A Novel Methodology Proposed for Optimizing the Degree of Hybridization in Parallel HEVs using Genetic Algorithm

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***Abstract*—**In this paper, a new Genetic Algorithm (GA) based methodology is proposed to optimize the Degree of Hybridization (DOH) in a passenger parallel hybrid car. At first step, target parameters for the vehicle are decided and then using ADvanced VehIcle SimulatOR (ADVISOR) software, the variation pattern of these target parameters, across the different DOHs, is extracted. At the next step, a suitable cost function is defined and is optimized using GA. In this paper, also a new technique has been proposed for deciding the number of battery modules for each DOH, which leads to a great improvement in the vehicle performance. The proposed methodology is so simple, fast and at the same time, so efficient.

***Keywords*—**Degree of Hybridization (DOH), Electric Motor, Emissions, Fuel Economy, Genetic Algorithm (GA), Hybrid Electric Vehicle (HEV), Vehicle Performance

I. Introduction

ENVIRONMENTAL pollution and limited resources of fossil fuels are two serious problems that urge us for finding a solution. Electrification of the conventional vehicles is the best solution put forwarded till now. Electrification means to add an electric motor as an auxiliary power source beside Internal Combustion Engine (ICE). So, Hybrid Electric Vehicles (HEVs) combine propulsive power from an ICE with that produced by electric energy stored in battery pack. HEVs utilizing power from more than one power sources can effectively improve fuel economy and reduce air pollution at the same time. In a parallel HEV, the power required for propulsion is provided as mechanical power from the ICE and torque from the Electric Motor (EM). In recent years, a new parameter called Degree of Hybridization (DOH) has been defined which specifies the portion of the power provided by the electric motor and the internal combustion engine. The DOH is defined mathematically as follows: [1], [2], [4] and [5].

$$DOH = \frac{P_{EM}}{P_{EM} + P_{ICE}} = \frac{P_{EM}}{P_{Total}} \tag{1}$$

Where the P_{EM}, is the rated power of the electric propulsion motor and the P_{ICE}, is the rated power of the Internal Combustion Engine (ICE).

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P_{Total} is the total propulsive power of the Hybrid Electric Vehicle, which is sum of the P_{EM} and P_{ICE}. DOH is 0 and 1, for conventional and all electric vehicles, respectively. In design stage of a HEV, the most important question is how to decide the suitable sizes of P_{EM} and P_{ICE}. Inappropriate selection of these two parameters (which means inappropriate selection of DOH), may increases the fuel consumption and result in unpleasant dynamic performance of the vehicle. So it is necessary to find the optimal DOH of the hybrid car [1], [2].

In [3], the optimal DOH has been chosen by examining the efficiency map of the ICE (as the main power source) at various operating points. In this method, the P_{EM}, is calculated in such a way that, ICE operates at high efficiency operating points. In [4] and [5] each target parameter has its own optimal DOH, but nothing has been discussed about the optimal DOH considering different target parameters. So this methodology seems to be incomplete and impractical. No other serious research work is reported about the optimized determination of DOH. In this paper, the authors complete the methodology proposed in [4] and [5] by applying the Genetic Algorithm (GA) while a new technique for determining the number of battery modules is proposed and used to optimize the whole problem.

Following to this introduction about the degree of hybridization, the second section of this paper introduces the new technique, proposed for deciding about the number of battery modules. Proposed methodology and the applied GA algorithm are discussed in third section. Section four elaborates the vehicle definitions under study and simulation methodology. Following to fifth section presenting the simulation results, a conclusion is given in the section six.

II. A New Technique Proposed For Deciding About The Number Of Battery Modules

In recent years, different methods have been proposed for determining the number of battery modules in HEVs, like: Minimum number of battery modules, power matching and so on [1], [2] and [5]. But in this study, a new technique is proposed for satisfying two key designing factors, which will be described in the following sections.

