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Hybridization of Samand Vehicle with Minimum Mechanical Modifications

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ABSTRACT

In this paper an idea for hybridization of conventional vehicles has proposed. The case study performed on one of the common vehicles on country roads i.e. Samand. This vehicle has high production volume but low fuel performance therefore hybridization of it could be attractive for its manufacture. This paper aims that the hybridization idea and its structure to need minimum mechanical modifications. In consequence attractiveness of this idea for industry could be high. A cost optimization has been performed for sizing of additional components such as electric motors and battery modules and the simulation results has been adopted to verify the proposed idea for case study with hybrid simulation of GT-Suit and MATLAB softwares.

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1 Introduction

The development of combustion engines is one of the greatest achievements of modern vehicles technology. But they are considered as one of main sources of air pollution and greenhouse gases. Also energy shortage is also a matter of concern for the era and there are always ways to reduce fuel consumption in cars. The development of electric and hybrid electric vehicles is one of the solutions to these concerns.

This paper aims the hybridization of common vehicles with minimum mechanical modifications. It is obvious that the establishment of new manufacturing lines for production of new vehicles needs high volume investments and the modification of current production lines for producing new products is very attractive for industry. Samand is one of the famous vehicle family trade mark in our country with high production volume. This vehicle has some comparative advantages to similar products in its class such as lower cost and ruggedness but it has one important disadvantage related to its high fuel consumption. This important disadvantage is the motivation of this study. In this study, the Samand gasoline vehicle would be hybridized conceptually by adding some additional parts such as two in wheel electrical motors and battery pack and modified energy management strategies. A cost optimization has been performed for sizing of additional components and the simulation results has been reported to verify the proposed idea for case study with hybrid simulation of GT-Suit and MATLAB/Simulink softwares.

Because of validity of GT-SUITE software for modelling and simulation of mechanical systems, the vehicle body and road conditions, internal combustion engine (ICE) and power transmission line such as gear box and differential gears have been modelled in this software. But the control strategies and electrical components have been modelled in MATLAB/Simulink and two sofwares have been on-line connected. The MATLAB/ Simulink code sends and receives commands from GT-SUITE model. In such a way by applying the desired driving cycle, the amount of controlling values of the gas pedal, brake pedal, clutch pedal and the gear number is determined at any time and send to GT-SUITE model. After simulating the base car, the model turned into a hybrid type by choosing the right structure. In this study, the selected structure is independent parallel structure and two electric motors will ne added to the rear wheels.

In order to optimize the electric motors and batteries nominal values, the hybrid vehicle was simulated in MATLAB and the optimum values for these components were be obtained using searching the total space of optimization problem. After that, the performance of the designed hybrid vehicle has evaluated and the simulation results were compared with the petrol model.

The remainder of this paper has been organized as follows. In section 2 modelling of gasoline Samand Vehicle has proposed. Structure selection and Optimization of additional components sizing has depicted in sections 3 and 4 respectively. Section 5 presents the simulation results. Finally some conclusions provided in section 6.

2 Modelling of gasoline Samand Vehicle

As shown in figure 1, in conventional vehicles structure the demanded power for propelling supplied by ICE and transferred to wheels through clutch, gear box, differential gears and some mechanical parts.

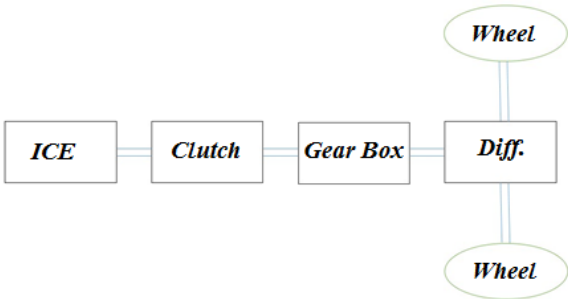

Figure 1. Power train of conventional vehicles

More precise design of any industrial product needs more precise models for simulating that in design stage. There are two approaches for simulating of vehicles power train. Forward approach and backward approach [19]. In forward approach, driver model is not required and at first the propelling force has been calculated by vehicle mathematical model and the values of torques and speeds for all power train components such as ICE can be calculated from tire radius, gears ratios and components efficiencies. In backward

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simulation approach, closed loop real driving environment has been simulated and the driver model must be included. In this study, the backward simulation has used for conventional and hybrid vehicle simulation but forward simulation has been applied in optimization stage.

