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A Simple Technique for Optimal Selection of Degree of Hybridization (DOH) in Parallel Passenger Hybrid Cars

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Original scientific paper

In this paper, a simple but efficient Non-dominated Sorting Genetic Algorithm (NSGA) II based technique is proposed for optimizing the Degree of Hybridization (DOH) in parallel passenger hybrid cars. The authors' objective is to improve performance, maximize fuel economy and at the same time, minimize mass and emissions as much as possible, by optimal selection of DOH. The NSGA-II, which is a multi-objective optimization algorithm, is applied to optimize this multiple objective problem. The ADvanced VehIcle SimulatOR (ADVISOR) software is used as simulation tool. To validate high efficiency of proposed methodology, necessary simulations have been carried out on a small-size test car. The results indicates that the proposed methodology is very fast and efficient and can be well applied to any other types of Hybrid Electric Vehicles (HEVs).

Key words: Degree of Hybridization (DOH), Electric motor, Emissions, Fuel economy, Performance

Jednostavna metoda za optimalan odabir stupnja hibridizacije (DOH) u paralelnim putničkim hibridnim automobilima. U radu je predložena jednostavna i efikasna metoda zasnovana na nedominirano-sortirajućem genetičkom algoritmu (NSGA) II u svrhu optimiranja stupnja hibridizacije (DOH) u paralelnim putničkim hibridnim automobilima. Cilj je unaprijediti performanse, maksimizirati ekonomičnost goriva te istovremeno minimizirati emisiju koliko god je moguće uz optimalni odabir DOH. NSGA-II algoritam, koji spada u višekriterijske optimizacijske algoritme, korišten je za optimiranje problema s više ciljeva. Napredni simulator vozila (ADVISOR softver) korišten je kao simulacijski alat. Simulacije su provedene na umanjenom testnom vozilu kako bi se validirala visoka efikasnost predložene metodologije. Rezultati ukazuju da je predložena metoda vrlo brza i efikasna te ju je moguće primijeniti i na bilo koji drugi tip hibridnog električnog vozila (HEV).

Ključne riječi: Stupanj hibridizacije (DOH), elektromotor, emisije, ekonomičnost goriva, performanse

1 INTRODUCTION

Fossil fuel consumption and air pollutants are increasing dramatically during recent decades. The conventional vehicles are considered as the main cause of these two serious problems [1-6].

The best solution put forward till now is to electrify the conventional vehicles [7]. It means that beside the Internal Combustion Engine (ICE) as main power source, an auxiliary power source is needed which in most cases, is an electric motor. Depended on how powertrain propels the vehicle, the hybrid electric vehicle is classified into three main types: parallel, series and series-parallel. In this work, the parallel type is just taken under study. Basic configuration of a parallel hybrid car is illustrated in Fig. 1. A parallel hybrid car is propelled by both the internal combustion engine (ICE) and electric motor connected to a mechanical transmission. Power distribution between the Internal Combustion Engine (ICE) and electric motor is altered so both operate in their optimum operating region as much as possible. There is no separate generator in a parallel hybrid. Whenever the generator's operation is needed, the motor functions as generator.

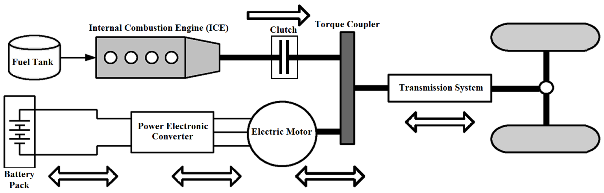

Fig. 1. Basic structure of a parallel hybrid car

The Degree of Hybridization (DOH), which specifies the portion of the power provided by the electric motor and

Internal Combustion Engine, is defined as follows [1-6]:

$$DOH = \frac{P_{EM}}{P_{EM} + P_{ICE}} = \frac{P_{EM}}{P_{Total}}, \quad (1)$$

whereP_{EM} and P_{ICE} are the powers provided by the electric motor and the internal combustion engine (ICE), respectively. Also P_{Total} represents the total power of vehicle, which is sum of P_{EM} and P_{ICE} [1-6].

