**ASSIGNMENT NO: 6**

**ADVANCED PROPULSION OF HYBRID ELECTRIC VEHICLES**

**Technology survey and comparison of E-machines and Electric Drives**

**GROUP 06.ASSIGNMENT06.MEEM 5295**

**GROUP MEMBERS:**

**Arjun Sai Santosh Darbha (adarbha@mtu.edu)**

**Guangchen Xiong (gxiong@mtu.edu)**

**Pratik Mahamuni (ppmahamu@mtu.edu)**

**Sunit Menon (ssmenon@mtu.edu)**

**INSTRUCTOR:**

**DR. WAYNE WEAVER**

**Introduction:**

Fuel Economy and reduced fuel consumption are the two eternal challenges faced by automobile manufacturers. Hybridization and electrification are considered to be modern technologies which enable reduction in fuel consumption reduction and are envisaged as the future of automobile technology. However, electrification has been an integral part of vehicle propulsion since the inception of automobile technologies. In fact, the first four wheeled electric car dates back to 1828 when a Hungarian inventor, Anyos Jedlik came up with a model car[1]. Electric drive vehicles were the only four wheeled vehicles around for most of the 19th century until the dawn of IC-Engines in the beginning of the 20th century. Also, hybrid technology came into existence by around the same time. Porsche Mixte was the first hybrid electric vehicle which was presented in the 1900 Paris World Fair [2]. This was a series hybrid and was not built with an objective of reducing the fuel consumption. Its prime purpose was to provide torque and power with increased efficiency which the IC Engines lacked during their early stages of development. However, electrification (for propulsion) at this point in time was totally overtaken by the advances in IC Engine technology, easy availability of motor oil and also meager development in battery technologies used for energy storage in Electric vehicles.

The context of hybridization in modern times is majorly focused around fuel economy. Not surprisingly, the technology comes with a price which means that the most important factor under scrutiny would be Payback Period. This value of payback period depends on a lot of factors like degree of hybridization; electric technology used battery technology used and so on. For example, Integrated motor assist(IMA) used in Honda Civic (Hybrid) which is the lowest form of hybridization where only a bigger e-motor is used in place of an existing alternator comes at a very low cost and payback period, but an electric vehicle which runs exclusively on an E-motor, for example Tesla Model S comes with huge price tag.

The objective of this report is to present the details on various motor technologies used in contemporary vehicles. Motors, as discussed, are used for propulsion in Hybrid Electric Vehicles (HEVs) and Electric Vehicles (EVs). It has to be realized at this point that E-motors are used for various purposes in a vehicle but this report aims at providing the details of those motors that are directly used for propulsion. [1][2]

**Overview of motor technologies in current vehicle:**

**Table 1 Details of motors used in some of the current HEVs/EVs [3][4]**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Price** | **Car** | **Technology** | **E-motor type** | **E-machine power (HP)** | **Torque (ft-lb)** |
| $60,000 | Tesla Model S 2012 | EV | IM - 3 phase 4 pole | 235 | 310 |
| $110,000 | Tesla Roadster | EV | IM - 3 phase 4 pole | 288 | 273 |
| $40,000 | Chevy Volt | EV-Extended Range | IPM | 149 | 273 |
| $30,000 | Nissan Leaf | EV | IPM | 110 | 210 |
| $32,000 | Prius PHEV V 2 | PHEV | IPM | 80 | 153 |
| $20,000 | Honda Insight | HEV | IPM | 13 | 58 |
| $50,000 | Mitsibushi I MIEV | EV | IPM | 63 | 145 |
| $50,000 | Toyota RAV 4 Electric | EV | IM | 154 | 273 |
| $56,000 | Mercedes Benz E-class Hybrid | HEV | IPM | 27 | 207 |
| $97,000 | Porsche Panamera Hybrid | HEV | IPM | 47 | 221 |

From Table 1, it can be clearly seen that the price of all the vehicles with any degree of hybridization/electrification is above the average cost of a normal gasoline vehicles of about $25000. Also, the cost of electric drive only vehicles is much higher than HEVs. This cost is mostly attributed to the battery technologies and power electronics rather than the cost of the E-motor itself. As discussed previously, battery technology hasn’t seen significant development in recent years and since any new improvement in the technology comes with a cost this additional cost of electric vehicles is intuitive.