Samand is one of the Iran Khodro company products offered to market at 2003. Because of its relative benefits, this vehicle is used widespread in urban and rural travels and global transportation but it suffers by one important drawback i.e. low fuel economy. Therefore this vehicle is a proper candidate for hybridization. Figure 2 represents the simulation model of Samand LX vehicle. This vehicle has been modelled by conventional blocks of GT-SUIT software such Engine, vehicle body, road conditions, clutch and transmission and driver model in MATLAB/Simulink with real parameters depicted in Table 1. The simulation has been performed with backward approach and hybrid simulation with online data exchanging between two programs.

GT-SUIT is a multi-purpose software platform that has numerous component libraries for simulation. Using its libraries, engineers are able to simulate spread types of systems. But this platform has specially developed for vehicle modelling and simulation and one can develop sophisticated and integrated models using its motor, engine, electrical equipment, thermal and control libraries [5].

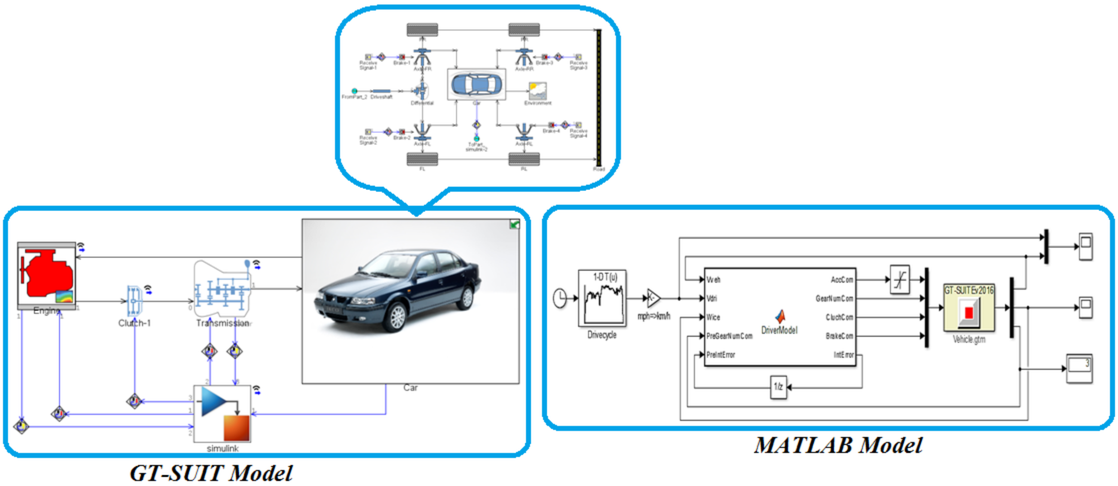

Figure 2. Hybrid simulation of Samand LX vehicle in GT-SUIT and MATLAB

The driver model consists of a PI controller with vehicle speed reference value, generated by one of the standard driving cycles such as FTP-75and vehicle speed feedback as its inputs and percentage of acceleration, brake and clutch pedals and command gear number as its outputs. The outputs pass to GT-SUIT software as driver commands to propel the vehicle at desired speed simultaneously.