The Degree of Hybridization (DOH) has great effect on the fuel economy, emissions and performance of the Hybrid Electric Vehicle (HEV) [2-6]. So, our main objective in this work is to satisfy all these target parameters as much as possible by optimizing the degree of hybridization. During recent years, several papers have been proposed for optimizing the degree of hybridization. Optimization algorithm is the main content in the optimal sizing of the propulsion system of the hybrid electric vehicles [2-6]. In [1], Fellini used two optimization methods namely DIRECT (Divided RECTangles) and Complex and linked them to the ADVISOR, to optimize the Degree of Hybridization in HEVs. Both optimization algorithms were able to converge to approximately the same solution. However, DIRECT was the most efficient for the problem. This methodology takes long time to run the simulations and find the optimal Degree of Hybridization. Also, studies show that these two used optimization algorithms aren't as efficient as newly proposed evolutionary algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and so on.

In [2] a Particle Swarm Optimization (PSO) based technique has been used for finding the optimal degree of hybridization. The Particle Swarm Optimization (PSO) is simple and fast but its main deficiency is poor accuracy. It may converge to local optimal solutions instead of global ones. In [3], the degree of hybridization has been chosen by examining the efficiency maps of the internal combustion engine (as the main power source) at various operating points. The calculated Degree of Hybridization using this methodology is not necessarily the optimal one but it guarantees the optimal operation and performance of the internal combustion engine. In [4-5] multiple objective algorithms have been used but, these papers have just focused on the fuel economy and/or emissions and the performance of the vehicle has not been considered as target parameters.

In this Paper, an efficient technique is proposed. Since the problem is a multi-objective one, Non-dominated Sorting Genetic Algorithm II (NSGA II), which is a multi-objective optimization algorithm, is adopted. Beside the fuel economy and emissions, the performance of the vehicle is improved by proposed technique. Also, much better and efficient approach is used for deciding about the number of battery modules, compared to that used in [2]. This technique will be explained in the following section.

2 DECIDING ABOUT THE NUMBER OF BATTERY MODULES

In this paper, the power matching method has been used for deciding about the number of battery modules of the energy storage system. In this method, the number of battery modules must be decided in a way that the energy storage system be always able to produce the power needed by the electric motor. Maximum amount of propulsion power that can be requested during the driving cycle from the electric motor is its rated power (P_{EM}). So maximum amount of power production that the energy storage system should be capable is as follows [6, 11-12]:

$$\text{Maximum Discharge Power} = \frac{P_{EM}}{\eta_{converter}}, \quad (2)$$

where $\eta_{converter}$ represents the overall efficiency of the converters used between the energy storage system and electric motor and the electric motor itself, also.

3 PROPOSED METHODOLOGY

It is assumed that the performance of test vehicle is characterized by maximum speed, gradeability, 0-60, 40-60, 0-85 mph acceleration times and distance covered in 5 seconds. There were several other parameters like; range of vehicle, time of 0.25 mile and maximum acceleration rate that could be considered as performance parameters too, but in this work, have not been taken under study. Thus in this paper, the objective is to maximize fuel economy, gradeability, maximum speed and distance covered in 5 seconds, and at the same time, minimize the 0-60, 40-60, 0-85 mph acceleration times, mass and emissions of the vehicle. The emission of the vehicle is described as equation (3) [12]:

$$\text{Emissions} = \frac{[HC + CO + NO_x]}{3} \quad (3)$$

Steps of the proposed methodology are as follows:

1. The total power of test vehicle is selected and is kept constant during the simulations.
2. The Degree of Hybridization (DOH) of the vehicle is altered by increment steps of 0.05 within its valid range. For each degree of hybridization, corresponding value of target parameters are extracted from the ADVISOR software. The gathered data are interpolated using 'cubic' method in MATLAB R2010a software. Since the difference between the corresponding values of target parameters of two adjacent DOHs are small, interpolation error can be neglected.
3. Suitable cost function is defined.
4. The Non-dominated Sorting Genetic Algorithm II (NSGA II) is applied to the cost function and the optimal degree of hybridization is calculated [10].