From Table 1, it can also be seen that most of the technology is developed around the synchronous AC motors, colloquially called, brushless DC motors. This has been represented by IPM (Internal Permanent Magnet) in the motor type which essentially denotes the exact same motor type as discussed above. Moreover, brushless DC motors come in two variants, Surface magnet machines and Interior Permanent Magnet (IPM) machines. However, IPM is the only technology used in vehicle propulsion because it does not involve a maintenance cost. If a magnet encounters failure in the surface magnet machines, there is a possibility of the magnet flying away from the rotor which results complete breakdown of the machine. To overcome this possibility, a magnets embedded inside the rotor is used and hence the name interior permanent magnet. [4]

Also permanent magnet machines use a permanent magnet which is natural resource not different from oil. In fact efficient permanent magnets, namely, Neodymium magnets, are very difficult to occur in nature with only a handful of mines across the globe. Hence, the current research is towards eliminating the use of permanent magnets in motors and finding a permanent solution. [8],[9]

One of the solutions is to use Induction motors which do not use a permanent magnet. From Table 1 it can be seen that Tesla Motors is currently using this technology in all its vehicles with appreciable values of torque (ft-lb) and power (hp). Though Induction motors are not that difficult to manufacture and do not contain any exotic materials, (all it contains is an iron stator and copper rotor), it is quite evident that Tesla vehicles are quite expensive. This attributed to control and power electronics of these motors. As a matter of fact, it is not easy to control a 3-phase Induction motor which these vehicles use. Hence, this technology ensures a promising future, but when compared to the current technology costs, it is still highly priced. Also, the efficiency of an induction motor (about 75%) is slightly lower than that of an IPM (about 83%).[10]

Fig.1 is based on the data presented in Table 1 and Table 2.Though the power of Tesla cars is much higher than the other cars, it comes with a price, as already discussed. Also a close look at the price and cost of technology reveals that cost of electronics in case of Induction motors is substantial. Mitsubishi IMIEV’s cost of technology is very similar to the cost of the vehicle. This can again be attributed to the fact that the cost electronics in this case much lower because the control of IPM motors is well established. Overall, the figure manifests that hatchback still use IPM DC motors and high-tech sedans like Tesla use AC Induction machines. Also, eventually, EV market is moving towards, Induction machines, for reasons previously discussed. For example, Toyota RAV-4 Electric, an SUV scheduled for 2013 runs on an Induction Machine.

**Fig 2. Graphical representation of Power, cost of vehicle and cost of E-motor for different EV’s/HEV’s**

Table 2 reports the technical details of different electric motors used in the current vehicles. In case of Induction motors used in Tesla vehicles, it is evident that, a cooling technology is used to enhance the speed and torque range of the motor. This is important because, the vehicle is propelled only by an Induction motor with a copper cage and it would heat-up if there is induction of high currents in the rotor, hence the cooling.

Also the cost discussed in the last column of Table 2 is the cost of the motor from the perspective of OEMs. It does not include the cost of power electronics and also the retail price factor (RPF) which contributes a substantial portion to the cost especially in the case of AC induction motor.

**Table 2: Comparing E-motor technology in contemporary EV’s/HEV’s [4][5][6]**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Car** | **E-motor type** | **E-machine power(hp)** | **Torque(ft-lb)** | **Weight (kgs)** | **Volume (L)** | **Torque density(Nm/L)** | **Cost (100 US $)** |
| Tesla Model S 2012 | IM - 3 phase 4 pole, Air cooled | 235 | 310 | 80 | 30.38 | 13.83 | 115.04 |
| Tesla Roadster | IM - 3 phase 4 pole, Air cooled | 288 | 273 | 35 | 30.38 | 12.18 | 50.33 |
| Chevy Volt | IPM | 149 | 273 | 70 | 20.93 | 17.68 | 100.66 |
| Nissan Leaf | IPM | 110 | 210 | 60 | 15.87 | 17.90 | 86.28 |
| Prius PHEV V 2 | IPM | 80 | 153 | 41 | 3.67 | 56.46 | 58.96 |
| Honda Insight | IPM | 13 | 58 | 12 | 11.66 | 6.69 | 17.26 |
| Mitsibushi I MIEV | IPM – water cooled | 63 | 145 | 34 | 30.38 | 12.42 | 48.89 |
| Toyota RAV 4 Electric | IM | 154 | 273 | 69 | 20.93 | 17.68 | 99.22 |
| Mercedes Benz E-class Hybrid | IPM | 27 | 207 | 17 | 5.72 | 48.93 | 24.45 |
| Porsche Panamera Hybrid | IPM | 47 | 221 | 43 | 15.87 | 18.91 | 61.83 |

