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# Influence of Amorphous and Silicon Steel on Performance of Permanent Magnet Synchronous Motors Used in Steering Pump of Electric Vehicles

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**Amorphous materials have the advantages of high permeability and low core losses. Their application in the motor can reduce the energy consumption and improve the efficiency. To investigate the advantage of amorphous materials on the performance of permanent magnet synchronous motors (PMSMs) at lower speed situation, three 1.5 kW motors used in steering pumps of electric vehicles are analyzed and compared. Two prototypes and the experimental platform are built. The experimental results indicate that the efficiency of the PMSM motor with amorphous materials increases by 1.4 % at 1200 rpm, which shows that amorphous materials can also improve the motor performance at lower speed. To further take advantage of amorphous materials, the particle swarm optimization algorithm is used to optimize the dimensions of amorphous motor and the efficiency is increased by 0.54 %.**

**Keywords :** amorphous material, core loss, efficiency, particle swarm optimization algorithm, permanent magnet synchronous motor, silicon steel

## 1. Introduction

With the rapid development of economy, there is an increasing contradiction between the fuel energy supply and the worsening of environment. Countries around the world are actively seeking efficient and energy-saving electrical equipment to improve energy utilization and ease the energy crisis. The emergence of new energy electric vehicles can reduce the consumption of fossil fuels, the emission of greenhouse gases, and release the environmental pressure. Motor control, motor design and battery are the three key technologies of electric vehicles. Since the vehicle battery storage capacity is limited, improving the efficiency of the motor and reducing the power consumption can improve the duration of battery and increase the mileage of electric vehicles. However, the development of motor has arrived at a bottleneck in that the efficiency can hardly be improved. One possible solution might be considering from the material field as a breakthrough. Amorphous alloy, a new type of green soft magnetic material, was firstly invented in the 1960s. Due to the ultra-rapid cooling, the amorphous alloy can be barely crystallized during solidification, and retains the liquid atoms in a disorderly arrangement of condensed state at room temperature or low temperature. It turns into a long-range disordered structure eventually, without crystal alloy grains and grain boundaries. Owing to its high resistivity, low iron losses and low coercivity, amorphous alloys have great potential to reduce core loss and have attracted much attention of researchers. The amorphous materials have already been applied in the transformers and magnetic sensors. The study has found that when using amorphous alloys instead of silicon steel, the no-load loss of transformers can be reduced by nearly 70 % [3].

The use of amorphous alloys for induction motors and high-speed permanent-magnet synchronous motors has been explored for preliminary study. In [4], a 2-pole, 250W amorphous alloy induction motor (IM) is introduced, in which stator core is made of amorphous materials. The core loss was reduced by 80 % and the efficiency was increased by 0.6 % at a rotating speed of 3422 r/min. Taking a 4-pole, 402W small IM (stator core using amorph-


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**Table 1.** Performance Comparison with Amorphous Alloys in Different Types of Motors.

| Power | 250W | 402W | 1.2 kW | 2.4 kW | 400W |
|---|---|---|---|---|---|
| Motor type | IM | IM | IM | SRM | BLDC |
| Speed/rpm | 3422 | Different | 11000 | 8500 | 5500 |
| Core loss reduction | 80 % | 50 % | 80.4 % | 63 % | 40 % |
| Efficient improvement | 0.6 % | - | 4.4 % | 6 % | 2 % |

ous alloy 2605SA1, rotor core using silicon steel M600-50A) as an example, authors compared the no-load core losses of the two motors at different frequencies. The results show that the no-load core loss of amorphous alloy motor is reduced by about 50 % [5]. A 1.2 kW, rated speed 11000 r/min IM has been studied [6]. The results show that the core loss of amorphous motor drops by 80.4 % and the efficiency increases by 4.4 % at the same frequency. In [7], compared with the same 2.4 kW switched reluctance motor (SRM) using low-loss silicon steel, the core loss of the SRM with the amorphous material was reduced by 63 % and the efficiency increased by 6 % at 8500 r/min. In [8], amorphous alloy is used for manufacturing the stator teeth of radial magnetic field surface mounted permanent magnet brushless direct current motor (BLDC). Compared with the same permanent magnet synchronous motor in which stator is made of conventional electrical silicon steel, the core loss of the motor is reduced by about 40 % and the efficiency is increased by 2 % at 5500 r/min. It can be seen from the above studies that the application of amorphous materials in the motor industry has gradually been taken seriously due to its excellent magnetic properties. Table 1 is the list of the above analysis results.

From Table 1, the amorphous alloy material significantly reduces the core loss when the motor runs at a higher speed and the advantages of the amorphous materials are obvious. However, it is not clear whether the advantages of amorphous materials still exist in low-speed motors. The performance comparison between amorphous alloy motors and ordinary silicon steel motors at low speeds needs to be comprehensively studied.

This paper focuses on the study of the amorphous materials' performance in low speed motors. To analyze the performance of amorphous materials used in the PMSMs of electric vehicle steering pump, three schemes are proposed for comparison. The first scheme is the silicon steel motor in which both the stator core and the rotor core adopting the silicon steel. The second scheme is Amorphous Motor I (AM I) in which the stator core uses amorphous alloy and the rotor core uses silicon steel. The third scheme is Amorphous Motor II (AM II) in which both the stator core and the rotor core adopt the amorphous material. The structures and dimensions of the three motors are the same. The influence of material on the performance of motors would be analyzed and tested.

## 2. Main Parameters of PMSMs

### 2.1. PMSM Construction

Figure 1 is the structure of the permanent magnet synchronous motor analyzed in this paper. The motor adopts 10 poles, 12 slots and double-layer fractional-slot concentrated winding structure. The three motors analyzed in this paper have the same structure. The basic parameters of the motor are shown in Table 2.

### 2.2. Properties of Materials

With the same structure, three prototypes are made of amorphous alloy and silicon steel 50WW470. Table 3

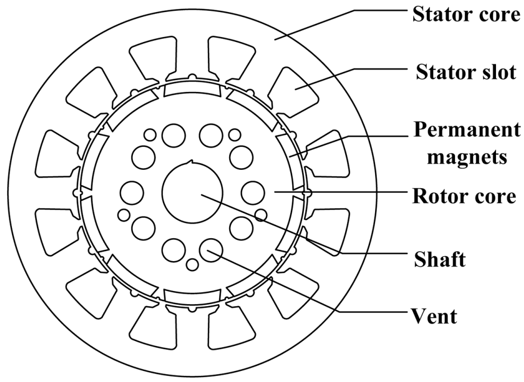


**Fig. 1.** Motor construction diagram.

**Table 2.** Basic Parameters of Three Motors.

| Items | Data |
|---|---|
| Rated power/kW | 1.5 |
| Pole number | 10 |
| Stator slots | 12 |
| Length of the core/mm | 110 |
| Outer diameter of the stator/mm | 128 |
| Inner diameter of the stator/mm | 80 |
| Outer diameter of the rotor/mm | 78 |
| Inner diameter of the rotor/mm | 21 |
| Types of the permanent magnet | N35UH |

**Table 3.** Properties Comparison of Two Materials.

| Program | Amorphous | 50WW470 |
|---|---|---|
| Thickness/μm | 25 | 500 |
| Saturation magnetic flux density/T | 1.58 | 2.03 |
| Resistivity/μΩ·cm | 130 | 45 |
| Density/kg·m$^{-3}$ | 7 180 | 7 700 |
| Core loss at 100 Hz, 1T/W/kg | 0.53 | 4 |
| Core loss at 100 Hz, 1.5T/W/kg | 0.71 | 7 |

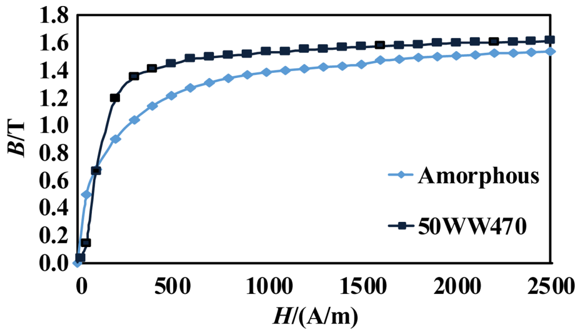


**Fig. 2.** (Color online) Magnetization curve of two materials.

shows the properties comparison between the two materials. Since the resistivity of amorphous alloys is three times larger than the silicon steel, high resistivity inhibits the eddy current loss of amorphous alloy [9]. The amorphous has a thickness of 25 μm, which is very thin, and it has high mechanical brittleness, resulting in high difficulty to manufacture the stator core. This is the big issue that exists in the processing of the amorphous material currently.

Figure 2 shows the magnetization curve of amorphous material and silicon steel 50WW470. The saturation flux density of amorphous materials is lower than that of silicon steel materials. The design of amorphous motors needs to consider the influence of saturation flux density.

Figure 3 shows the core loss curve of amorphous material and silicon steel material. The outstanding advantage of amorphous alloy is its extremely low core loss. From core loss values of the two materials at the 100 Hz, 1T and 100 Hz, 1.5T, we can see that the core loss of amorphous alloys is much lower than that of silicon steels. With the increasing of magnetic flux density, the core loss of amorphous material grows slowly and can barely be affected by the increasing of magnetic flux density. However, the core loss of silicon steel increases rapidly with the increasing of magnetic flux density. Thus, if the amorphous replaces silicon steel used in the motor, the core loss can be significantly reduced.

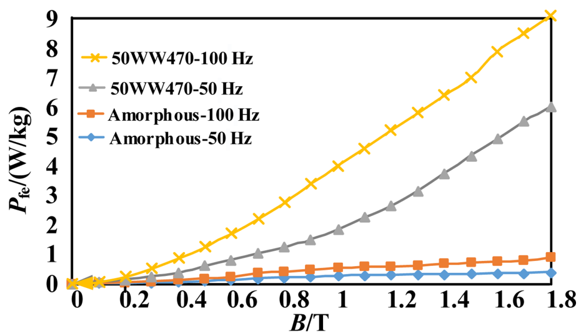


**Fig. 3.** (Color online) Core loss curve of two materials.

**Table 4.** Weight Comparisons of Three Motors.

| Program | Silicon steel motor | AM I | AM II |
|---|---|---|---|
| Armature Copper Weight/kg | 1.15 | 1.15 | 1.15 |
| Permanent Magnet Weight/kg | 0.63 | 0.63 | 0.63 |
| Armature Core Weight/kg | 4.43 | 4.07 | 4.07 |
| Rotor Core Weight/kg | 2.81 | 2.81 | 2.63 |
| Total Net Weight/kg | 9.02 | 8.66 | 8.48 |

Table 4 is the weight comparison of the three motors. The weight of the amorphous motor with the same volume is lower than silicon steel motor because the material density of the amorphous alloy is lower than that of the silicon steel.

## 3. Performance Analysis and Comparison of Three Motors

### 3.1. Finite Element Analysis Model

To investigate the performance change of the motor caused by the amorphous material, the finite element method (FEM) is used to analyze the transient electromagnetic field. In the two-dimension electromagnetic field boundary problem, the magnetic vector potential $A_z$ satisfies the following Poisson Equation,

$$\begin{cases} \Omega : \dfrac{\partial}{\partial x}\left(\dfrac{1}{\mu}\dfrac{\partial A_z}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(\dfrac{1}{\mu}\dfrac{\partial A_z}{\partial y}\right) = -\left(J_z - \sigma\dfrac{\mathrm{d}A_z}{\mathrm{d}t}\right) \\ \Gamma_1 : A_z = 0 \end{cases} \quad (1)$$

where, $\Omega$ : solution area;

$\Gamma_1$ : stator outer circle and rotor inner circle boundary of the motor;

$\mu$ : magnetic permeability;

$\sigma$ : conductivity;

$t$ : time;

$\sigma\dfrac{\mathrm{d}A_z}{\mathrm{d}t}$ : eddy current density;

$J_z$ : the external axial current density;

### 3.2. Performance Calculation of Three Motors

The performance of the three motors are analyzes at 100 Hz and 1200 r/min, with the same voltage excitation

