Development of BLDC Motor using Metal Powdered Core for 42V Fan Application of Hybrid Electric Vehicle

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Abstract: - This paper aims to develop the 42V BLDC fan motor for hybrid electric vehicle using metal powdered core. So, the influence on a motor design by metal powder is described and the powder is applied as a direct replacement of lamination core. This point is focused upon a comparison of brushless dc motors, built with a powdered stator and Si laminated stator, which also has been redesigned to take an advantage of the powdered core for improving their performance on the same volume.

Key-Words: - 42V cooling fan motor, BLDC motor, Metal powdered core, Si laminated core, EMCN method

1 Introduction
The demands being placed on a car’s electrical system today are unprecedented and so the 42V power system will be applied to service the electrical needs of future vehicle such as Luxury vehicle, HEV (Hybrid Electric Vehicle) and FCEV (Fuel Cell Electrical Vehicle) [1]. The load voltage for motors also is recommended to be 42V because of several benefits due to the higher voltage. The cooling fan motor is one of main power consumed electric loads at the present vehicle. So, the development of 42V fan motor is needed. Generally, the 12V Brush type DC motor is used for fan because of use of the existing infrastructure. However, this need to be rated for continuous operation at the highest current and the motor lose 15 percent of their energy in the brushes alone. So, brushless DC motor will be the choice for most application such as fans and pumps because of its efficiency at high voltage as well as it easy control and high quality and reliability [2]. This paper presents the development of BLDC motor using metal powdered core for 42V cooling fan.

Metal powder materials as new magnetic materials for improving the capability of magnetic circuit of electric machine devices have been continually developed and its applications have been expanded according to the requirement of high performance. That is, a magnetic material is used for all kinds of motors converting an electromagnetic energy to a mechanical energy and plays an important role in their performance. So, much research is performed for improving the performance. In such side, metal powder materials allows improvements over the lamination core with the respects of design freedom, low manufacturing cost, simple manufacturing processes, and low eddy current losses [3], [4],[5].

Since the particles of the powder are insulated by the surface coating and adhesive used for composite bonding, the eddy current loss is much lower than in laminated steels, especially at higher frequencies, and the hysteresis loss becomes the dominant component of core loss. Motor designers can handle 3-D structure for a more effective magnetic flux path contrary to conventional laminated steel and expect the more improved motor efficiency due to design trends of smaller size, higher output in recent years [6].

In this paper, the design of BLDC motor for 42V fan is performed first, and then the new structure of BLDC motor with teeth overhang using the metal powdered core, as shown in Fig. 1, are investigated to improve the characteristics of the conventional structure manufactured by Si laminated steel.

Fig. 1 SPM type BLDC Motor with Teeth overhang
That is, the designed 42V conventional type BLDC motor for cool fan has been redesigned and rebuilt using the metal powdered core with the objective of maximizing the performance. It must be noted that the proposed structure using metal powder core has a great advantage over conventional type for maximization of the output.

2 Design of BLDC motor for 42V Fan

The fan with motor can be utilized for relatively long operating hours in the vehicle. The BLDC motor is especially advantageous for fan application because of their wide speed range, easy speed controllability, high efficiency and long lifetime expectancy. The Fig. 2 shows the designed motor and their distribution of magnetic flux density. The motor is inner-rotor type BLDC motor with 8 poles and 12 teeth designed for low torque ripple.

2.1 Design of Teeth overhang

In spite of many advantages of the metal powder materials afore-mentioned, it has a disadvantage of low permeability and high specific iron loss at low frequencies. So, although it became very attractive for use as magnetic core parts or for manufacturing the stator cores of PM motor in general, it causes output power density to be reduced [6]. In this paper, a stator shape with teeth overhang of the BLDC motor is designed and manufactured by the metal powder core in the same volume as conventional type motor laminated Si steel to maximize the effects of end winding.

In order to analyze the effect of the teeth overhang on the stator of BLDC motor, in this design, the simplified magnetic equivalent circuit (MEC) model considering the teeth overhang is developed as shown in Fig. 3. As design variables, the overhang at the top of stator core, $R_a$ and $R_b$, is depicted.

This MEC model is applied to the initial design of the overhang and investigation on the effect according to the different overhang length. The advantage of this kind of structure having teeth overhang is to be generated the magnetic torque at the teeth overhang region as well as at the conventional stator region, which results in an increase of higher total torque. However, due to their 3-D shape by the teeth overhang, this type structure cannot be achieved by lamination of steel sheet. This property makes the metal powder core very attractive for producing a complex shaped stator such as designed type. So, this structure makes up for the weak point in the performance due to a low permeability of metal powder.

The applied machine is a 150W BLDC motor, and its stator has 12 slots and the rotor is built of 8 poles of radial magnetic, Ferrite magnet. In order to compare of the metal powder BLDC motor with lamination core one, three BLDC motors manufactured by conventional type Si core (Si model), conventional type metal power core (MP model) and proposed metal powder core with teeth overhang (OH model) are applied to examine metal powder motor of the same dimension as previously designed lamination core one.