A. Maximum Charge and Discharge Capability

The energy storage system of a HEV should be always able to produce the power needed by the electric motor. Maximum amount of propulsion power that can be requested during a 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:

$$\text{maximum discharge power} = \frac{P_{EM}}{\eta_{converter}} \quad (2)$$

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

On the other hand, energy storage system (battery pack) must be able to absorb the total regenerative power of wheels, during the regenerative braking conditions. The maximum charging power of energy storage system during the regenerative braking conditions can be calculated from (3):

$$\text{maximum charge power} = P_{EM} \times \eta_{converter} \quad (3)$$

B. Satisfaction of the PNGV Criteria

In order to guarantee the high performance of the newly designed HEVs, some measures have been introduced, assigned by the PNGV (Partnership for a New Generation of Vehicles) organization [7]. These measures are as follows: [2].

- 0-60 mph acceleration time must be equal or lower than 12 sec.
- 40-60 mph acceleration time must be equal or lower than 5.3 sec.
- 0-85 mph acceleration time must be equal or lower than 23.4 sec.
- Distance covered in 5 seconds must be at least 140ft.
- Maximum speed must be at least 90 mph.

It is worth to note that, there is also an additional criterion about the gradeability of the vehicle but in this paper, this criterion has not been considered. The number of battery modules must be determined in such a way that, both the aforementioned A and B factors be satisfied. Using the ADVISOR software and this new approach, the number of battery modules for the different DOHs from 0.3 to 0.65 is determined. For DOHs higher than 0.65, the ICE is not capable of providing the requested propulsion power. The same thing happens for EM, for DOHs lower than 0.3. So the valid range for the DOH is [0.3-0.65]. While keeping the total needed power of the vehicle under study, constant, the DOH is altered from0.3 to 0.65 by increment steps of 0.05. Then, the proposed new approach is applied to determine the number of the battery modules for each DOH. This task is done automatically by sequential simulating and a target finding software. The results are shown in Fig. 1.

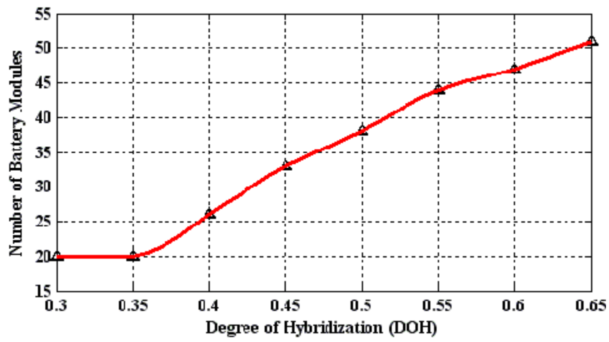

Fig. 1 Number of the Battery Modules vs. DOH

As Fig. 1 shows, for some DOHs the obtained value representing the number of battery modules is not integer, so these values must be rounded.

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III. Proposed Methodology

In this study, our objective is to improve the fuel economy and minimize the vehicle mass and emissions. As mentioned before, using the new technique proposed for deciding about the number of battery modules, improves the vehicle performance but it is not enough. So another objective of this paper is to optimize the vehicle performance. Here, it is assumed that the performance of the vehicle is characterized by 0-60 mph acceleration time, maximum speed, distance covered in 5 seconds and gradeability. On the other hand, the HC, CO and NO_X emissions are the air pollutants that we tend to minimize them as much as possible. The proposed methodology is as follows:

Step 1: Total power of the test vehicle is selected for a certain car and is kept constant, during the simulations.

Step 2: The DOH is altered by increment steps of 0.05 within a valid range. For each DOH, 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 values of target parameters of two adjacent DOHs are small, interpolation error can be neglected.

Step 3: As mentioned before, it is of interest to maximize the fuel economy, maximum speed and gradeability, and on the other hand, minimize the vehicle mass, 0-60 mph acceleration time and emissions, which is described by (4).

$$\text{Emissions} = \frac{HC+CO+NO_X}{3} \quad (4)$$

In this paper, the cost function is defined as (5).

$$Cost = K_{F.E} \times \left(\frac{1}{Fuel\ Economy}\right) + K_{G.A} \times \left(\frac{1}{Gradeability}\right)$$

$$+K_{M.S}\times\left(\frac{1}{Maximum\ Speed}\right)+K_{Dis5}\times\left(\frac{1}{Distance\ in\ 5}\right)+$$
$$K_{E.M}\times(Emissions)+K_{A.T}\times(0-60\ acceleration\ Time)$$
$$+K_{V.M}\times(Vehicle\ Mass) \quad (5)$$