Table 1. Samand LX vehicle parameters [18]

Parameter	Value	Unit
Vehicle Mass (Without passenger and Full fuel Tank)	1220	kg
Maximum vehicle Mass	1610	kg
Frontal Area	2	m^2
Drag Coefficient	0.3	$\frac{kg \times m}{s^2}$
Vehicle Length	4.502	m
Vehicle Width	1.72	m
Height of Centre of Gravity	0.57	m
Distance of two axles	2.761	m
Horizontal Distance of rare axle	1.452	m

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to Centre of Gravity		
Tire Radius	0.305	m
Rolling Resistance Coefficient	0.01	m
Engine Type	XU7JP	-
Engine Volume	1761	cc
Engine Maximum Power	100	hp
Maximum Torque	153	Nm
Idle Speed	850	rpm
Urban and Highway Fuel Economy (According ECER 101)	8.34	Lit per 100 km
1th Gear Ration	3.454	-
2nd Gear Ration	1.869	-
3th Gear Ration	1.29	-
4th Gear Ration	0.951	-
5th Gear Ration	0.74	-
Differential Gear Ratio	4.529	-

3 Structure Selection

There are three conventional structures for hybrid vehicles named series (electrically coupling), parallel (mechanically coupling) and series-parallel (electrically and mechanically coupling) structures. Among these structures, parallel structure benefits low mechanical modifications requirement to convert conventional vehicle to hybrid counterpart compared to other structures. Also parallel structure implements in various topologies. Some parallel structure topologies have listed in Table 2.

Table 2. Various topologies for parallel hybrid vehicle [20]

Torque coupling	**With gears or pulleys or chains**
	With electric machine (Pre-transmission or post-transmission)
	With road (Separated axle)
Speed coupling	With planetary gear box
	With transmotor (floating stator)
Alternating torque and speed coupling	With planetary gear box
	With transmotor

In minimum mechanical modifications point of view, the separated axle topology with in wheel motors is the best choice. In this topology, summing or subtracting of ICE and electric motors torques is performing by road. This means the ICE will drive the front wheels but the in wheel electric motors will drive the rear wheels therefore vehicle will be propel with two actuators independently. In this topology only rear wheels would be replaced by two similar wheels with embedded electric machines and the battery pack would occupy a part of rear cargo volume. Authors in [21] are showed that the speed and torque characteristics of two axel parallel structure and independent structure are same.

4 Optimum design of hybrid Vehicle

In this section an optimum design for converting the Samand vehicle to its hybrid counterpart with parallel separated axle structure has proposed. In optimization process the cost function formed by cost of additional components and consumed fuel have been used.

4.1 Battery Modules

The battery modules for optimum design process have been selected as same as Toyota Prius 2004 modules. Specifications of these modules has depicted in table 3. In optimization process weight and cost and ageing of these modules has been considered. In this study, the effective lifetime of battery modules considered to be 5 years.

Table 3. Specifications of Toyota Prius 2004 battery modules

Specification	Value
Type	**Ni-MH**
Capacity	**6.5 Ah**
Voltage	**7.2 Volt**
Price	**40 $**
Weight	**1.04 Kg**
Num. of cells	**6**

4.2 Electric machines

As previously mentioned, in selected topology two in wheel motors must be replaced by rear wheels. For optimization, the relationship

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between machine weight and cost by its torque must be known. For this purpose, these relationships has been studied for one of the in wheel motor series (M series), manufactured by Elaphe company. The weight/torque and cost/torque coefficients for these series approximately are 1 Kg/Nm. and 1.5 USD/Nm respectively. M700 is a machine in this series and its specifications depicted in Table 4.

Table 4. Specifications of M700 electric motor

Specification	Value
Type	**Permanent magnet**
Pole Pairs	**28**
Maximum Speed	**1500 RPM**
Nominal Torque	**400 Nm.**
Weight	**25.2 Kg**
Cooling fluid	**Water**
Maximum Power	**60 KW**
Maximum Efficiency	**93 %**

4.3 Energy management strategies

The proposed hybrid vehicle has four operational modes named Braking mode, Low SOC Mode, High SOC mode, Normal Mode. At any time, the sign of driver command torque (witch acceleration or brake pedals have pressed) determines the braking mode or other three propelling modes. In braking mode, related to barking command, pure electrical braking or hybrid electrical and mechanical braking could be applied. If driver commands positive torque, related to battery state of charge (SOC), three modes can be selected. If SOC is lower than minimum allowable SOC, the low SOC mode must be selected. In this mode any discharge of battery could not be allowed. Similar to this mode, if SOC is higher than maximum allowable SOC, the high SOC mode has been selected. In this mode any charge current to battery could not be permitted. In normal mode priority is the ICE to operate on optimum operation line (OOL). The proposed strategy has shown in figure 3. In this figure some modes finally reach "Fail" means the selected number of battery modules or the selected torque for in wheel motors could not propel the vehicle according the selected driving cycle.