Fig 2 presents a Donut chart on the data reported in Table 2. This figure is counter-intuitive in the sense that Torque density in not proportionally to cost of the E-motor. Tesla’s induction motor has the highest cost, but its torque density is not as high when compared to the other motors. Prius PHEV which has an IPM has the highest torque density, but the cost of this motor is not extravagantly high. Also, in general, IPM has a higher torque density. This is essentially one of the major advantages of using permanent magnets in motors. It can also be seen that most of the hybrids use IPMs so their Torque Density is higher. Prius PHEV is a clear winner in this segment when Torque density and cost of the E-motor are compared

**Fig 2. Graphical representation of Cost of E-motor v/s torque density for different vehicles**

Torque Density(Nm/L)

**Conclusions**

* Almost every vehicle with hybridization/electrification uses an IPM with permanent magnets
* The high end EVs Tesla’s and Toyota RAV4 SUVs use Induction Machines
* Electrification and hybridization can be seen in almost all the segments-sedans, hatchbacks, SUVs, saloons, coupes etc.
* EV-only vehicles other than Tesla’s are usually hatch-backs. This may allow the car-makers to reduce the cost but in a long run, this technology is going get obsolete because of the limited resource of quality magnetic material used in E-motors
* Induction machines are the best replacement for Permanent magnet machines. However their market penetration involves a lot of research in order to cut down cost of power electronics so that they can completely replace IPMs

**References**

[1] http://www.tecsoc.org/

[2] http://www.nowpublic.com/tech-biz/hybrid-car-history-porsche-4wd-1900

[3] http://www.staveb.ch/downloads/3ph\_motoren\_ie1.pdf

[4] W. Wang; B. Fahimi; Comparative study of electric drives for EV-HEV propulsion system

[5] Mohamed El Hachemi Benbouzid; Mounir Zeraoulia; Demba Diallo; Electric Motor Drive

Selection Issues for HEV Propulsion Systems: A Comparative Study

[6] M. Duoba, H. Ng, R. Larsen, "Characterization and comparison of two electric vehicles (hevs) - honda insight and toyota prius", SAE paper 2001-01-1335, SAE 2001 World Congress, Detroit, MI, March,2001

[7] K. Rahmanri, M. Anwar, S. Schulz, etc, 'The voltec 4et50 electric drive system" SAE paper 2011-01-0355, SAE 2011 World Congress &Exhibition, Detroit, MI, April, 2011

[8] C. M. Krishna, “Managing battery and supercapacitor resources for realtime sporadic workloads,” *IEEE Embedded Syst. Lett.*, vol. 3, no. 1, pp. 32–36, Mar. 2011.

[9] A. Y. Saber and G. K. Venayagamoorthy, “Plug-in vehicles and renewable energy sources for cost and emission reductions,” *IEEE Trans. Ind.Electron.*, vol. 58, no. 4, pp. 1229–1238, Apr. 2011.

[10] A. Boglietti, A. Cavagnino, and M. Lazzari, “Computational algorithms for induction-motor equivalent circuit parameter determination—Part I: Resistances and leakage reactances,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 9, pp. 3723–3733, Sep. 2011.

**Evaluation Sheet**

Group Number: 6

Students Names

|  |  |  |
| --- | --- | --- |
| **Last** | **First** | **M Number** |
| Darbha | Arjun | M-94248207 |
| Xiong | Guangchen | M-41405583 |
| Mahamuni | Pratik | M-35468719 |
| Menon | Sunit | M-05453441 |

|  |  |  |
| --- | --- | --- |
| **Area** | **Points** | **Score** |
| **Report** |  |  |
| Introduction | 20 |  |
| Results and Discussion with tables / Figures | 50 |  |
| Summary and Conclusions | 20 |  |
| References | 10 |  |
| **Total =** | **100** |  |