4 PROBLEM DEFINITION

As mentioned before, we deal with a multiple objective problem in which our objective is to maximize fuel economy, maximum speed, gradeability and distances covered in 5 seconds, and at the same time, minimize emissions, 0-60, 40-60, 0-85 mph acceleration times and vehicle mass. Because of several conflicting objectives (for example: choosing higher DOHs, improves the fuel economy and reduces the emissions but leads to poor vehicle performance), the single objective algorithms like Genetic Algorithm, Particle Swarm Optimization would not be as efficient as Multiple Objective optimization Algorithms (MOA) like the Non-dominated Sorting Genetic Algorithm (NSGA) [14]. However the NSGA is a multiple objective optimization algorithm but its high computational complexity of non-dominated sorting, lack of elitism and need for specifying the sharing parameter, has introduced it as a very complex optimization algorithm [10]. In [10] a modified version of Non-dominated Sorting Genetic Algorithm (NSGA) named NSGA II has been presented which has worked out the aforementioned drawbacks of NSGA. Therefore, in this study the NSGA II has been applied to the problem [10].

The NSGA-II is one of the commonly used Evolutionary Multiple objective Optimization (EMO) algorithms that attempt to discover multiple Pareto-optimal solutions in a multiple objective optimization problem. It has the following three characteristics:

1. It uses an elitist principle,
2. It uses an explicit diversity preserving mechanism,
3. It emphasizes non-dominated solutions.

At any generation *t*, the offspring population (*Qt*) is first created by using the parent population (*Pt*) and the usual genetic operators. Thenceforth, the two populations are combined together to form a new population (*Rt*) of size 2*N*. Then, the population *Rt* classified into different non-domination categories. Thereafter, the new population is filled by points of different non-domination fronts, one at a time. The filling starts with the first non-domination front (of class one) and continues with points of the second non-domination front, and so on. Since the overall population size of *Rt* is 2*N*, not all fronts can be accommodated in *N* slots available for the new population. All fronts which could not be accommodated are deleted. When the last allowed front is being considered, there may exist more points in the front than the remaining slots in the new population. Instead of arbitrarily rejecting some members from the last front, the points that will make the diversity of the selected points the highest, are selected. The crowded-sorting of the points of the last front which could not be accommodated fully is achieved in the descending order of their crowding distance values and points from the top of the ordered list are chosen. The crowding distance *di* of point *i* is a measure of the objective space around *i* which is not occupied by any other solution in the population. Here, we simply calculate this quantity *di* by estimating the perimeter of the cuboid formed by using the nearest neighbors in the objective space as the vertices (we call this the crowding distance). Complete description of applied NSGA II has been presented in [10].

In our proposed technique, two independent cost functions are defined, one for parameters that we tend to maximize and another for those, that we want to minimize, as equations (4) and (5):

$$\begin{aligned} F_1 = K_1 \left(\frac{1}{\text{fuel economy}}\right) + K_2 \left(\frac{1}{\text{gradeability}}\right) \\ +K_3 \left(\frac{1}{\text{maximum speed}}\right) \\ +K_4 \left(\frac{1}{\text{distance in 5 sec}}\right), \end{aligned} \tag{4}$$

$$\begin{aligned} F_2 = K_5 (\text{mass}) + K_6 (\text{emissions}) \\ +K_7 (0-60 \text{ acceleration time}) \\ +K_8 (40-60 \text{ acceleration time}) \\ +K_9 (0-85 \text{ acceleration time}), \end{aligned} \tag{5}$$

where K_i are the weighting factors of the target parameters. In these two cost functions, depended on the importance of each target parameter, a weighting factor is assigned to. The weighting factors should also satisfy the equation (6):

$$\sum_{i=1}^{9} K_i = 1. \tag{6}$$

Using the information and data gathered in step 2, all the (1/fuel economy), (1/gradeability), (1/maximum speed), (1/distance covered in 5 seconds), (0-60 mph acceleration time), (40-60 mph acceleration time), (0-85 mph acceleration time), (mass) and (emissions) are normalized.

