Development of a 48 V Integrated Starter Generator for Mild Hybrid Vehicles

Masaya Inoue* a) Senior member, Junji Kitao** Member, Yoshihiro Miyama* Member, Moriyuki Hazeyama** Member, Hitoshi Isoda* Non-member, Hideaki Arita** Member, Koji Nishizawa* Non-member, Tatsuo Nishimura*** Member, Masatsugu Nakano* Member

(Manuscript received Jan. 00, 20XX, revised May 00, 20XX)

This paper presents the development of a 48 V integrated starter generator (ISG) for mild hybrid vehicles. The motor needs to satisfy power and torque performances requirements under the 48 V system voltage as well as the passenger vehicle's specific requirements, such as acoustic noise and layout space. Several processes have been explored to obtain a 48 V ISG such as the pole number selection process, the electromagnetic design approach for reducing acoustic noise, and a novel position sensor topology. By using the developed technologies, a 48 V ISG motor is designed, built, and tested. Furthermore, the developed motor is demonstrated to achieve 180 Nm, 15 kW exceeding the 95% motor efficiency with acoustic noise reduction design and thin axial motor length.

Keywords: Permanent magnet motor, Integrated Starter Generator, DC 48 V, Mild-Hybrid

1. Introduction

Recent demands for reducing greenhouse gas against global warming issues are becoming more and more important topics. To cope with the requirements of reducing the fuel consumption and CO$_2$ emissions from the internal combustion engines (ICEs) (1), the vehicle electrification trends are accelerated continuously. There are numerous kinds of vehicle electrification levels such as pure battery electric vehicles, plugin, full and mild hybrid vehicles. The 48 V vehicle system is one of these trends. The 48 V system can offer a large amount of the high voltage hybrid vehicle benefits such as the idling start-stop and the recuperation (2,3). Most of the existing 48 V vehicles equip a belt-driven starter generator (BSG) (4,5,6). The advantageous point of the BSG is minimized vehicle design changes by adding the inverter circuit into the conventional belt-driven alternator. However, due to the mechanical torque transmission capability of the belt drive, the generating power is not high enough to install the high power electric auxiliary systems such as electric turbochargers (7,8), electric water pumps, and electrically heated catalysts (9), and so on. The mechanical torque capability of the belt drive also limits the engine start-stop operation within the low vehicle speed ranges. Because the high speed vehicle runs with the high engine speed, which means the acceleration torque for recovering the engine speed becomes high at the start-stop operation. The 48 V integrated starter generator (ISG) is an ideal solution that receives cost-effective benefits of 48 V, solving the limitations of the belt drive. The ISG is a system that is installed a large diameter thin axial length motor between the ICE and the transmission gearbox (10,11). However, the system voltages of the existing ISG vehicles are 100 V or higher. Compared with these high voltage ISG systems, there are some difficulties in introducing the ISG into the 48 V system. For example, a large amount of field weakening copper loss appears in most of the motor operational range. Therefore, the high copper fill factor is an important technology to reduce copper loss. Segmented core manufacturing is a suitable solution for these purposes (12). Another difficulty of the ISG is the electromagnetic acoustic noise. The ICE usually stops during the recuperation and the ISG is the main power device in the vehicle at that time. The passengers can notice the ISG acoustic noise. Therefore, less acoustic noise is one of the important design requirements for passenger vehicle ISGs (13,14). Since the ISGs have to achieve high torque within the limited layout space, the multi-pole number design is preferred. However, it tends to result in a low stiffness stator and the resonant frequency appears in the operational range. Therefore, the reduction of the electromagnetic force becomes a topic that needs to be tackled.

The position sensor for motor control is also another issue to be solved. Variable reluctance resolvers are common in automotive usages (15,16). However, a large inner diameter rotor is required to integrate the e-motor into the transmission gearbox. This also requires a large diameter position sensor, which is uncommon for the existing resolver applications (17).