4.4 Driving Cycle

In this study for optimization, the hybrid NEDC driving cycle has been used. This driving cycle has 1180 seconds driving time, 10.93 km driving distance, 43.1 km/h average speed and 120 km/h maximum speed [23]. This driving cycle has shown if figure 4.

4.5 Cost function

For any optimization, a proper cost function essentially is needed. In this study the overall additional induced cost caused by hybridization in common lifetime of a vehicle has been used as cost function. The average lifetime of vehicle considered to be 15 years thus the battery pack must be changed three times in this period. Also annual driving distance assumed to be 20000 km and the gasoline price 0.83 USD per litter. The hybridization needs some initial main costings for motors and batteries and has earnings related to lowering the fuel consumption during the vehicle lifetime. Additional earning such as reduction of pollutants and enhanced performance factors has not considered. The equation 1 formulates the proposed cost function and equation 2 formulates the vehicle weight during the optimization process.

$$\begin{aligned}\text{Total Cost} &= (\text{NEDC Fuel Consumption}) \times 20000 \times 0.83/10.93 \\ &+ \text{ModuleNum} \times 40 \\ &+ \text{MotorsTorque} \times 1.5\end{aligned} \tag{1}$$

$$\text{Weight} = 1650 + \text{ModuleNum} \times 1.04 \times 3 + \text{MotorsTorque} \times 0.1 \tag{2}$$

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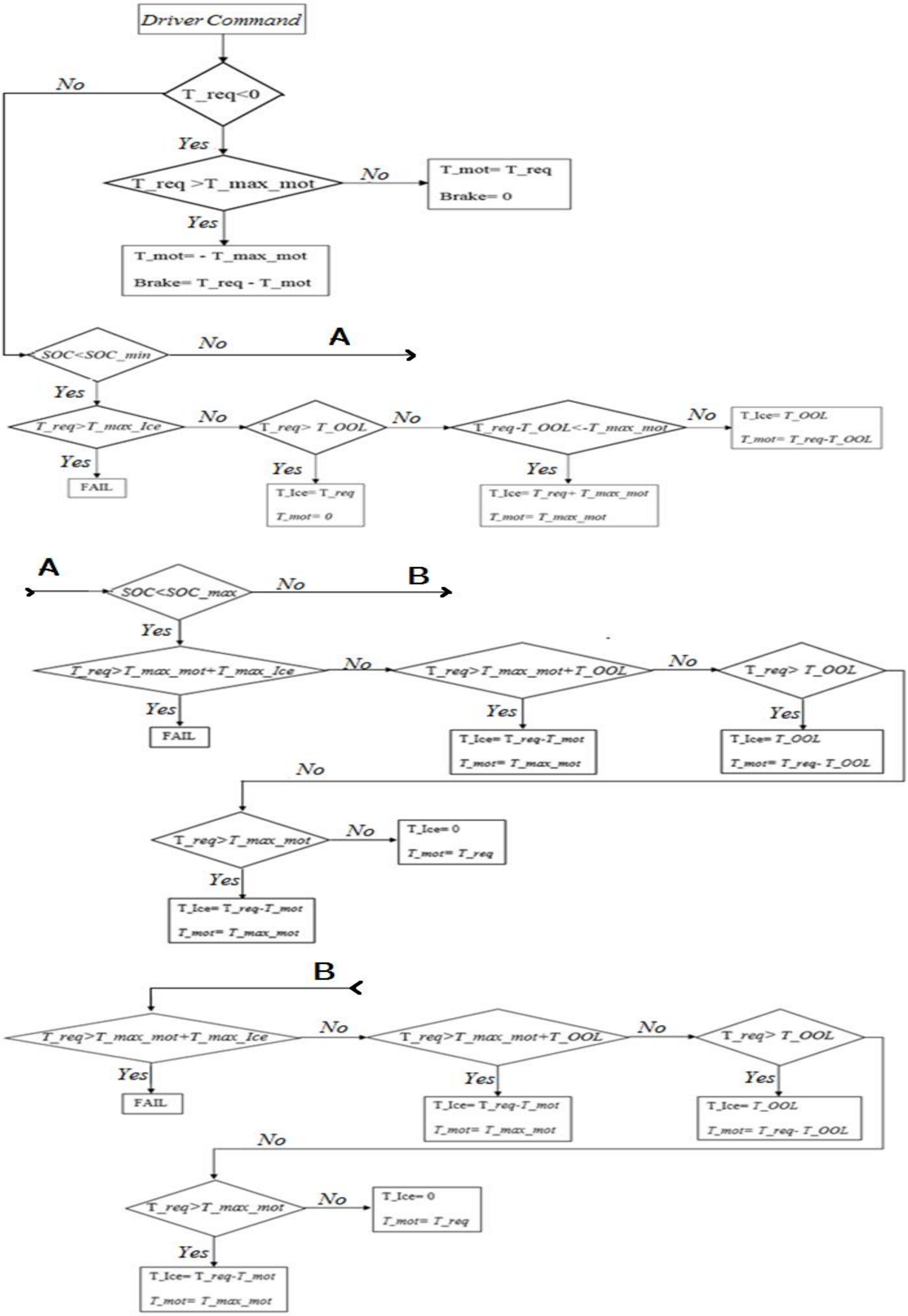