5 VEHICLE DEFINITION AND SIMULATION CONSIDERATION

In this paper, a small size parallel passenger hybrid car has been used as the test vehicle. This test car has been modeled in the ADvanced VehIcle SimulatOR (ADVISOR) software based on the (7) [13]:

$$\frac{dV}{dt} = \frac{\sum F_t - \sum F_r}{\delta M}, \tag{7}$$

where V represents the vehicle speed, $\frac{dV}{dt}$ is the vehicle acceleration, $\sum F_t$ is the total tractive effort of the vehicle that is provided by both the internal combustion engine and electric motor, $\sum F_r$ is the total resistance, M is the total mass of the vehicle and δ is the mass factor that equivalently converts the rotational inertias of rotating components into translational mass [13].

The rolling resistance of tiers (F_r), aerodynamic drag (F_w) and grading resistance (F_g) are the main resistances against a moving car, so the total resistance of vehicle can be calculated from (8) [13]:

$$\sum F_r = F_r + F_w + F_g, \tag{8}$$

where:

$$\begin{aligned} F_r &= M \cdot g \cdot f_r \cdot \cos\alpha, \\ F_w &= \tfrac{1}{2} \cdot \rho \cdot A_f \cdot C_D \cdot V^2 \cdot (1 + C_w), \\ F_g &= M \cdot g \cdot \sin\alpha, \end{aligned} \tag{9}$$

where, g is the gravity acceleration, f_r is the rolling resistance coefficient, α is the road angle (in this study $\alpha = 0$), ρ is the air density, A_f is the frontal area of the vehicle, C_D is the coefficient of air drag and C_w is the wind speed coefficient [13].

Rated powers of used electric motor and Internal Combustion Engine (ICE) are respectively, 31 kW and 63 kW. So the total power of the test vehicle is considered to be 94 kW. A combination of Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET) has been used as the driving cycle in the simulations (Fig. 2) [11].

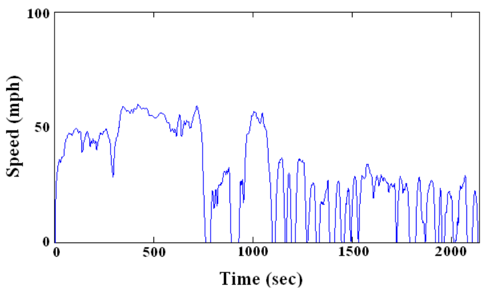

Fig. 2. Combined driving cycle (UDDS + HWFET)

For DOHs lower than 0.3 ($DOH < 0.3$), the electric motor is not capable of providing needed power. For $DOH > 0.6$, exactly the same story happens to the Internal Combustion Engine (ICE). So the valid range of Degree of Hybridization (DOH) is [0.3-0.65]. Since the test vehicle is supposed to be a passenger car, the weighting factors have been selected as Table 1.

Vehicle and propulsion parameters are given in the Tables 2 and 3, respectively.