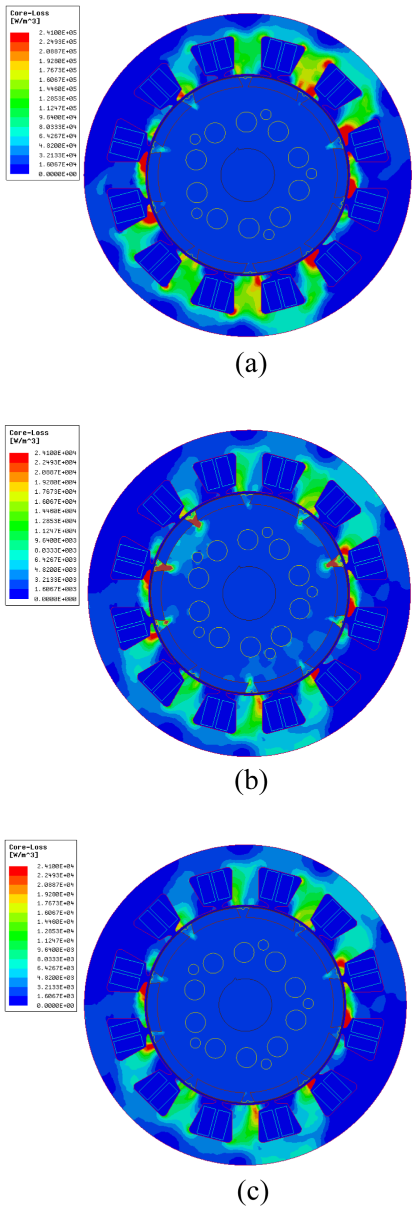


**Fig. 4.** (Color online) Core loss distribution of the three motors. (a) Core loss distribution of the silicon steel motor. (b) Core loss distribution of the AM I. (c) Core loss distribution of the AM II.

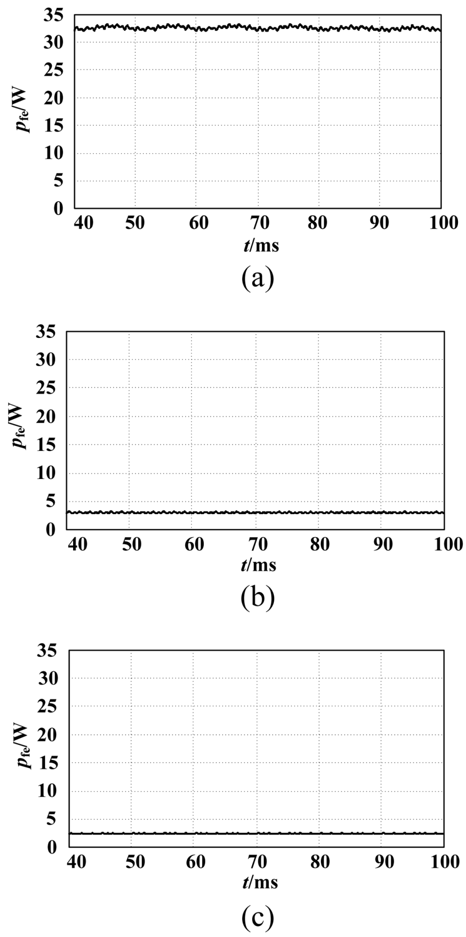


**Fig. 5.** Core loss curve of the three motors. (a) Core loss curve of the silicon steel motor. (b) Core loss curve of the AM I. (c) Core loss curve of the AM II.

and mechanical torque load.

Figure 4(a), (b), (c) show the core loss distribution of the silicon steel motor, AM I, AM II respectively. The core loss is mainly distributed in the stator, while the rotor has only a small amount of loss distribution. The stator core loss of AM I and AM II are lower than that of the silicon steel motor.

Figure 5(a), (b), (c) show the core loss curves of the amorphous motor and the silicon steel motor while the motor operation is stable.

The core loss of silicon steel motor is 31.87W, the core loss of AM I is 3.05W and the core loss of AM II is 2.54W. It can be seen from the Fig. 5 that the core loss of the AM I is 28.82 W lower than that of the silicon steel motor, and the core loss of the AM II is 29.33 W lower than that of the silicon steel motor. The results verify the low iron loss characteristics of amorphous material. Comparing the two amorphous motors the advantages of the AM II on reducing the core loss are not obvious, which is because the magnetic flux nearly keep constant on the rotor and the core loss on rotor is close to zero. The amorphous materials used in rotor core cannot reflect its low iron loss advantage. Then AM II will not be analyzed further, and the amorphous motor mentioned later means AM I.