In this paper, a design approach and an optimization for 48 V ISG for a mild hybrid are described. A proper pole number is selected in the initial e-motor design stage to achieve high torque and high power. After that, the magnetic design is improved to reduce electromagnetic force for noise, vibration, and harshness (NVH). The development of a new type of position sensor is also presented, which is suitable for the larger diameter sensor applications. The performance of the developed ISG is also shown in the following description.
Fig. 1. A configuration of a crankshaft-mounted 48 V-ISG system.

Table 1. Targeted design specification of the developed ISG.

| Parameter              | Specification |
|------------------------|---------------|
| Max. Power (kW)        | >15           |
| Max. Torque (Nm)       | >180          |
| Max. Speed(r/min)      | 6000          |
| Stator O.D.(mm)        | <300          |
| Rotor I.D. (mm)        | >200          |
| Active Length (mm)     | < 45          |
| Rated Voltage          | DC 48 V       |
| Max. inverted current  | 500Arms       |

2. Schematics of the 48 V-ISG system

2.1 Configuration of the crankshaft-mounted 48 V-ISG

Figure 1 illustrates the configuration of this system. An electric motor is installed between the engine and the transmission gearbox and categorized as the P1 system\(^{(18)}\). The rotor is directly mounted on the ICE crankshaft, which enables the high torque starting of the ICE. Due to the specific configuration, the motor needs to be formed in a thin axial space. Therefore, a permanent magnet synchronous motor with the concentrated winding is selected to meet the thin axial motor layout space requirement.

2.2 Performance requirements

The targeted design specifications are shown in Table 1. Figure 2 illustrates the operational range and function of the 48 V ISG system. To restart the ICE, a high torque is necessary at the ICE start timing. During energy recuperation from decelerating vehicles, high power regeneration is required. Additionally, since the rotor is mounted on the ICE crankshaft engine, the system needs to rotate throughout the entire operating range of the ICE, and continuous operation with a large amount of field weakening current is required.

3. Motor design

3.1 Consideration of the pole number

Increasing pole numbers can help higher torque avoiding the magnetic saturation and the less magnetic flux per pole can help design flexibility for coil area which reduces the copper loss. On the other hand, increasing the pole number may reduce motor power due to the poor power factor and it increases the iron loss. Therefore, the selection of the optimum pole number and the sizing an optimum rotor diameter become the important design topics and should be investigated at the initial motor design stage.

The motor design parameters are shown in Table 2. The outer diameter of the stator and inner diameter of the rotor is fixed in this study. The core back width of each model is changed to achieve the same flux density level. The teeth width of each model is changed with the motor pole number to be the same current density for the coil, which is related to the thermal limit of the continuous operation. The rotor diameter of the model 4 is increased thanks to moderated magnetic saturation. Figure 3 shows motor shape schematics with electromagnetic field analysis results at the maximum torque. As shown in Fig. 3, the magnetic flux density of 16-pole and 20-pole are saturated level, which reduces the maximum torque. The relationship between maximum torque at the 0-r/min speed versus pole number is shown in Fig. 4. Figure 4 also shows that when the number of poles exceeds the 20-pole, the maximum torque no longer increases. Because the increase of pole number leads the increase of the magnetic leakage flux through the magnet supporting bridges in the rotor. The relationship between the maximum power versus pole numbers is also shown in Fig. 4. The maximum power decreases when the higher poles are selected. Because the increasing pole tends to lead the poor power factor. Considering these trade-off balances, the pole number is optimized as the 24-pole in this development. It should be noted that the result changes with boundary conditions such as performance requirements, the inverter current, the layout space, the cooling condition, and so on.

3.2 Consideration of the minimizing motor NVH

3.2.1 Modal deformation and resonant frequency of the ISG

Table 2. Motor design parameters for the design study.

| Parameter                  | Model 1 | Model 2 | Model 3 | Model 4 |
|----------------------------|---------|---------|---------|---------|
| Slot number                | 24      | 30      | 36      | 42      |
| Pole number                | 16      | 20      | 24      | 28      |
| Turn number / one tooth    | 24      |         |         |         |
| Teeth width (mm)           | 12.2    | 12      | 11.5    | 10      |
| Back iron width (mm)       | 12.8    | 10.2    | 8.5     | 7.3     |
| Stator O.D. (mm)           | 294     |         |         |         |
| Rotor O.D. (mm)            | 228     | 232     |         |         |
| Rotor. I.D. (mm)           | 200     |         |         |         |
| Active Core Length (mm)    | 45      |         |         |         |
There are a lot of researches regarding acoustic noise and vibration behavior of permanent magnet synchronous motors (PMSMs). It is found that acoustic noise of the automotive traction motor is caused by the deformation of spatial mode-0 [19]. In the 3-slot/2-pole PMSMs, the spatial mode-0 with 6f frequency, where f is the fundamental frequency of the motor current, is the mode that may cause acoustic noise issues. The issue may appear when the 6f frequency corresponds to the stator resonant frequency. The specific spatial mode number, which is the greatest common measure (G.C.M) between stator slots number and rotor poles number, is also the mode that has to be considered. Because the frequency of the electromagnetic force is 2f, which may appear within the ISG operation range. Considering the information, the investigation regards pole number selection at the initial design stage is examined as the following procedure.

The spatial order n describes the number of full sinusoidal radial deflections along the air gap in the tangential direction. The stator natural frequency n can be approximated as the thin cylinders by;

For n=0
\[
f_{n=0} = \frac{1}{2\pi} \sqrt{\frac{E}{\rho R_c^2}}
\]
For n=2
\[
f_{n=2} = \frac{n(n^2 - 1)}{2\pi \sqrt{n^2 + 1}} \sqrt{\frac{EI}{ApR_c^2}}
\]

The definition of each parameter in the equations is explained in Fig. 5 and Table 3. The corresponding points between the resonance frequency and the electromagnetic force excitation frequency are shown in Table 4. As shown in Table 4, increasing the pole number makes the resonant frequency lower. The stiffnesses of the spatial mode of G.C.M are high enough and these are not necessary to the consideration. However, the resonant frequency of spatial mode-0 appears within the operational range when the pole number is selected as 20 or higher in this case. Therefore, the lower pole number is preferable from the NVH point of view. On the other hand, a multi-pole number such as 20-pole or higher is necessary to achieve the torque requirements of 180 Nm as shown in figure 4. Therefore, reducing the resonant acoustic noise excited by mode-0,6f is one of the key design topics for the ISG motor design. The efforts and technologies for reducing the electromagnetic force are described in the following section.

**3.2.2 Reduction of NVH by the electromagnetic design**

It is well known that the spatial mode-0 with 6f is induced by the interaction between the 5th and the 7th magnetic space harmonics. These harmonics can be minimized by adjusting the stator teeth.
width $\alpha$ and permanent magnet width $\beta$, which are shown in Fig. 6. The standardized electrical degree is applied for the $\alpha$ and the $\beta$ in the following discussion.

The details of the radial force behavior are investigated by applying FEA for 24-pole model 3 with the $\alpha = 92$, $\beta = 128$ configuration. Fig. 7 shows each of the U-, V-, W-phase radial forces at the 40 Nm which is the typical torque level for the recuperation. Since the stator deformation is excited by the combination of these radial forces, the total of the U-, V-, W-phase teeth force is also plotted in Fig. 7. As shown in the figure, the total radial force cycle is 6 times the fundamental electric period, which means the total force is the root cause of mode-0, 6f. Since the amplitude of the mode-0, 6f teeth radial force changes with the teeth width $\alpha$ and the magnet width $\beta$, the force amplitude changing trends are investigated for the several magnet widths $\beta$ as the function of the stator teeth widths $\alpha$. The results are plotted in Fig. 8. The minimal amplitude is obtained at the $\alpha=72$, $\beta=138$ for example. It can be seen that there are the minimum force points a, b, c, d for each teeth width $\alpha$ in Fig. 8. Moreover, there seems to be a certain relationship between the teeth width angle $\alpha$ and each magnet width $\beta$ for each a, b, c, d points. This trend is confirmed in Fig. 9. It is founded that the relation can be described as $\beta = -2.5\alpha + 320$ in this case. This equation helps an approximate design optimization to reduce the mode-0, 6f NVH.