![Fig.2 Distribution of magnetic flux density](image)

![Fig.3. MEC model](image)
In order to accurately analyze the three models of the BLDC with different stators, a calculation of the magnetic field has to be performed for both models by 3-D equivalent magnetic circuit (3-D EMCN) method [7], because 3-D analysis is required to evaluate and design this type motor. 3-D EMCN method supplements magnetic equivalent circuit by network construction for getting the distribution of field variable. In this method, the analysis model is divided into hexahedral element and then equivalent magnetic circuit network is constructed by connecting the node of every elements center. The field variable of their centroids, magnetic scalar potential (MSP), is decided by the permeance involved with them. Thus, the magnetic flux between two nodes \((i, j, k)\) and \((i, j-1, k)\) are calculated such that

\[
\phi_{i(j,k)} = \sqrt{R_{N(i,j,k)}} \left( U_{i(j,k)} - U_{i(j-1,k)} + F_{i(j,k)} \right)
\]

The system matrix equation applied the magnetic flux continuity condition can be obtained to all nodes as following,

\[
[p]_{n \times n} \{u\}_{n \times 1} = \{f\}_{n \times 1}
\]

where, \(n\) is total number of node, \([p]_{n \times n}\) is the permeance coefficient matrix which is symmetric and has a good sparsity and bandwidth, \([u]_{n \times 1}\) is the matrix of MSP and \([f]_{n \times 1}\) is the forcing matrix.

The local values of flux density are calculated by the solved MSP. Fig. 4 shows the mesh shape in \(x-y\) plane of the designed motor. The comparison of 2D FEA result and 3D EMCN results is shown in Fig. 5. Fig. 6 shows also the torque characteristics according to the rotation angle. As shown in Fig. 6, the proposed type with a teeth overhang for using the flux leakage of end winding have a superiority over the conventional type in the torque point of view.

From these results, although the metal powder has a disadvantage of low permeability, it can be overcome the weakness by designing the 3D structure using the advantage of metal powder. Also, it is noted that the decision of overhang length is very important and one can get a BLDC motor with the much improved torque characteristics in the same volume.

The inductance of the proposed model (OH model) compared conventional type (MP model) using metal powder is described in Fig 7, which is increased by overhang effect. From the analysis results, more fluxes inclined into the stator, which is due to increased linkage area as much as the area of the teeth overhang and reduced leakages.

It means that the air gap flux becomes increased and as the results of that the inductance is also increased. The increased flux can be contributed greatly to the torque characteristics of the motor.
So, if the winding is redesigned to get the same EMF, a design result of effective motor with higher efficiency can be obtained by reducing the copper loss. Therefore, in case of this kind of motor, if applying the metal powder core can modify the stator, one can dramatically increase the output characteristics in view of torque, efficiency.

2.3 Analysis of Iron Loss

The flowchart for iron loss calculation is shown in Fig. 8 and the data for calculation of Iron loss, which is interpolated using limited data, is also shown in Fig. 9.

As shown in Fig. 8, the flux density at each element, $B_e(t)$, is calculated and then analyzed by a Discrete Fourier transform (DFT) as (3).

$$B_{pk}(k) = \sum_{n=0}^{N-1} B_p(n) e^{j\pi nk/N}$$

where $k$ is the harmonic order, $N$ is the number of the discrete data, $B_{pk}(k)$ is the peak value of the magnetic flux density of the $k$-th harmonic, and $B_p(n)$ is the magnitude of the point $n$ ($n = 0, 1, 2, \cdots, N-1$).

It is used for summation of iron loss according to harmonics of the magnetic flux density using a curve of magnetic flux density vs. Iron loss. So, the total iron loss in the whole core is calculated by summation of iron loss at the each element. Fig. 10 shows the analysis results for iron loss in both motor, non-overhang (MP model) and overhang model (OH model). At 3,000[rpm] the iron loss are respectively 7.0 [%] in non-overhang model and 8.8[%] in overhang model.
Because the main design objective of this paper was the increase of torque per volume using the teeth overhang, the different amount of iron loss can be explained by the increased core due to the teeth overhang. So, this result is totally acceptable for using the overhang, because the improvement of motor performance by using the overhang is predicted by 10% and over at the rated operation.

3 Experimentation Validations

A prototype of conventional type Si-laminated Core, metal power core and proposed type metal powder core has been realized. Fig. 11 presents the three-type stator of BLDC motor mad of Si-core and metal powder; Si, MP and OH model respectively.

![Fig. 11 Prototype of Stator of BLDC motor](image)

Fig. 11 Prototype of Stator of BLDC motor

The experimental EMF waveforms of three-type motors are shown in Fig. 12. The distinction for EMF waveforms is very clear from the different of the magnitude of the EMF. The use of overhang is increasing the total flux and EMF by 10% when compared to the non-overhang type, MP model.

Fig. 13 presents together the experimental results for efficiency vs. the torque characteristics and Speed vs. the torque characteristics respectively. This result means that the use of the teeth overhang is very helpful scheme for improving the motor performance. Generally the copper losses take up much portion of total loss at the rated operation and it means that the reduction of copper loss has been obtained by the overhang effect.

So, even though the core loss is little increased, the efficiency vs. torque characteristics of the proposed type is improved as shown in Fig. 13. Also, it is noted that the optimal design for the teeth overhang is necessary to maximize the effects of end winding in the motor.
4 Conclusion

In order to successfully apply the metal powder materials on BLDC motors, three different type BLDC motors, conventional type Si core (Si model), conventional type metal power core (MP model) and proposed metal powder core with teeth overhang (OH model), with the same dimensions are investigated.

From experimental results, the torque performance of the lamination core motor is little higher than the metal powder material motor on the whole. However, the performance of the new structure of stator teeth made of metal power core having a teeth overhang can be much the same as the Si lamination core. So, it is highly expected that this kind of model with teeth overhang can be applied for mass production of various application required high power density.

References:


