Recent Related Technologies for EV/HEV Applications in JAPAN

Kan Akatsu[1], Naoki Watanabe[2], Masami Fujitsuna[3], Shinji Doki[4], Hiroshi Fujimoto[5]

1 Dept. of Electrical Engineering, Shibaura Institute of Technology
Toyosu, Tokyo, Japan
Email: akatsu@sic.shibaura-it.ac.jp

2 Shin-Etsu Chemical Co.,Ltd.
Echizen, Fukui, Japan

3 DENSO Corporation
Kariya, Aichi, Japan

4 Nagoya University
Chikusa-ku,Nagoya, Japan

5 University of Tokyo
Kashiwa, Chiba, Japan

Abstract -- The paper reports on recent related technologies for electric and/or hybrid electric vehicle applications. These technologies have been investigated and/or developed by authors who belong to an Investigating R&D Committee of Vehicle Technologies in IEE Japan. For this paper, the important technologies especially the materials, the power devices and the vehicle control method are described.

Index Terms -- Electrical Steel Sheet , Electric Vehicle, Hybrid Electric Vehicle, Neodymium Magnet, SiC power device, Vehicle Stability Control

I. INTRODUCTION

Although the motor as an electric machine has been researched and developed for many years, a solution what is the specialized motor for vehicle application, has, however, not been established. Since the required characteristics which are widely known as the wide speed range, the high torque and the high power density are actually different in each type of vehicles. Adding that, the related technologies, for example the electric steel core, the magnet, the power electronics technique and so on which are requested to establish not only the motor but also the vehicle are very important since these related technologies effect to the size, cost, electric capacity and efficiency of the motor. Also these technologies sometimes may change the motor itself by the evolution of these technologies. Thus an investigation of these related technologies is very important.

From the viewpoint of the above description, we, an Investigating R&D Committee of Vehicle Technologies which is composed by about 20 members from the car manufacture companies, the industrial electric companies, the material companies and the academics have been investigating and/or developing these technologies. In this paper, from these investigating results, some technical trends of the neodymium magnet, the magnetic material, the electrical insulation material as the motor materials and the SiC power device, which impacts on the power converter for the motor drive are introduced. Finally, the reduction gear which is essential for an electric power train and the vehicle motion control by using in-wheel motor, which also requires the gear as a key device, are also touched.

II. MATERIALS

A. *Neodymium magnet*

As everyone knows the price of the neodymium and the dysprosium had been increased in recent years. However, owing to a lot of developments; such rare earth less / free motors and a development of the high coercive force magnet without the dysprosium and the establishment the recycling method, the price has been decreased from last year. In here, the recent approach of the magnet recycling and the recent magnet development are described.

The recycling of the neodymium magnet under the magnet making process actually has been established since almost 30-40% magnet material of the production becomes a dust. The recycling is performed under two conditions;

1) the wet condition

2) the dry condition.

In 1), the neodymium and the dysprosium are extracted as the ion into the acidic medium. Since high purity rare earth materials can be obtained by this

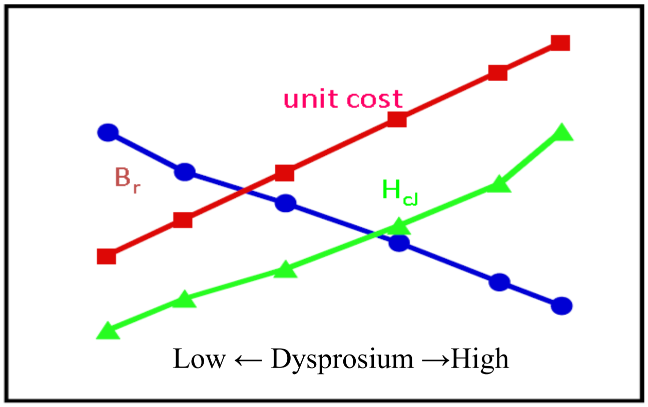

Fig. 1 A trade-off between Hcj and Br. Adding the dysprosium realizes high Hc however Br becomes low.

method, the obtained materials can be used as the usual new materials. Thus, this method is frequently used in the industry because of the low cost. In 2), the dust is directly used as the mixture with the new materials. Although the process is easy the quality is worth because of the impurities of the dust. On the other hand, a new method that the rare earth materials are collected from the scrap of the air conditioner and the vehicles has been focused. However, since the volume ratio of the rare earth into the scrap is very low and the process to select only the magnet from the scrap is very complex, this method is hard for the practical use. Thus the total system from the scrap collection to the magnet production should be established with a government support.

Recent magnet development direction is increasing the coercive force to ensure the high temperature condition without the dysprosium. Usually a relationship between the coercive force and the remnant flux density is a trade off as shown in Fig. 1. Then almost 10% dysprosium of the neodymium volume had been used for high coercive magnet, the magnet cost was much expensive. To decrease the high coercive force magnet without increasing the dysprosium, the alloying process by grain boundary diffusion has been developed and now the magnet by this process has been released [2]. In this method, sintered bodies are coated with the rare earth compound and then heat treated at lower temperatures than sintering temperatures (diffusion treatment). Using this new process, the amount of the dysprosium diffused into magnets can be appropriate and more efficient usage of heavy rare earths can be realized (see Fig. 2). Some techniques based on this technique have been developed by each magnet company, the motor with this less dysprosium magnet has already designed and the electric vehicle with the motor has been released in Japan.

B. *Electrical steel sheet*

As well as the magnet the electrical steel sheet has a trade-off between the iron loss and the saturated flux density as shown in Fig. 3. Thus the development direction is how to reduce the iron loss without decreasing the saturated flux density. One of the results of the developments is non-crystallize material, amorphous materials. Actually a part of the pole transformers has used the amorphous core, the efficiency has been much improved. Also an axial type flux PM motor with the amorphous core has been reported [4]. However the amorphous steel sheet is very thin, 0.02 mm or less, and very hard and fragile. Thus the improvement of the punching, its process and die design is a problem.

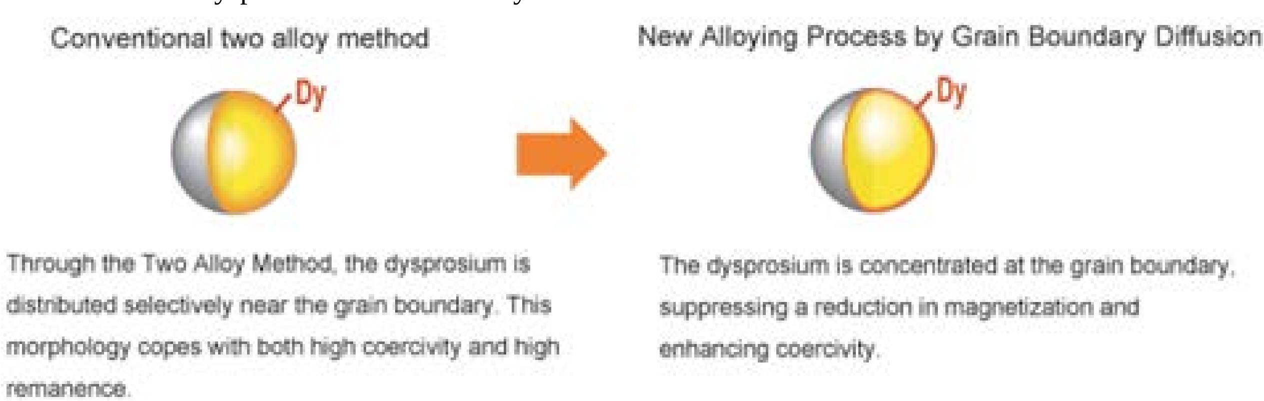

Fig. 2 New alloying process by grain boundary diffusion.

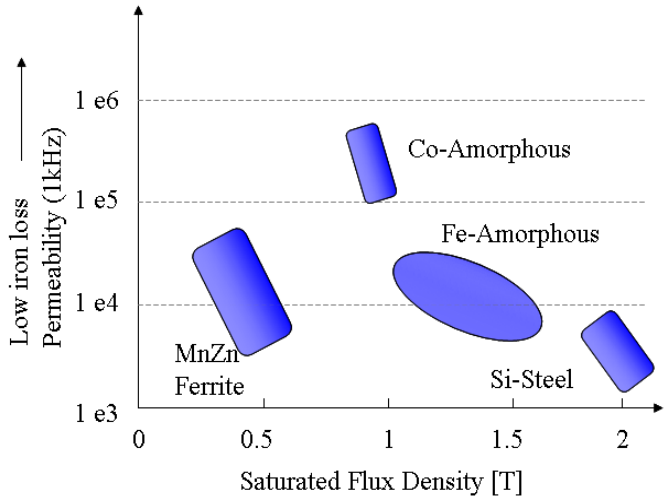

Fig. 3 A trade-off between the iron loss and the flux density. Amorphous is attractive since it has high saturated flux density and low iron loss character.

Further investigation material is a nano-crystallize material. 10nm size of α-F_e is surrounded by P or Cu, the material has a similar saturated flux density, 1.8T-1.9T with the silicon steel sheet, and also the permeability of the material is 10 times larger than the silicon steel core. It has been reported that the iron loss is almost half of the 0.27mm grain oriented steel core at the condition of 1.7T/50Hz [3]. However, the reported shape of the material is only a ribbon shape, 0.02mm thickness and 50mm width. As well as the amorphous steel sheet, it is very hard to use the nano-crystallize material for the motor core. Thus the breakthrough of the production technology has been expected. Table I summarizes the characteristics of these materials.

C. *Insulation materials*

Insulation materials will be the key materials for the traction motors. Especially the thermal conductivity of the material, insulation sheet is a key. This is because it is important how to cool the winding heat which comes from high current density of the winding to realize the higher torque density. Also high voltage insulation technology is important since the higher power density motor is obtained by higher DC bus voltage of the inverter.

Recently the Poly Phenylene Sulfide , PPS has been used because of its high thermal conductivity, 5 - 10W/m K, on behalf of the metalized material. PPS is made of mixture plastic and filler, the filler contributes to increase the thermal conductivity. However, the filler is usually low resistance, the break down voltage becomes low, and the flexibility becomes also low. Thus as well as the magnet and the electrical steel sheet, this material has also trade-off between the thermal conductivity and the breakdown voltage. Thus further development to break the trade-off has been expected.

III. POWER DEVICES AND INVERTERS

A. The advantages of SiC device for EV/HEV application

SiC switching device has a lot of advantages against to the Si device. Fig. 4 shows advantages of SiC device. Especially the high breakdown voltage and the high thermal conductivity realize 2 – 3 times current density and the switching around 200 deg. condition becomes possible. Owing to this high temperature

Table I Characteristics of the materials for the motor core

		High Permeability (Low iron loss)		High saturated flux density
		Minimize magneto-anisotropy	Minimize magneto-strict ion	High density Fe
Crystal	Fe	Yes	Yes(-)	
Non-Crystal Amorphous	Fe-	No	Yes(+)	Mixture material is required Low saturated flux density
	Co-	No	Yes(-)	
Nano-Crystal	Fe-	No	No	α-Fe nano Crystal is rounded by amorphous

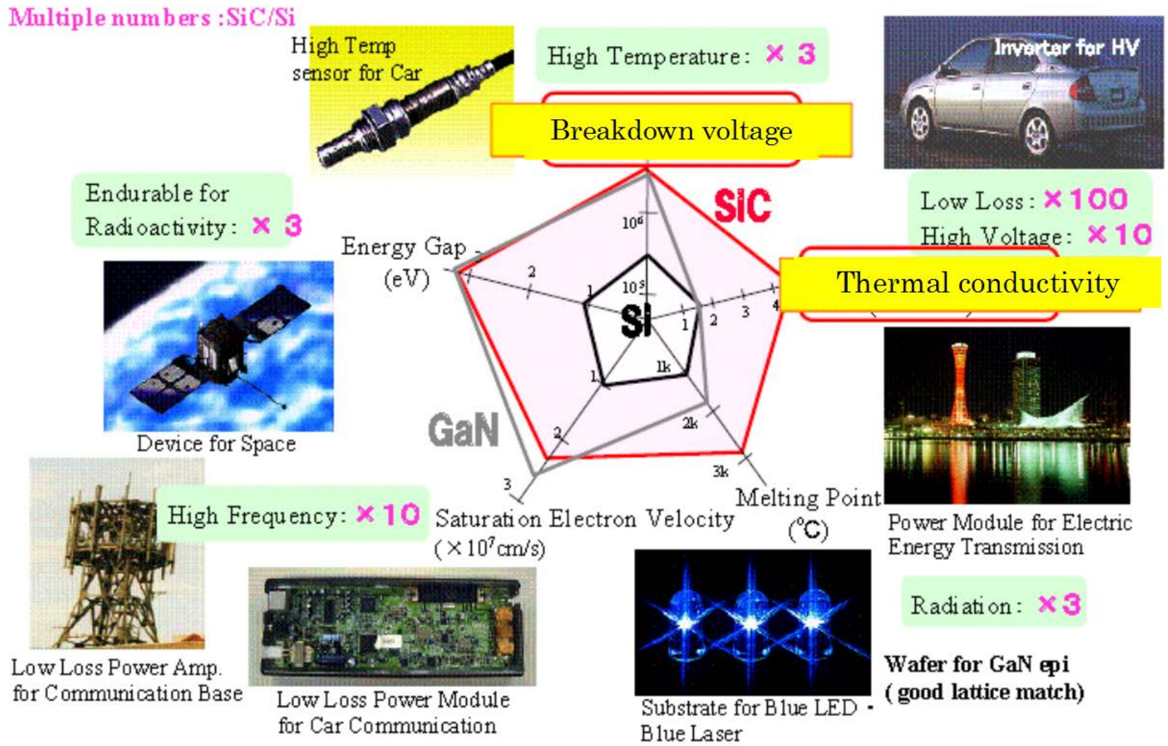

Fig. 4 Advantages of SiC device

operation the engine coolant can combine with the cooling system of the inverter and the motor. Thus much small power train system can be realized as shown in Fig. 5.

Another advantages such a low conductive loss and a high frequency switching characteristic realize high efficiency and high power density inverter. These advantages realize smaller inductance and capacitor, the inverter or the chopper will be integrated with the motor. Thus the layout where the motor and inverter is has much freedom. Actually about 5 -10% fuel consumption will be improved in HEV by the small inverter system.

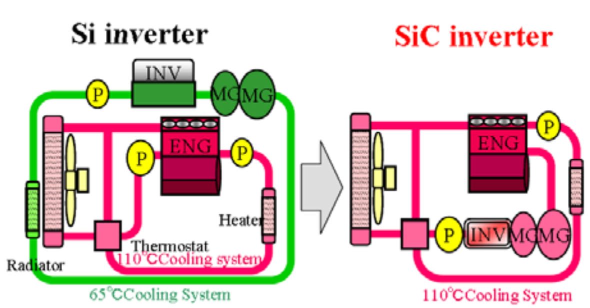

Fig. 5 SiC inverter system. Two cooling systems are combined by using SiC inverter.

Here shows some development examples of SiC inverter. In EV/HEV applications the SiC device which has 600V – 1200V breakdown voltage, 100 – 400A MOS-FET and SBD are requested. DENSO developed 100A SiC-MOSFET with SiC-SBD inverter module in 2007, NISSAN developed an inverter with SiC diode for FCV in 2008 [5]. ROHM also developed 1200V 230A high power inverter module by SiC-SBD and SiC-MOSFET with HONDA. In this module one phase converter and three phase inverter are integrated within a package. The switching loss is reduced one forth compared with Si inverter, this can realize 80kHz switching [6]. In 2009, MITSUBISHI ELECTRIC developed 11kW inverter with SiC-MOSFET and SiC-SBD, 5.2mm square chip, 70% loss reduction and 75% volume reduction are realized [7]. The recent development is shown in Fig. 6, which power density is 60kW/L.

As described the above, the devices achieved enough characteristics for EV/HEV applications. However, the reliability that means ensuring capacity for the surge voltage and the short circuit at the condition from-40deg. to 200deg. has to be confirmed. Also the cost is the main problem to solve. Since Si-IGBT for HEV/EV is made by 8 inch wafer, 6 inch wafer for

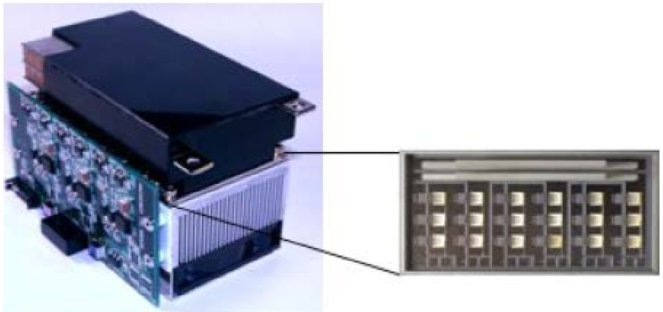

Fig. 6 A picture of 60kW/L inverter

SiC is required to realize the similar cost with Si-IGBT. However CREE has reported 6 inch wafer is possible in [8], it will be solved in nearly future.

IV. Power Train, Gear and Vehicle Stability Control

A. *Reduction gears*

To make a small motor the reduction gear is very important equipment for EV/HEV, because the space for the motor is strictly limited in the vehicle, the maximum revolution speed of the motor must be considered not only from the electrical frequency but also from the mechanical speed with the reduction gear to realize the best power train system. There are a lot of types of the reduction gears, planetary gears, cycloid gears and so on. Thus which type gear should be selected is considered by taking into account of the maximum motor speed, the reduction ratio, efficiency and so on. One of the examples has been reported in [9], the in wheel motor with the cycloid reduction gear which reduction ratio is 8.5.