Figure 3. Energy management flowchart

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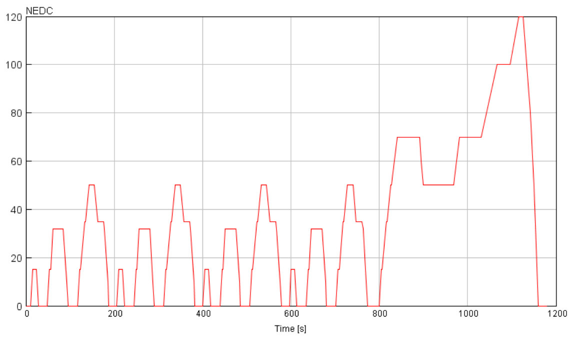

Figure 4. NEDC driving cycle

4.6 Optimization methodology and result

For optimization, i.e. fining the battery modules number and two in wheel motors nominal torque, because of large span of search space and time consuming of hybrid simulation model, a model developed in MATLAB/Simulink based on forward simulation method and has shown in figure 5. In this approach the battery modules number and two motor torques are varied one by one and model is run and after searching the whole space, the optimum numbers for battery modules and motors torque can be extracted.

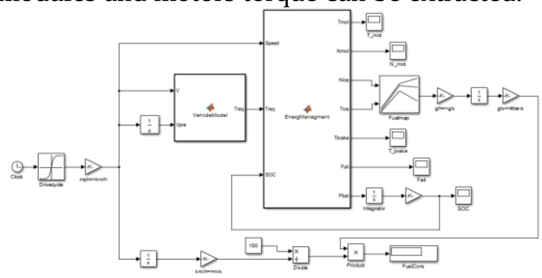

Figure 5. Forward simulation model for optimization process

After running the model for all reasonable battery module numbers and motor torques, the optimum battery module number and any in wheel motor torque became 6 and 175.5 respectively. It seems to be logical result because Samand ICE has sufficiently high power for propel the vehicle in standard driving cycle and mild hybridization can enhance its fuel economy and performance factors and reduce its emissions.