Where, Ks are weighting factors of target parameters. In (5), all the target parameters have been normalized. In this cost function, depended on the importance of each target parameter, a weighting factor is assigned to. The weighting factors should also satisfy the following equation.

$$K_{F.E}+K_{G.A}+K_{M.S}+K_{V.M}+K_{Dis5}+K_{E.M}+K_{A.T60}=1 \quad (6)$$

Step 4: Genetic Algorithm (GA) is applied to the problem (for minimizing the cost function) and the optimal DOH is calculated.

IV. Vehicle Definition And Simulation Consideration

In this paper, a small-size passenger parallel hybrid car is considered for study and simulations. Vehicle and propulsion parameters have been shown in tables I and II, respectively. As table II shows, rated powers of the used EM and ICE, are 31 and 63 kw, respectively. So the total power of the vehicle is considered to be 94 kw. ADVISOR software has been used as the simulation tool and a combination of UDDS[1] and HWFET[2] has been used for driving cycle.

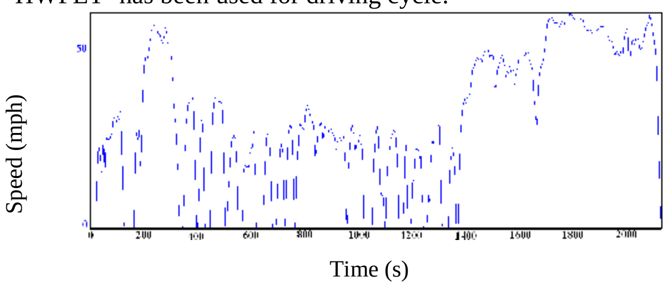

Fig. 2 Combined driving cycle used in simulations (UDDS+HWFET)

TABLE I
VEHICLE PARAMETERS

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

[1] Urban Dynamometer Driving Cycle
[2] High Way Fuel Economy Test

TABLE II
PROPULSION PARAMETERS

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	57 kg
	Peak Efficiency	0.91
Battery Pack	Manufacturer	Hawker Genesis
	Type	Lead-Acid
	Number of Modules	25
	Module Weight	11 kg
	Nominal Module Voltage	12 VDC
	Nominal System Voltage	308 VDC
	Nominal Pack Capacity	25 Ah

Table III elaborates different components of vehicle used for modeling in ADVISOR. Maximum and minimum values, used for normalizing the target parameters, are shown in table IV. Also, selected weighting factors have been given in table V.

TABLE III
COMPONENTS USED IN THE ADVISOR FOR MODELING THE TEST VEHICLE

Component Name	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

TABLE IV
MAXIMUM AND MINIMUM VALUES OF TARGET PARAMETERS

Target Parameter	Maximum Value	Minimum Value
Fuel Economy (mpg)	65.7	51.3
Gradeability (%)	18.1	16.1
0-60 mph Acceleration Time (s)	11	10.3
Vehicle Mass (kg)	1974	1666
Distance Covered in 5 seconds (ft)	160.1	158.1
Maximum Speed (mph)	126.9	126.7
CO (grams/mile)	1.115	0.569
HC (grams/mile)	0.256	0.14
NO_X (grams/mile)	0.217	0.157

TABLE V
SELECTED WEIGHTING FACTORS

Weighting Factor	$K_{F.E}$	$K_{M.S}$	$K_{G.A}$	$K_{A.T60}$	$K_{Dis.5}$	$K_{V.M}$	$K_{E.M}$
Value	0.2	0.15	0.1	0.15	0.05	0.15	0.2

Control strategy, has a significant effect on the fuel economy and performance of the vehicle. In the selected control strategy, the highest and lowest desired States of Charge (SOC) of the battery pack are 0.8 and 0.55, respectively. High and low electric launch speeds are considered 16.8 and 5(m/s) respectively. Off torque fraction and minimum torque fraction parameters are also, 0.6 and 0.8 respectively. The Genetic Algorithm described in [6] is used for optimizing the problem. Population size and maximum number of generations are 50 and 250, respectively. Also tournament selection method has been used for selecting, mutating and crossing over of the members. 50% and 10% of new population members are generated by using the cross over and mutation operators, respectively. The remaining is selected from the best solutions of last iteration. It should be noted that, for DOHs lower than 0.3 and higher than 0.65, the propulsion system is not able to provide the needed power for tracing the drive cycle. So, as mentioned before, the valid range of DOH variation is considered to be [0.3-0.65].