Table 1. Selected weighting factors

Parameter	K_1	K_2	K_3
Value	0.2	0.15	0.1
Parameter	K_4	K_5	K_6
Value	0.05	0.05	0.2
Parameter	K_7	K_8	K_9
Value	0.15	0.05	0.05

Table 2. Vehicle Parameters

Parameter	**Value**	**Parameter**	**Value**
Coefficient of Drag	0.3	Vehicle Cargo Mass (kg)	136
Frontal Area (m^2)	1.746	Wheel Radius (m)	0.282
Wheelbase (m)	2.55	Air Density (kg/m^3)	1.2
Glider Mass (kg)	918	Coefficient of Rolling Resistance	0.009
Mass Factor	1.035	Wind Speed Coefficient	0.2

Table 3. Propulsion Parameters

Component	**Parameter**	**Value**
Internal Combustion Engine (ICE)	***Manufacturer***	-
	Type	Saturn 1.9L SOHC SI
	Max. Power	63 kW
	Peak Efficiency	0.34
Electric Motor (EM)	***Manufacturer***	Toyota Prius
	Type	Permanent Magnet
	Max. Power	31 kW
	Mass	51 kg
	Peak Efficiency	0.91
Battery Pack	***Manufacturer***	Hawker Genesis
	Type	Lead-Acid
	Number of Modules	25
	Nominal Module Voltage	12 VDC
	Nominal System Voltage	308 VDC
	Nominal Pack Capacity	6.5 Ah

Control strategy has a significant effect on the performance, fuel economy and emissions of the vehicle. In this study, the charge sustaining method has been used as the control strategy of the hybrid electric vehicle. In this paper, the electric assist control strategy has been used for controlling the test vehicle. This control strategy uses the electric motor for additional power when needed by the vehicle and maintains charge in the batteries. In this control strategy, the highest and the lowest desired battery States of Charge (SOC) are respectively 0.8 and 0.5. During the simulations, the states of charge of the batteries is monitored to ensure that the batteries never discharge below a certain set point (low_SOC). Assigning this minimum set point of the states of charge is necessary to prevent low efficiency from the ICE. When the states of charge is higher than 0.5 (low_SOC), vehicle speed of 5 m/s (electric launch speed) is the maximum speed with which the engine can be off, below this speed, vehicle operates as Zero Emission Vehicle. If the states of charge drops below 0.5, the ICE must be on and run at a higher torque in order to recharge the

Table 4. Data Obtained in Step 2 for Each DOH

DOH	P_{EM} (kw)	P_{ICE} (kw)	Number of Battery Modules	Mass (kg)	Fuel Economy (mpg)	0-60 mph Acceleration Time (sec)	40-60 mph Acceleration Time (sec)	0-85 mph Acceleration Time (sec)	Maximum Speed (mph)	Gradeability (%)	Distance in 5 Seconds (ft)	Emissions (grams/mile)		
												HC	CO	NO_X
0.3	28	66	18	1644	50.7	10.4	5.1	20.5	126.7	17.8	158.3	0.257	1.118	0.217
0.35	33	61	20	1661	52.8	10.7	5.3	21.3	126.7	17.1	159.1	0.239	1.035	0.21
0.4	38	56	21	1668	54.8	11.2	5.6	22.5	126.8	16.1	156	0.222	0.956	0.202
0.45	42	52	23	1686	56.6	11.5	5.8	23.2	126.8	15.6	154.9	0.208	0.894	0.197
0.5	47	47	26	1713	58.8	11.8	6	23.9	126.3	15	154.1	0.192	0.819	0.189
0.55	52	42	29	1742	60.9	12.1	6.2	24.7	124.9	14.5	153.6	0.174	0.738	0.181
0.6	56	38	31	1759	62.7	12.4	6.3	25.5	123.5	14	152.3	0.16	0.666	0.171
0.65	61	33	34	1787	65.3	12.7	6.5	26.4	122.1	13.5	151.8	0.141	0.575	0.157

batteries. In this study, the initial states of charge of the energy storage system is 0.65. Table 4, shows the control parameters used in the control strategy [11].

Table 5. Values of Control Parameters

Control Parameter	Value
cs_hi_soc	0.8
cs_lo_soc	0.5
$cs\_electric\_launch\_spd\_hi\ (m/s)$	16.8
$cs\_electric\_launch\_spd\_lo\ (m/s)$	5
$cs\_off\_trq\_frac$	0.4
$cs\_min\_trq\_frac$	0.8

Table 5 shows the components used for modeling of this vehicle in the ADVISOR.

