Series Hybrid Power Train for Automotive Application

Shekaina Justin¹, Samia Larguesh², Wafaa Shoukry³, Ghada Naif Alnemer⁴ and Shermina J⁵

¹,²,³,⁴ Department of Electrical Engineering, Princes Nourah Bint Abdulrahman University, KSA.
⁵Department of Computing, Muscat College, Sultanate of Oman

Abstract. In this paper a series hybrid powertrain is presented; factoring in the existing fossil fuel infrastructure established in oil producing economies, environmental impact, drivability characteristics, utilization patterns, advancement in automobile control sub-systems and appropriateness of technology. The prime mover employed for this hybrid are electric hub motors, powered by a super capacitor bank [SCB], which in turn is connected in with a relatively smaller battery pack [BP]. An IC engine is added in the loop to energize the SCB when the charge in the BP falls below the sub-optimal level; and, when the destination or fast charging facility are not reachable with the charge left in the SCB-BP module. A fast charger or a regular charger is plugged in to charge the BP when the vehicle is stationary.

Keywords: Super capacitor bank, Battery pack, Power electronics, Hub motors, Engine-Generator

1. Introduction

About 14% of worldwide greenhouse gas emissions are contributed by the transportation sector and 25% by the electricity and heating sector [1]. It is also true that cities that have high density of automobiles tend to have poor air quality. Although pure plug-in electric vehicles have zero tailpipe emissions, if they are powered by non-renewable sources, their carbon footprint is comparable to that of petroleum powered automobiles. With an overall energy conversion efficiency of fossil fuel power plants being 33% [2] with transmission and distribution losses of about 9% [3]; and after accounting power train, charging and discharging efficiency of about 65 to 80%, for plug-in electric vehicle; the actual carbon footprint of a plug-in electric vehicle is comparable to the carbon footprint when petroleum heat energy is converted to vehicle kinetic energy, which is about 16% to 30% for gasoline powered automobiles and 18% to 40% for a diesel powered automobiles [4]. However, both IC engine vehicles and electric vehicles have some distinct advantages, some of which are listed below:

Table 1. Comparison of IC Engine and Electric power train

|   | I.C. ENGINE | ELECTRIC |
|---|-------------|---------|
| 1. Technology | Developed ✓ | Developing |
| 2. Energy density | Very high ✓ | Low |
| 3. Tail pipe emissions | Yes | No ✓ |
| 4. Efficiency | Poor | High ✓ |
| 5. Maintenance | Moderate | Low ✓ |
| 6. Replacement cost | Moderate ✓ | Very high |
| 7. Life span-prime mover | High | Very high ✓ |
In USA and China, electric cars are gaining popularity at present. But the technology of battery is not mature and appropriate to be adopted for most types of automobiles because of the high cost and mass of the BP. When we factor-in the energy involved in the battery manufacture, toxic materials used for their manufacture and disposal of degraded batteries; the overall advantages of plug-in electrics from the environmental perspective is not positive. Although the cost of running the electric vehicle is much lower when compared to the petroleum fuelled vehicle; when the factors such as initial cost; replacement cost of BP that has an average life span of 5 years, particularly for owners who use their vehicles for limited distances; the cost of ownership and the convenience are not favourable for electrics. And, for oil producing countries like Saudi Arabia, with competency in oil production and dependency of the economy on petroleum commerce; switching over to pure electric vehicles is not a prosperous and prudent preposition for the near future. However, improving the air quality in cities is a pressing need. Moreover, the acceleration and regenerative braking characteristics of the electric automobile cannot be ignored, as the users would appreciate the superior acceleration and lower energy cost of the electric vehicles. Also, the maintenance cost and time intervals of the electric vehicle is bound to be low, when we exclude the replacement cost of the battery pack. As far as utilization is concerned, for example in Saudi Arabia, the average passenger car covers 25000km per year. The pattern of usage varies depending on their profession, lifestyle etc. For a user driving less than 100km daily, the range of 64kWh battery fitted, for example, in HYUNDAI KONA EV is high. The extra mass on account of the battery, costs additional energy to increase the kinetic energy of the car. It also affects the handling and tyre life. But, when the user chooses to engage in a journey beyond 400km, the battery cannot be charged with a regular charger overnight, if he/she wants to return the same day or the next morning, as a regular charger takes 29 hours to charge from zero to full SOC [19]. In that scenario, the user had to utilize a fast charging station. The car cannot be used for long distance travel in roads lacking fast charging infrastructure. The anxiety level of the user will be high when SOC of battery is low and its impractical to use such vehicles during emergency situations. Extensive planning to undertake a trip is inconvenient. The cost to replace the BP after its average life span of 5 years is also very high. The operating cost of the vehicle should match the buyer’s purchasing power for vast market acceptability and the configuration of the powertrain should be in alignment with the pattern of usage.

