling factors, which when multiplied by the original values gives the actual values of the variables after optimization.

Table 5. Design variables used and their limits for SPHEV

Design variables	**Nomenclature**	**Lower bound**	**Upper bound**
ICE power scale	fc_pwr_scale	1.0	3
Electric motor torque scale	mc_trq_scale	0.8	3
Number of battery cells	ess_num	120	170
Battery capacity (Ah)	ess_cap_scale	10	20

Table 6. Design variables used and their limits for SHEV

Design variables	**Nomenclature**	**Lower bound**	**Upper bound**
ICE power scale	fc_pwr_scale	0.20	3
Electric motor torque scale	mc_trq_scale	1.80	3
Number of battery cells	ess_num	130	170
Battery capacity (Ah)	ess_cap_scale	10	20

Table 7. Constraint conditions for optimization process

Constraints	**Description**	**Requirements**
accel_time	Acceleration of 0-60 km/h	≤ 6.54 s
grade	Gradeability at 16 km/h	≥ 15% for 60 s
delta_trace	Difference between drive cycle requested speed and vehicle achieved speed at every second during the drive cycle	≤ 3.20 km/h
delta_soc	Difference between final and initial battery state of charge	≤ 0.50 %

The flow chart of the optimization procedure is shown in Fig. 5. The optimizer was numerically developed in MATLAB® based on DIRECT algorithm (Jones, 2001), which was integrated with the gui-free ADVISOR mode. Initially the vehicle model was simulated, using the initial design variables to calculate the numerical value of the objective function. Subsequently, the constraint functions were also calculated. These simulation results were fed back to the optimizer, generating a new set of design variables. The vehicle model was simulated again to get the new values of the objective and the constraint functions, with the values restricted within their upper and lower bounds. The iterative procedure went on until the convergence of the constraint functions were obtained, which subsequently gave the maximum mpgge for the vehicle for the given drive cycle.

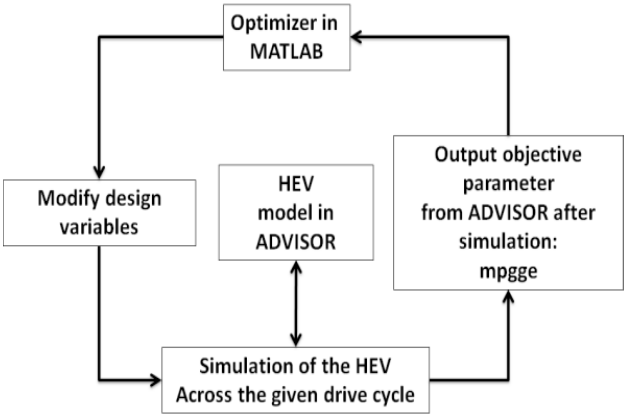

Fig. 5. Flowchart of the optimization process

7. SIMULATIONS AND RESULTS

Once the initialization was done, the optimizer was run for the MIDC (ARAI CMVR Type approval document) (Fig. 4) for 500 iterations, with the output in terms of fuel economy being fed back to the optimizer. In this study, convergence of the objective and constraint functions was obtained after the 100th iteration. Figure 6 presents a comparison between the two HEV powertrains in terms of objective function for the given MIDC to illustrate the convergence of the optimization. The comparison of the design variables for the HEV powertrains along with the ICE vehicle before and after optimization for the given drive cycle are listed in Table 8, and the corresponding observations are:

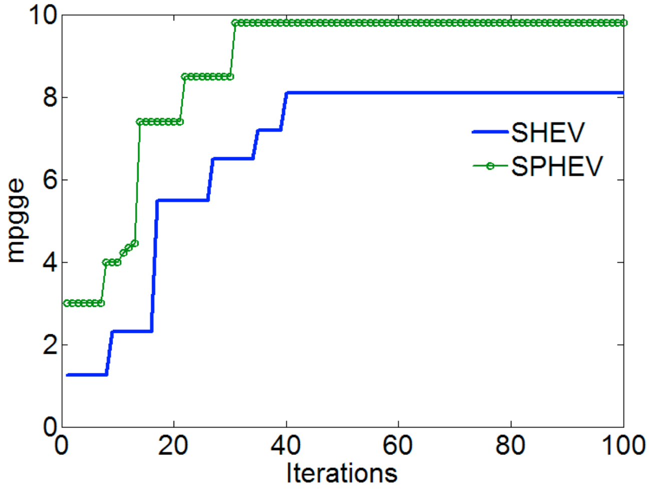

Fig. 6. Iterations of objective function

- When optimized for the given drive cycle, ICE could be downsized appropriately catering to the vehicle requirements. A percentage decrease of 16.44% and 16.33% of engine power could be found for the SPHEV and SHEV before and after optimization, respectively.
- During simulation and optimization of the vehicle powertrain for the drive cycle, the efficiency of the motors varied with the load torque to reflect the operating points of the motors. A reduction of 17.35% and 17.11% of the motor power was observed for the SPHEV and SHEV after optimization, respectively.

The vehicle performance outputs before and after optimization are given in Table 9. After optimization, the fuel economy was improved by 14.09% and 12.03% for SPHEV and SHEV respectively, when compared to the fuel economies before optimization. The fuel economy (in terms of mpgge) and the maximum longitudinal speed of the optimized SPHEV were better than those of the optimized SHEV by 20.99% and 12.24% respectively. The same trend in acceleration performance and gradeability could be observed with the optimized SPHEV performing better than the optimized SHEV by 13.33% and 2%, respectively. Thus, the optimized SPHEV showed an improvement in performance and fuel economy than an optimized SHEV for a highway drive cycle.

Table 8. Comparison of vehicle component parameters

Vehicle component parameters	**Conventional vehicle**	**SPHEV**		**SHEV**	
		Hybrid vehicle before optimization	***Hybrid vehicle after optimization***	***Hybrid vehicle before optimization***	***Hybrid vehicle after optimization***
Engine power (kW)	200	73	61	49	41
Motor power (kW)	-	135.24	111.77	152	126
Number of battery cells	-	150	147	160	163
Battery capacity (Ah)	-	70	68	72	86

Table 9. Comparison of vehicle performance

Vehicle performance	SPHEV		SHEV	
	Before optimization	After optimization	Before optimization	After optimization
Mpgge	8.59	9.8	7.23	8.1
Time to reach 0-50 km/h	8.2	7.8	9.20	9
Max. longitudinal speed (km/h)	110.2	110.72	98	98.65
Gradeability (%)	16.20	17.20	16.60	16.90

8. CONCLUSIONS

This paper investigated a SPHEV powertrain and a SHEV powertrain for an Indian highway drive cycle in terms of vehicle performance and fuel economy. From analysis of vehicle dynamics and driving conditions, an initial parameterization of both powertrains was done. The initial component sizing was followed by an optimization procedure to meet the design objective of maximizing the fuel economy subjected to a set of vehicle performance constraints. The optimization of the SPHEV powertrain showed an improvement in the fuel economy by 20.99% and as compared to the optimized SHEV for the Indian highway drive cycle. The result analysis also showed an improvement in the vehicle performance of the optimized SPHEV in terms of acceleration performance, maximum longitudinal speed and gradeability, when compared to the optimized SHEV. This analysis showed that for a HCV, SPHEV powertrain performed better in a highway drive where a high cruising speed needs to be maintained. The comparative analysis before and after optimization also showed that a HEV powertrain is sensitive to driving conditions and the component characteristics of the powertrain need to be optimized for a drive cycle.

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