Table 6. Components Used For Modeling the Test Vehicle in ADVISOR

Component	Model
Fuel Converter	FC_SI63_emis
Electric Motor	MC_PRIUS_JPN
Exhaust After-treatment	EX_SI
Transmission	TX_5SPD
Wheel/Axle	WH_SMCAR
Power train Control	PTC_PAR_CD
Energy Storage System	ESS_PB25

6 SIMULATION RESULTS

Using the proposed methodology, all the target parameters are plotted across the [0.3-0.65] range of Degree of Hybridization (DOH). Simulation results have been shown in Table 6. Variation pattern of target parameters versus degree of hybridization, have been shown in figures 3-11.

According to Fig. 3, fuel economy increases by increment of degree of hybridization. Optimal degree of hybridization for fuel economy is 0.65. Also, it can be seen from Fig. 4 that gradeability decreases by increment of degree of hybridization. Optimal DOH for gradeability is about 0.3.

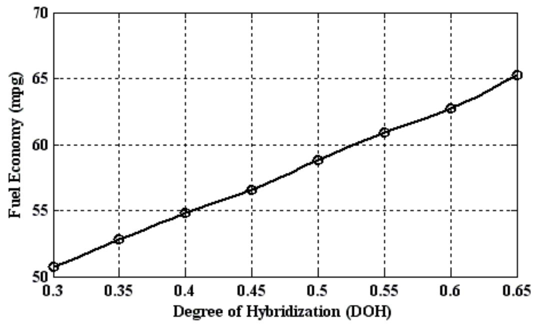

Fig. 3. Fuel Economy vs. DOH

Fig. 5 indicates that optimal degree of hybridization for

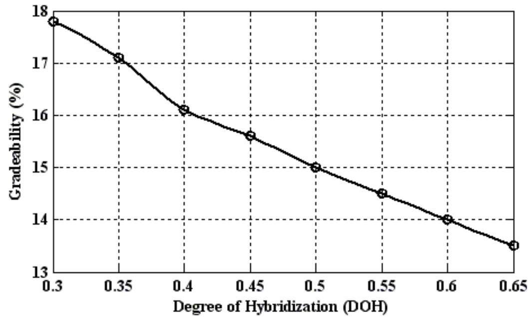

Fig. 4. Gradeability vs. DOH

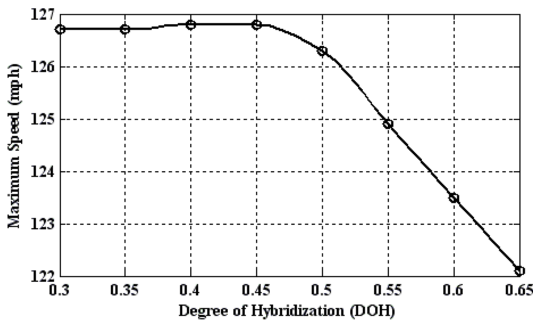

Fig. 5. Maximum Speed vs. DOH

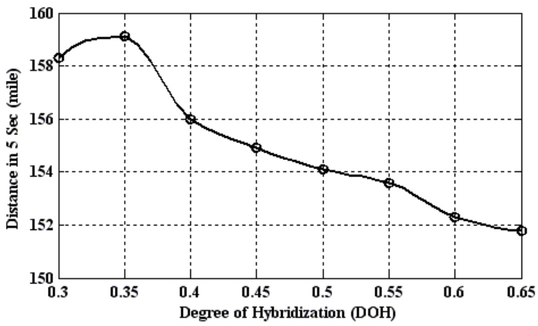

Fig. 6. Distance Covered in 5 seconds vs. DOH

maximum speed is 0.45. Relationship between degree of hybridization and distance covered in 5 seconds of the test vehicle has been described in Fig. 6. Optimal degree of hybridization for this parameter is 0.35.