On the other hand, the IC Engine has been around for a very long time. Hence the manufacturing and the fuel infrastructure is well established. Also, there is scope for improvement in efficiency of the IC engine, particularly when operated at steady conditions. The superior life and power density of super capacitors ensure that they could be employed in vehicles, where the variation in the energy demand is very high. As the field of power electronics for automotive energy management has developed considerably, seamless flow of quality power from BP to SCB is made possible; improving the life of the BP significantly and reducing the heat generated in the BP, thereby reducing its cooling requirements.

2. Literature survey
An in-depth study into the efficiency of IC engine powered automobiles show that the fuel energy to kinetic energy conversion efficiency is between 16% to 40% [21], depending on the driving patterns and road conditions, type of vehicle and fuel used, etc. Automobile companies are investing in improving the fuel efficiency mainly because of the carbon footprint targets imposed by various governments [5]. Toyota has developed HCCI with modification in bore-stroke ratio and claims a thermal efficiency of 40%. Mazda has modified the combustion chamber, the inlet manifold and uses a HCCI combined cycle to achieve a thermal efficiency of 38%-41% [7]. The other engine developments having high thermal efficiencies are Achates Power’s opposed piston engines of about 50% [8][6][9], RCCI engine of about 60% [10], etc. Emission levels of carbon dioxide, carbon monoxide, particulate matter and nitrous oxide were also reduced. However, these high brake thermal efficiencies don’t translate into substantial high mpg/kpl for different drive cycles, as the conditions are
of transient nature [17]. The continuously varying torque demand and energy losses on account of braking, idling and transmission are some of the factors that contribute for poor on road efficiency.

In hybrid vehicles with li-ion battery, only part of the energy lost during braking is recovered by converting to electric energy as the degradation of the battery on account of sudden charging [16], [18]imposes a limit on the energy that could be recovered; although the battery chemistry is designed taking into account the quick charging and discharging requirements, compromising on the energy density. Although the fuel consumption of the latest hybrid models is much lower than their gasoline counterparts, scope for improvement using the same configuration without compromising on acceleration characteristics appears to be limited. The transmission systems of these hybrids are complex and, milder the hybrid configuration, the electrical energy regenerated and stored for usage is limited. A hybrid configuration which is efficient in city driving cycle is inefficient for highway.

3. Proposed Drivetrain

![Diagram](image)

**Figure 1.** Block Diagram of the Proposed Drivetrain

**HUB MOTORS:** H1,2,3,4 are Permanent Magnet Synchronous Machines [PMSM] fitted to the wheels for better response and distribution of mass, to maximize the regeneration during braking and to integrate the functions of anti-lock braking [ABS] and electronic stability program [ESP] within the functions of the hub motors [12]. Mechanical/ magnetic braking is added only for critical conditions.

**SUPER CAPACITOR BANK:** SCB powers the hub motors. The power electronics and control strategy design support to maximize the energy generated and stored during braking and deceleration [14]. As the heavy charging and discharging is handled by the SCB, and as the life cycle of the SCB is at least ten times that of the battery, the life span of SCB- BP module increases substantially [11, 13]. A thiol-functionalized, nitrogen-doped, reduced graphene oxide electrode super capacitor bank that has high power/ energy density of 32kW/kg (9.8 kW/L)/ 9.8 Wh/kg at a current density of 50 A/g [15] is utilized.

**BATTERY PACK:** BP is charged using a fast charger or a regular charger, when the vehicle is stationary. The BP charges the SCB when the state of charge in the SCB reaches the prescribed optimal level and, when the charge in the SCB reaches the minimum set value, and when the charge in the BP
also reaches sub-optimal level; the engine-generator [E-G] starts to power the SCB. Based on the destination inputs and SCB charge level, the E-G stops at the appropriate instant.

VEHICLE CONTROL UNIT & POWER ELECTRONICS: VCU along with PE functions as a power rationalization module by varying the current supplied to the hub motors. It also varies the flux of the stator to change the PMSM from motor to generator mode and vice versa. Based on the voltage at the SCB, the torque demand and the contact conditions of wheels with the road, it provides the current required for desirable traction, without compromising stability and eliminating tyre slip. PE module functions as a DC to DC converter, DC to AC converter and as AC to DC converter, depending on the required amplitude and direction of charge flow. When the E-G is generating current, the PE directs the current required by the hub motors and transfers the surplus to the SCB. During instances when the current required by the hub motors are more than the current generated by the E-G, the PE balances the difference by drawing from the SCB.