5 Results

At first, gasoline Samand vehicle model described in section 2, simulated for various standard driving cycles to validate the basic model especially in view of fuel economy. Results for fuel consumption have shown in Table 5. Compared to company information in vehicle manual that declared Samand consumes 8.36 litters at 100 km driving distance in hybrid driving cycle, it can be seen the results are valid.

Table 5. Fuel economy simulation results of gasoline Samand model

Driving Cycle	Fuel Consumption (litter/100km)
FTP75	**9.26**
HWFET	**6.72**
NEDC	**8.75**

The proposed structure, energy management strategies with optimum results for battery and in wheel motors size have been modelled and simulated with backward hybrid simulation method in GT-SUIT and MATLAB/Simulink. The modified vehicle model with in wheel motors and batteries has shown in figure 6. As conventional Samand vehicle model, the driver model and energy management have been developed in MATLAB model.

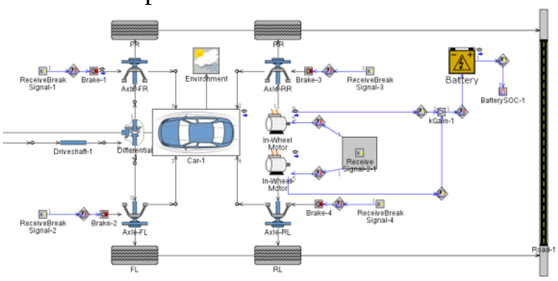

Figure 6. Modified vehicle model with in wheel motors and batteries

Figures 7-13 show only the key simulation results of designed hybrid Samand vehicle for NEDC driving cycle.

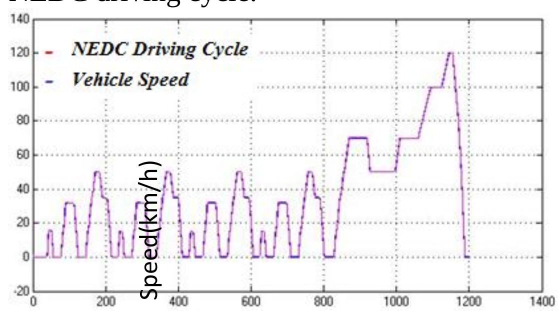

Figure 7. Successful traveling the NEDC driving cycle by designed hybrid Samand vehicle

Time(s)

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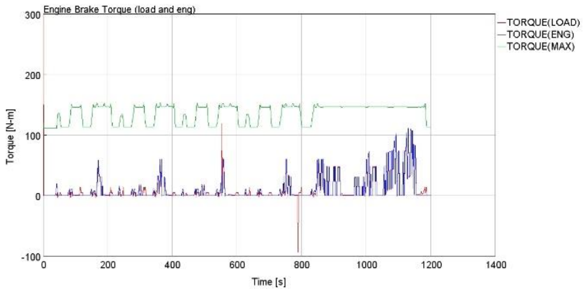

Figure 8. The load, engine produced and engine maximum capacity torques in NEDC driving cycle

As shown in figure 8, the engine torque capacity is very higher than demanded torque because the electric motors supply a part of load demanded torque.