### 3.3. Performance Comparison at Different Frequencies

To compare the efficiency of the amorphous motor and the silicon steel motor at different frequencies, the cal-

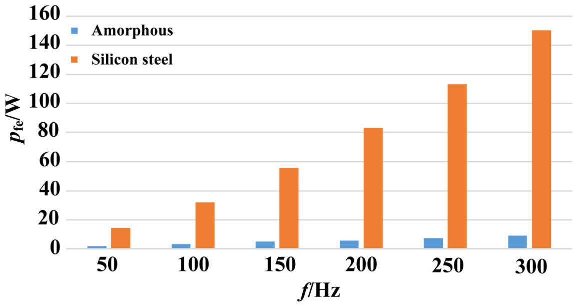


**Fig. 6.** (Color online) Comparison of core loss of two motors at different frequencies.

culations are performed for both motors from 50 Hz to 300 Hz with the same output power with finite element calculation.

Figure 6 shows the comparison of core loss curves between two motors at different frequencies. It shows that the core losses of amorphous motors are significantly lower than those of silicon steel motors at different frequencies. The core loss of the amorphous motor increases slowly with the increasing of frequency. Whereas, the core loss of the silicon steel motor increases rapidly with the increasing of frequency.

## 4. Experiments and Discussion

Experimental platform for the silicon steel PMSM and the amorphous PMSM was built and the experiment results are compared with the simulation results. Figure 7 shows the prototype of the amorphous motor. The experimental platform is shown in Fig. 8. The excitation voltage applied to the test motor. A three-phase asynchronous motor is used as a dynamometer, and the power analyzer outputs the experimental data including the voltage and current values. The torque meter is located between two motors to measure torque, and the speed sensor measures the speed of rotation.

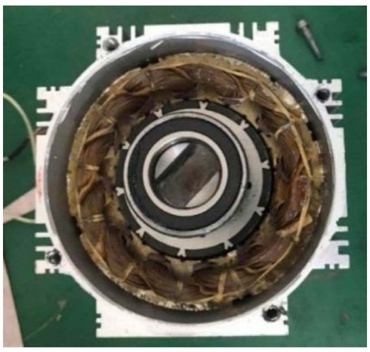

**Fig. 7.** (Color online) Prototype of the amorphous motor.

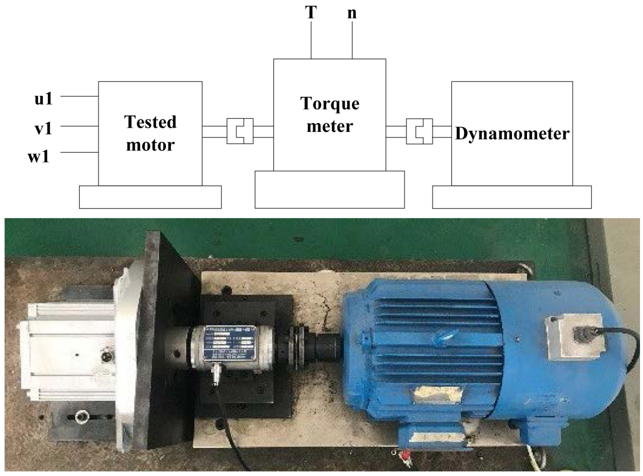


**Fig. 8.** (Color online) Experimental platform.

**Table 5.** Comparison of Experimental Results of Two Motors.

| Program | Amorphous | Silicon steel | Difference |
|---|---|---|---|
| Voltage/V | 248.6 | 248.6 | 0 |
| Current/A | 3.667 | 3.6 | 0.067 |
| Speed/ r/min | 1 199.5 | 1 199.7 | 0.2 |
| Torque/N·m | 12.05 | 12.01 | 0.04 |
| Power factor | 0.992 | 0.993 | 0.001 |
| Efficiency/% | 95.60 | 94.20 | 1.40 |

With two motors running at 100 Hz, 1200 r/min, with the same load, the measurement results are shown in Table 5. The efficiency of amorphous motor is 1.40 % higher than silicon steel motor. It has been found that the amorphous material can effectively reduce the core loss and improve the efficiency of the motor under lower speed.

Two motors were tested at 100 Hz with 5 different loadings. With the increasing of the load torque, the variation of the efficiency about the two motors is shown in Figure 9.