We are very careful about this reduction gear trend because sometimes the motor design becomes very easy by only using the reduction gear. For example a changeable winding motor has been reported in recent years, however, a question about which system is better, one changeable winding motor or a constant winding motor with the 2 range gear system, has not been considered. For example, 2 mode changeable winding motor and inverter called as QMET has been proposed in [10] and the system has been used for EV in Japan. The system can achieve overall high efficiency in the range which EV frequently uses. However, if the reduction gear has 2 mode, off course the loss of the gear is increased, the similar characteristics can be obtained. Then, further development of high efficiency gear is expected. Especially for EV/HEV application the motor design from the viewpoint of the total system is very important.

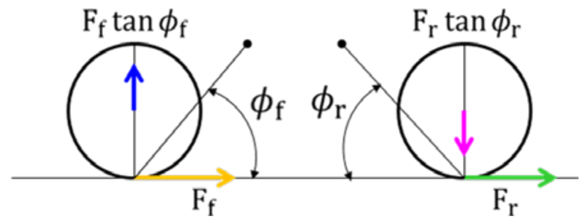

Fig. 7 Vertical force generation by the output torque of In-Wheel motor.

Fig. 8 Four In-Wheel motor vehicle (University of Tokyo)[11]

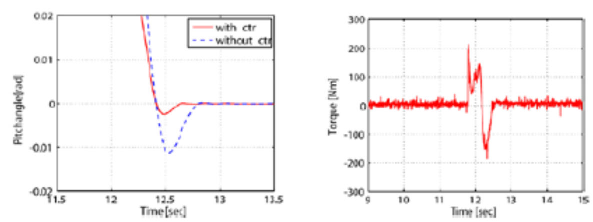

Fig. 9 Experimental result of the pitch angle (left) and the motor torque (right). In the left, the blue dash line shows the pitch angle without control, the red line shows it with the proposed pitch angle control.

B. *Vehicle dynamics control with In-Wheel motor*

By using the quick response of the electrical motor the research of the vehicle dynamics control with the In-Wheel motor has been achieved. Recent activity is the pitching moment control. As shown in Fig. 7, the In-Wheel motor can generate the force not only in the horizontal direction but also in the vertical direction because of the suspension angle. The combination of positive and negative torques can generate the pitching moment by In-Wheel motor, the effectiveness has been experimental proved by the four wheel drive car which is shown in Fig. 8. The result is shown in Fig. 9, the pitch angle is controlled by the motor control.

V. Conclusion

This paper described the related technologies of the traction motor for EV/HEV. Regarding the material for the motor, especially the technique of the dysprosium reduction in Nd magnet is a key to reduce the cost of the magnet. Also both the higher flux density and the lower iron loss electrical steel core is expected. The power electronics technique such as SiC inverter will change the motor design itself. Especially the high temperature operation is a key to integrate the motor and the inverter. Adding that the mechanical equipment such as the reduction gear is expected to reduce its mechanical loss. Finally the In-Wheel motor control technique to control the pitching motion was introduced. The motor design has been strongly affected by these related technologies, it is very important to watch the trends of these technologies. Each technology still has each problem to solve, the concurrent design method of the motor from the viewpoint of the vehicle characteristic by compensating these problems is required.

Acknowledgment

The authors wish to acknowledge the motivation provided by members of an Investigating R&D Committee of Vehicle Technologies in IEE Japan.

References

[1] N. Watanabe, M. Fujitsuna, H. Fujimoto and S.Doki, “ Seeds Technologies for Vehicle Motor”, *IEEJ IAS Annual Meeting*, Aug. 2012 (in Japanese)

[2] http://www.shinetsu-rare-earth-magnet.jp/e/rd/grain.html

[3] NIKKEI Electronics 2011.9.19 (in Japanese)

[4] H. Amano, Y. Enomoto, et. Al, “Examination of Applying Amorphous Rolled Core to Permanent Magnet Synchronous Motors”, The transactions of the Institute of Electrical Engineers of Japan. D, A publication of Industry Applications Society 130(5), 632-638, 2010-05-01 (in Japanese)

[5] NISSAN Motors Press Release 2008.9.5

[6] Rohm Press Release 2008.9.11

[7] Mitsubishi Electric Press Release 2009.2.18

[8] CREE Press Release 2010.8.30

[9] S. Murata, “Development of In-Whee Motor Drive Unit” , 2011 SAE World Congress No.28-10,pp5-9 (2010) (in Japanese)

[10] M. Swamy, T. J. Kume, A. Maemura, and S. Morimoto: “Extended High Speed Operation via Electronic Winding Change Method for AC Motors”, *IEEE Trans. on Ind. Applicat.*, Vol. 42, No. 3 pp. 742-752, May / Jun. 2006.

[11] H. Fujimoto and S. Sato, "Pitching Control Method Based on Quick Torque Response for Electric Vehicle", in Proc. IPEC-Sapporo, pp.801-806, 2010.