V. Simulation Results

Considering the aforementioned realistic conditions, all the target parameters are obtained for the [0.3-0.65] range of DOH. The variation patterns of these target parameters have been shown in Figures 3 – 13. Fig. 3 shows that, the higher the DOH, the better the fuel economy.

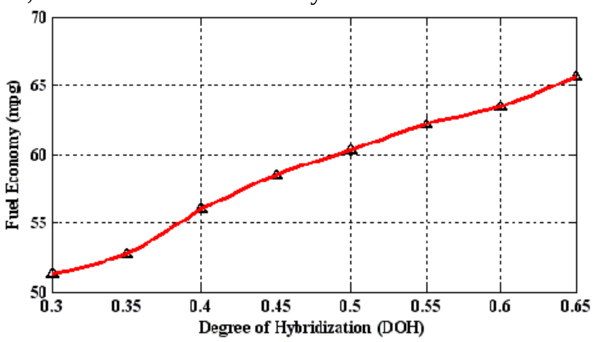

Fig. 3 Fuel Economy vs. DOH

Fig. 4 shows that, the increment of the DOH, results in reduction in gradeability of the vehicle. In most cases (depending on the control strategy), the power needed for the grade climbing of the vehicle, is provided by the ICE. By increasing the DOH, size of the ICE goes smaller and smaller, which leads to reduction in gradeability of the vehicle. In this study, for whole valid range of DOH, the gradeability of the vehicle is higher than 16%. This value is acceptable for a small passenger hybrid car. Fig. 5 shows that, the maximum speed of the vehicle is nearly constant across the [0.3-0.65] range of DOH. This means that, the fifth criterion of the PNGV is also satisfied. Figures 6 - 8 show the o-60, 40-60 and 0-85 mph acceleration times of the test vehicle. As it can be seen, variations of all these parameters satisfy the measures recommended by the PNGV.