Figures 7-9 respectively show the relationship between 0-60, 40-60, 0-85 mph acceleration times and degree of hybridization of the vehicle. Optimal degree of hybridization for all these three parameters is 0.65.

Also relationship between emissions and degree of hybridization of the test vehicle has been shown in Fig. 10. Optimal degree of hybridization for this mentioned parameter is 0.65. Fig. 11 shows the relationship between the degree of hybridization and Mass of the test vehicle. 0.3 is the optimal degree of hybridization for this target parameter.

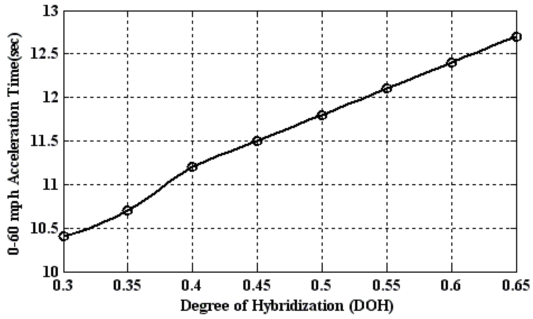

Fig. 7. 0-60 mph Acceleration Time vs. DOH

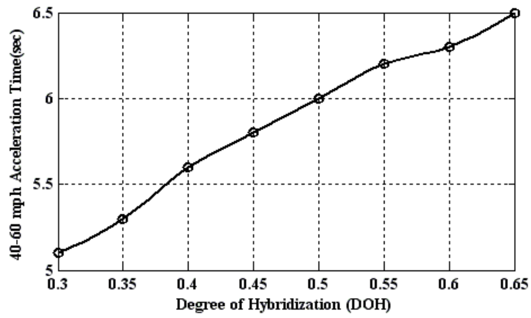

Fig. 8. 40-60 mph Acceleration Time vs. DOH

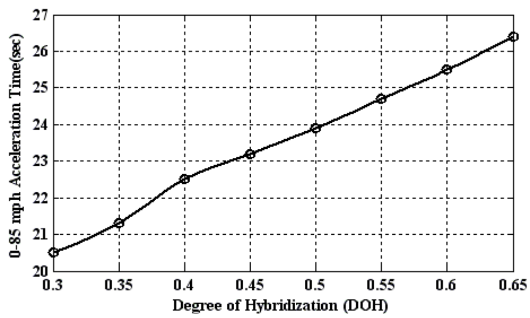

Fig. 9. 0-85 mph Acceleration Time vs. DOH

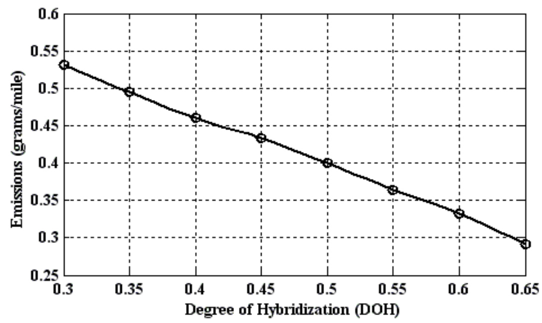

Fig. 10. Emissions vs. DOH

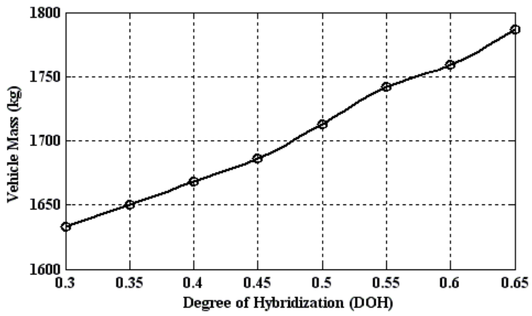

Fig. 11. Vehicle Mass vs. DOH

As mentioned before, in this study, the Non-dominated Sorting Genetic Algorithm II (NSGA II) has been used for finding the optimal degree of hybridization. Population size and maximum number of iterations of this algorithm are 80 and 100, respectively. The crossover probability (pc) is equal to 0.8. The mutation probability (pm) is equal to 0.3, the crossover operator (ηc) is equal to 15 and the mutation operator (ηm) is equal to 20.