It can be seen intuitively that at the same frequency and different load torques, the efficiency of the amorphous motor is higher than that of the silicon steel motor. It is

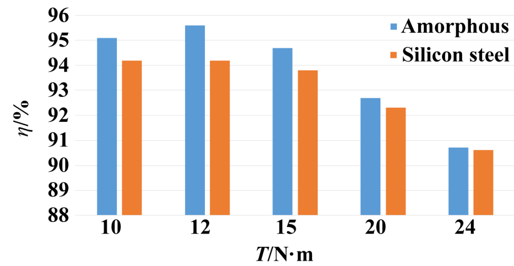


**Fig. 9.** (Color online) Comparison of the efficiency of two motors at different loading torques.

verified that the amorphous material has the advantage of improving the motor efficiency.

## 5. Amorphous Motor Design Optimization

Some researches show that the advantages of amorphous cannot be fully developed if directly replacing the silicon steel with amorphous. Therefore, it is necessary to optimize the design of the amorphous motor.

As a typical representative of the intelligent optimization algorithm, the particle swarm optimization algorithm has a simple structure and good global optimization characteristics. Therefore, the particle swarm optimization algorithm is used to optimize the design of the amorphous motor.

Selecting the stator inner diameter $D_{i1}$, air gap length *delt*, the variables of stator slot, permanent magnet thickness $h_M$, pole arc coefficient *ap*, number of conductors per slot $N_S$ and wire diameter *d* as optimizing variables, these variables vary by less than 15 %. Figure 10 shows the variables of stator slot. Table 6 shows the variables in optimized scheme and the original scheme.

Table 7 shows the performance comparison between the original scheme and optimized scheme of the amorphous motor, using ANSYS RMxprt software to verify the optimized scheme. As can be seen from Table 7, the efficiency of the optimized scheme is 0.54 % higher than the original scheme. Due to the lower saturation magnetization of the amorphous material, the magnetic density of stator tooth in the optimized design need to be reduced and it should be below 1.45T. By comparison, the stator core tooth density is 1.44T, which meets the requirements.

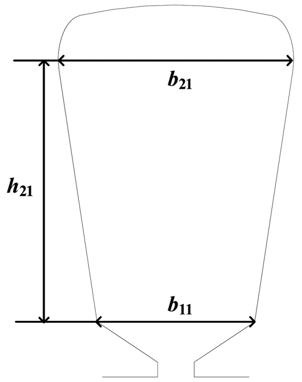


**Fig. 10.** Variables of stator slot of the amorphous motor.

**Table 6.** Variables Comparison Between the Original Scheme and the Optimized Scheme of the Amorphous Motor.

| Variable | Original | Optimization |
|---|---|---|
| $D_{i1}$/mm | 80 | 78.7 |
| *delt*/mm | 1 | 1.1 |
| $b_{11}$/mm | 11.36 | 10.85 |
| $b_{21}$/mm | 16.86 | 16.27 |
| $h_{21}$/mm | 10.87 | 11.86 |
| $h_M$/mm | 4 | 4.42 |
| ap | 0.75 | 0.75 |
| $N_S$ | 108 | 108 |
| *d*/mm | 0.67 | 0.70 |

**Table 7.** Performance Comparison between the Original Design and the Optimized Design of the Amorphous Motor.

| Program | Original | Optimized | RMxprt |
|---|---|---|---|
| Efficiency/% | 94.25 | 94.79 | 94.84 |
| Limited coil space factor $S_f$/% | 74.87 | 77.04 | 75.99 |
| Magnetic density of stator tooth $B_t$/T | 1.51 | 1.44 | 1.44 |

## 6. Conclusion

To study the influence of amorphous materials in motors with lower rotating speed, three PMSMs are comparatively analyzed. The calculation shows that the motor with amorphous stator core and silicon steel rotor core is a good combination. Experimental results show that the efficiency of the amorphous motor is 1.40 % higher than that of the silicon steel motor at a lower speed of 1200 rpm, which verifies the advantages of amorphous materials. It shows that amorphous materials can improve the efficiency of the motor both at lower speed and higher speed. And by the particle swarm optimization algorithm, the efficiency of amorphous motor has been increased by 0.54 %. The amorphous material used in electric steering pump motor can effectively improve efficiency, reduce motor weight and hence improve the mileage of electric vehicles.

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