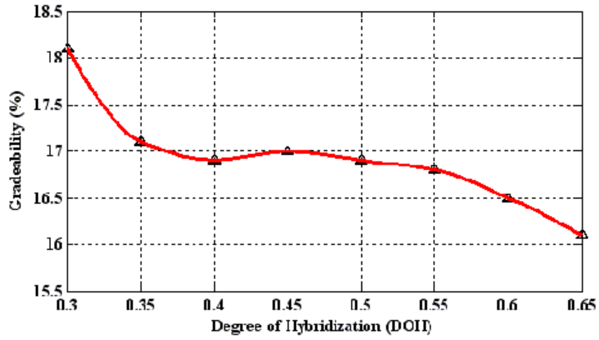

Fig. 4 Gradeability vs. DOH

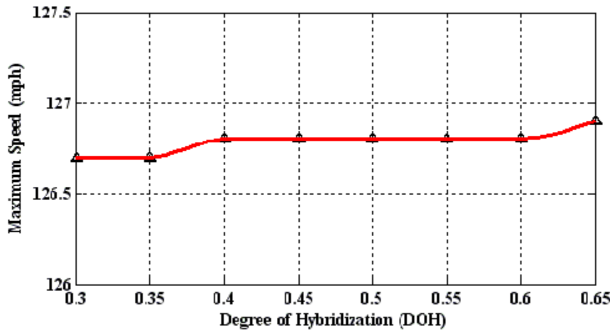

Fig. 5 Maximum Speed vs. DOH

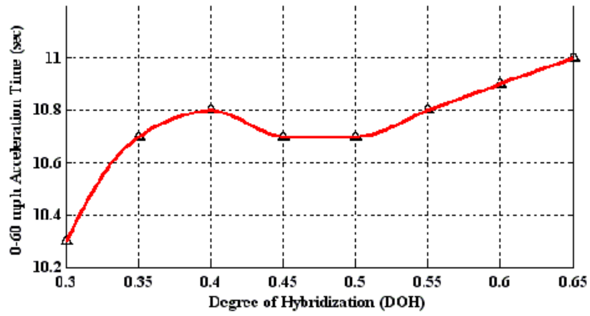

Fig. 6 0-60 mph Acceleration Time vs. DOH

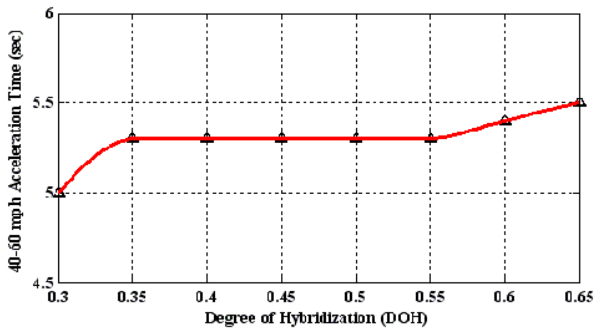

Fig. 7 40-60 mph Acceleration Time vs. DOH

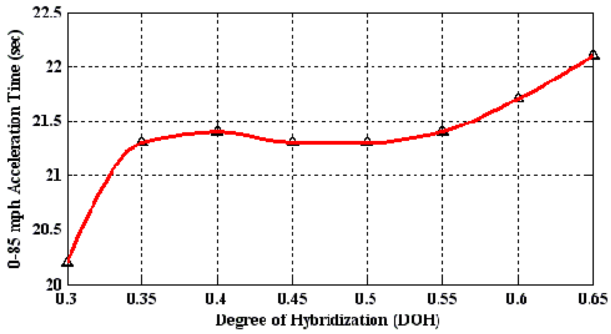

Fig. 8 0-85 mph Acceleration Time vs. DOH

Fig. 9 shows the distance covered in 5 seconds by the car. This parameter is always higher than 140 ft satisfying the fourth criterion of the PNGV. Vehicle mass has been also shown in Figure 10. To satisfy the PNGV criteria, it is necessary to increase the number of battery modules for higher DOHs, which leads to a dramatic increase in vehicle mass.

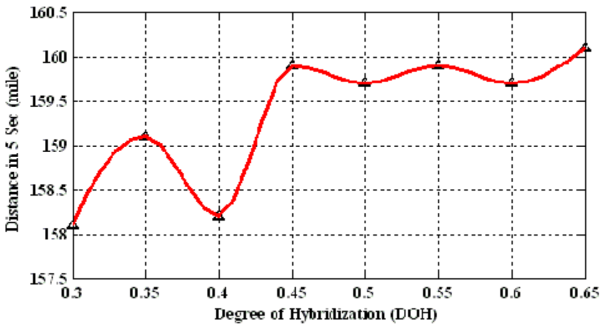

Fig. 9 Distance Covered in 5 Seconds vs. DOH

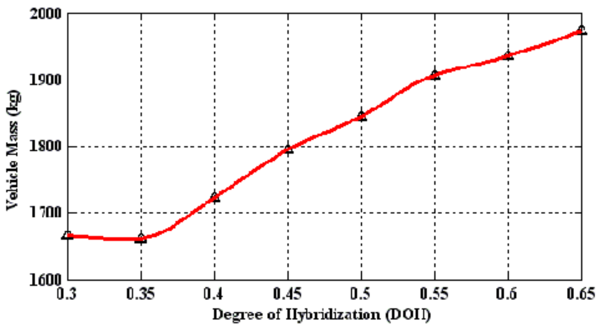

Fig. 10 Vehicle Mass vs. DOH

Figures 11 - 13 show the CO, HC and NO_x emissions. These figures show that, increasing the DOH reduces the emissions.