Multi-objective optimization algorithms usually produce a set of optimal solutions instead of an optimal one, at each iteration. In this work, for selecting one solution as optimal one, a new cost function has been defined like equation (10):

$$\text{Cost} = F_1 + F_2. \tag{10}$$

In this methodology, cost function ($F_1 + F_2$) is calculated for all the optimal solutions produced by Non-dominated Sorting Genetic Algorithm II (NSGA II) at each iteration. Solution with the lowest cost function is selected as the optimal solution of iteration. Fig. 12 shows the lowest obtained cost function of each iteration. Fig. 13 also shows the optimal degree of hybridization (best solution) achieved in each generation.

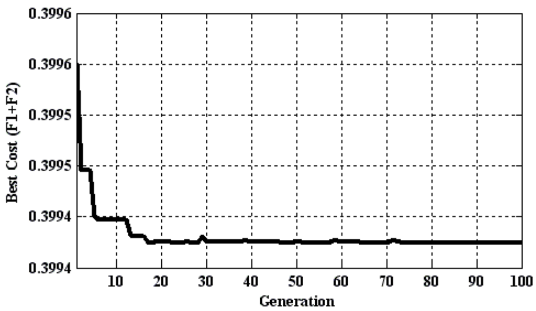

Fig. 12. Best Cost (F1+F2) vs. iteration (Generation)

These results show that, minimum obtained cost is 0.3994 and the optimal degree of hybridization is 0.3317. This means that optimal values of P_{EM} and P_{ICE} are 31.1798 kW and 62.8202 kW, respectively. These optimal

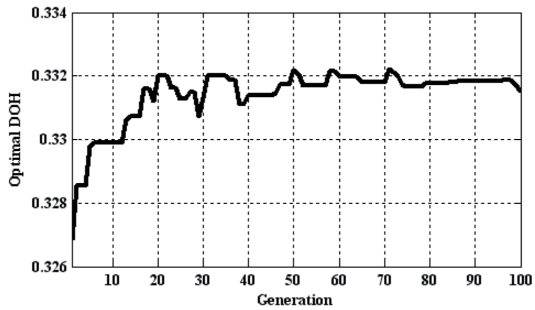

Fig. 13. Optimal DOH (Best solution) vs. iteration (Generation)

values happen at 75th generation. Table 7 shows the optimal values of target parameters.

Table 7. Optimal Values of Target Parameters

Target Parameter	Optimal Value
Fuel Economy (mpg)	52.0415
Gradeability (%)	17.3877
Maximum Speed (mph)	126.7000
Distance Covered in 5 sec (ft)	159.0605
Emissions (grams/mile)	0.5077
0-60 mph Acceleration Time (sec)	10.5704
40-60 mph Acceleration Time (sec)	5.2165
0-85 mph Acceleration Time (sec)	20.9660
Vehicle Mass (kg)	1643.7

Results show that, the newly proposed methodology is much faster and more efficient than that proposed in [1-5].

7 CONCLUSION

The proposed methodology is very fast and efficient. The Non-dominated Sorting Genetic Algorithm II (NSGA II), compared to Genetic Algorithm (GA), shortens the simulation running time and makes the simulations converge to optimal solution at lower number of iterations. This technique is much more accurate and efficient than Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) based techniques. Beside fuel economy and emissions, the performance parameters such as gradeability, maximum speed, acceleration times and so on, have been covered as target parameters which make our study more comprehensive. Also, this novel technique can be well applied to any kind of hybrid electric vehicle by selecting appropriate weighting factors.

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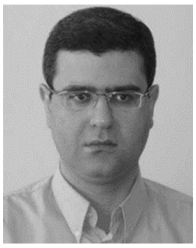

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