ENGINE-GENERATOR: The E-G is an IC engine coupled to an alternator that charges the SCB when it reaches the sub-optimal voltage and when the state of charge of BP is also minimum; and when the destination and or fast charging facility is not within reach, with the charge left in the storage module. The operating speed of the engine is optimized for maximum torque and minimum emissions.

4. **Novel Engine**

The proposed concept is modelled on HYUNDAI KONA EV to compare the different existing models with the proposed models. To reduce the complexity, the PMSM motor with the same specification of KONA EV is employed. The engine selected is a scaled down, stripped down version of a 0.9 litre, Achates Power Opposed Piston Gasoline Compression Ignition [OPGCI] two stroke engine that develops 63 kW at 2000 rpm and has a brake thermal efficiency close to 50% [10]; in which the variable geometry turbocharger is replaced by a fixed geometry turbocharger [FGT]; and the supercharger is replaced by an air accumulator, to maintain the air pressure in the inlet manifold high during starting. The displacement of the engine is taken as 374cc, bore as 60mm and stroke as 13mm. The compression ratio is 15.4. Based on the power output of the base engine selected, the power output of the engine is calculated as 20kW @2000rpm.

The block diagram of the proposed steady-state engine is shown below:

![Block Diagram of Proposed Steady-State I.C.E](image)

**Figure 2.** Block Diagram of Proposed Steady-State I.C.E

The alternator coupled to the engine is operated at constant load and has a rated output of 20kW.
The BP employed for the model is a 16kWh lithium-ion polymer battery like the one used in KONA EV. The SCB has a capacity of 1.5kWh.

5. Energy Consumption Analysis

Brake thermal efficiency of the base engine [gasoline] at maximum torque = 50% & diesel=55%
Net efficiency of the E-G [gasoline]= 45% & diesel=50%
Average energy required per km for combined drive cycle of KONA EV[20] =0.169kWh
Average energy required per km for the proposed series hybrid is calculated as =0.143kWh

[As the proposed model is lighter by about 250kg when compared to KONA EV (330kg reduction on account of BP and 80kg addition on account of SCB, E-G and fuel tank). This would result in energy savings of about 15% with better acceleration and braking characteristics.]

The energy required per kilometre to run the KONA with the proposed drivetrain=0.143kWh

The distance covered by KONA with the proposed drivetrain in E-G mode with:
Gasoline = 9.4/0.123*45/100= 29.6km/litre; Diesel=10/0.123*50/100 =35.0km/litre.

Table 2. Comparison of Energy Consumption in Different Configurations of Hyundai Kona

| Model                          | Gross Wt. | KP/L | kWh/Km   |
|--------------------------------|-----------|------|----------|
| 1. Petrol                       | 1350      | 12.5 | 0.713    |
| 2. Diesel                       | 1420      | 21.0 | 0.424    |
| 3. Petrol Hybrid                | 1450      | 18.7 | 0.476    |
| 4. EV                           | 160       | -    | 0.169    |
| 5. Concept EV with              | 1400      | 29.6 | 0.143/E-G|
| OPGCI(Gasoline)                 |           |      | 0.318(E-G)|
| 6. Concept EV with              | 1410      | 35.0 | 0.143/E-G|
| OPDDI(Diesel)                   |           |      | 0.286(E-G)|

6. Conclusion

The series hybrid concept presented can be successfully deployed for many automotive applications from small passenger cars to light duty trucks to heavy duty commercial vehicles. The arithmetic is positive for the proposed models with an electric range of about 115km on a 16 kWh battery and an additional 391km on a 13.5 litres of gasoline and 472km on a same quantity of diesel. Further studies need to be employed using computational fluid dynamics tools to validate the efficiency of the concept engines. As the size of proposed engine is much smaller than the selected base engine, there could be more heat losses that would reduce the efficiency. However, as the engine is to be operated in steady state, there would be enough room to reduce the cooling losses and modify the combustion chamber to improve upon the efficiency. Simulations need to be performed for various motor combinations to get the optimum acceleration, braking characteristics and energy consumption. Iterations have to be done after detailed simulations for power quality during traction; and optimize the BP, SCB and PE.

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