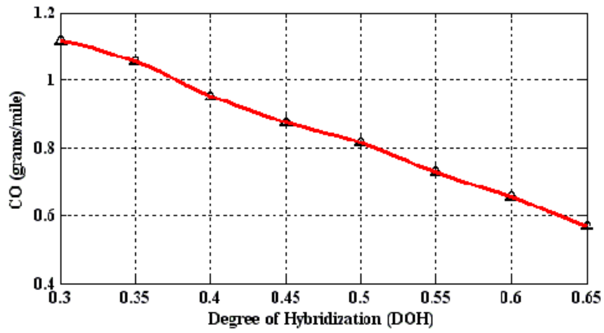

Fig. 11 CO Emissions vs. DOH

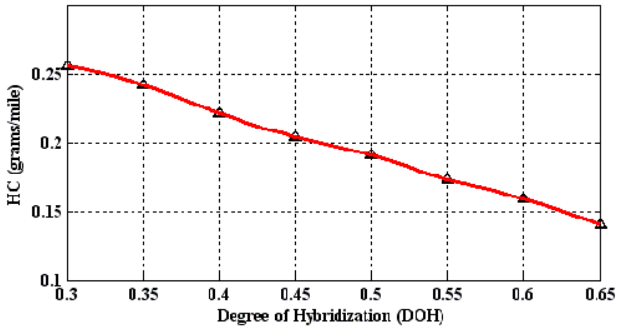

Fig. 12 HC Emissions vs. DOH

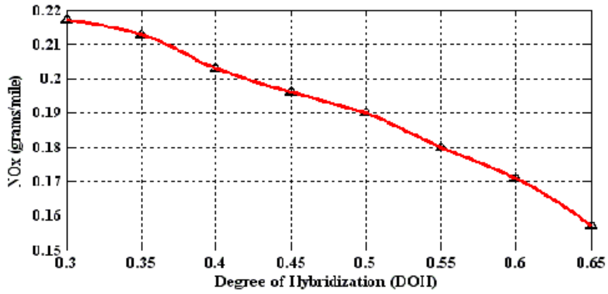

Fig. 13 NOx Emissions vs. DOH

After applying GA to the aforementioned cost function, the optimal DOH is found and shown in Fig. 14, presenting the optimal DOH versus the number of generations. Optimal value for the DOH is 0.65 which represents the minimum value of the cost function which is 0.45. Fig. 15 shows the cost function versus the number of generations.

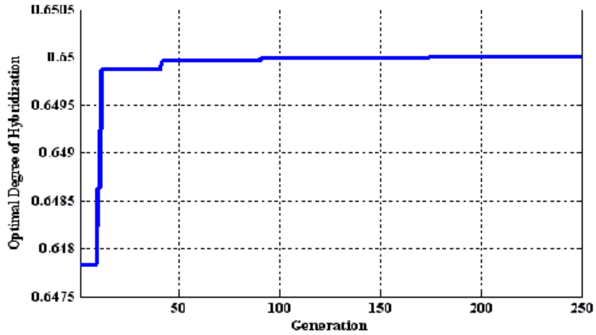

Fig. 14 Optimal DOH vs. Generation

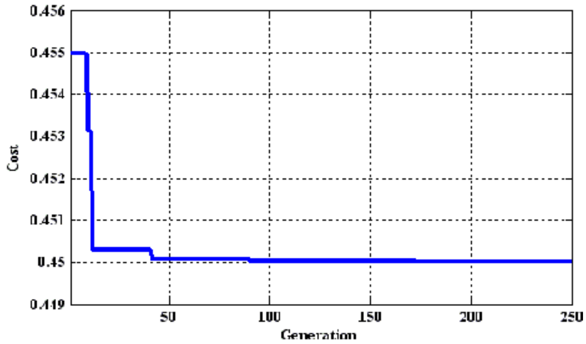

Fig. 15 Cost Function vs. Generation

VI. CONCLUSION

In this paper, a novel Genetic Algorithm based methodology has been proposed for calculating the optimal Degree of Hybridization (DOH) and applied to a passenger parallel hybrid car for example. This methodology is simple, fast and at the same time efficient. Also a new technique for determining the number of battery modules in hybrid vehicles is proposed. This technique guarantees high performance of the HEVs. The proposed methodology can be well applied to any kind of HEV by choosing appropriate values for the weighting factors of cost function.

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