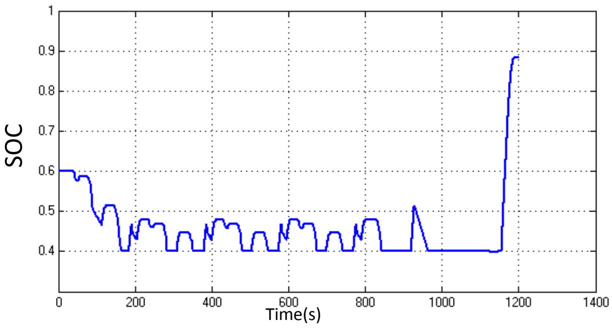

Figure 9. Battery pack SOC during the NEDC driving cycle

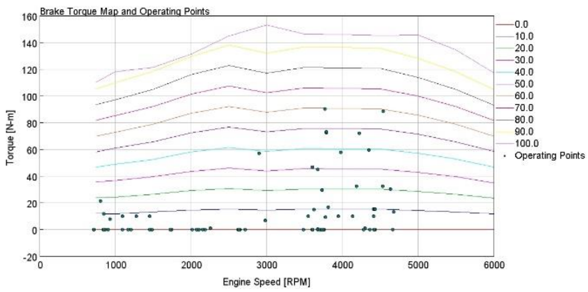

Figure 10. Engine operating points during the NEDC driving cycle

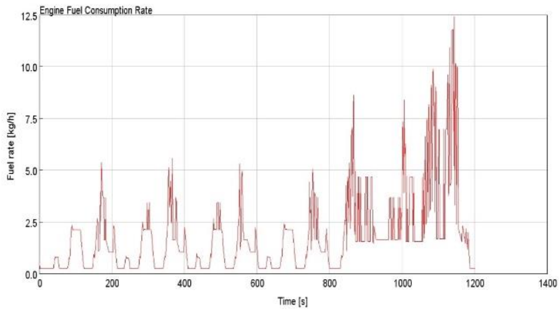

Figure 11. Fuel consumption rate during the NEDC driving cycle

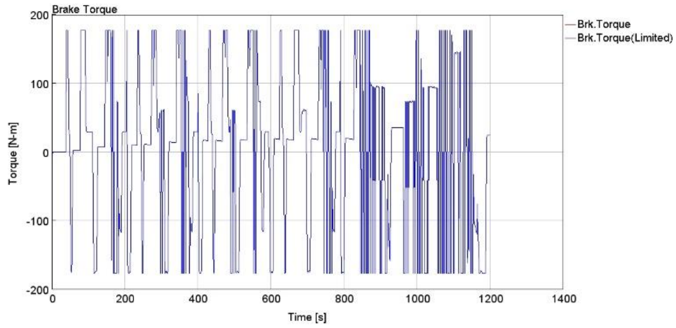

Figure 12. Electric motor torque during the NEDC driving cycle

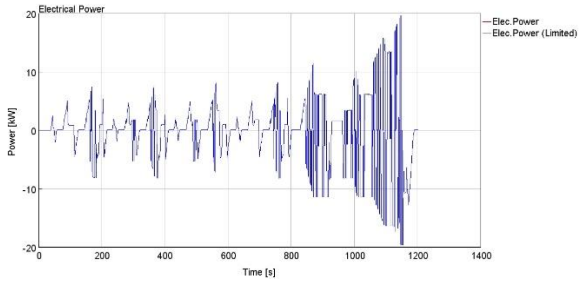

Figure 13. Electric motor power during the NEDC driving cycle

Table 6 shows the fuel economy of hybrid Samand for various driving cycles. Compared to gasoline counterpart, the designed hybrid Samand consumes 1.75 litters lower fuel at 100 km driving distance for NEDC drive cycle. By considering 20000 km for annual travelling, hybridization can save 350 litters per year and 5250 litters during 15 year lifetime. This benefits 4462 USD during vehicle lifetime. Compared to total initial cost of used two motors (175.5 Nm.) and three battery packs (total 18 modules during vehicle lifetime) i.e. 1246 USD, hybridization of Samand vehicle is beneficial.

Table 6. Fuel economy results of designed hybrid Samand

Driving Cycle	Fuel Consumption (litter/100km)
FTP75	**7.25**
HWFET	**5.79**
NEDC	**7**

6 Conclusions

The hybridization of conventional vehicles on one of the common vehicles i.e. Samand has proposed. The motivations for selecting this case study for hybridization were high production volume and low fuel performance. In this study a cost based optimization performed for sizing of additional components such as electric motors and battery modules. Hybrid simulation results using GT-Suit and MATLAB models verified that the fuel consumption of hybrid Samand, compared to gasoline counterpart is 1.75 litters lower for 100 km driving distance on NEDC drive cycle. It is resulted that compared to total initial cost of used two motors and three battery packs over]vehicle lifetime, hybridization of Samand vehicle is beneficial.

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