3.2.3 Double teeth design

A new design concept of double teeth design is invented to be more silent ISG. The principal of this new concept is canceling the teeth force using the two different sets of teeth angle $\alpha$. The magnetic width $\beta$ of 128 degrees is selected in this study. The actual method is described in the following sequence. The amplitude and phase angle of the teeth magnetic force are varied with the teeth width $\alpha$. The behavior of teeth force amplitude and phase angle are shown in figure 10 and figure 11. It is observed that both of the teeth force amplitude and teeth force phase angle are varied with the $\alpha$, which indicates the possibility of the teeth force canceling using two different teeth width sets for the axal core stacking direction.

The teeth widths of the $\alpha = 68$ and the $\alpha = 92$ degrees are selected as an example. These two points are shown as the point X and the point Y in Fig. 10 and Fig. 11 respectively. The magnetic force phase angle difference between the point X and the point Y is approximately 180 degrees. However, the ratio of the force at the point X and at the point Y is 1: 2.2 in Fig. 10. Therefore, the ratio of the two sets of core length for axial direction is adjusted as 2.2:1 which is the inverse of each tooth's force amplitude in order to equalize the amount of the teeth force. The obtained total teeth force in this manner is shown in Fig. 12. These original teeth force data before optimization and the synthesized teeth force data are summarized and shown in the table 5. The spatial mode-0, 6f
The measured teeth width design performs almost the same torque and power. Therefore, the double teeth width design is confirmed in the NVH test bench. The impact of this sensor topology is applied.

The double teeth width design is a technology to reduce spatial mode-0, 6f NVH by canceling teeth radial force axially. Additionally, the rotor skewing is also applied to the actual motor to be a more robust NVH design that covers the whole operation range including cogging torque reduction. Therefore, the double teeth width stator core stacking pattern is repeated twice to apply for each skewed rotor segment. The schematic of the motor and the segmented teeth before winding is shown in Fig. 14. The effect of the improved design is confirmed in the NVH test bench. The overview of the bench setup is shown in Fig. 15. The measured Campbell diagram is plotted in Fig. 16. The reduced acoustic noise of the spatial mode-0,6f are highlighted with the white ellipses and compared in the figure.

4. Position sensor development

Since the thin axial space and the large rotor diameter are the specific requirements of the ISGs, the position sensor becomes one of the key parts for the ISG applications. Because the resolver stator becomes heavy and it occupies the whole circle areas of the stator if a conventional resolver is applied. To solve the layout and less weight requirement, a new topology for the sensor was invented.

4.1 Principal of position sensor The schematic of the developed sensor is shown in Fig. 17. The rotor has a sinusoidal outer shape core for the permeance change with the rotor position. The sensor stator has a bias magnet in order to apply magnetic motive force between the magnet and the sensor rotor core. Three sets of the Hall IC sensors are installed on the surface of the permanent magnet locating 120 electric degree phase differences named as u, v, w. The signal process from the sensor is shown in Fig. 18. Because of this sensor topology, each signal contains the DC offset and the 3rd harmonics from the stator coil leakage flux. Therefore, the signals are preprocessed as;

Fig. 12. Improved teeth radial force vs. rotor position.

Table 5. Original teeth force amplitude data and synthesized teeth force amplitude. X,Y and Z are correspond to the symbol in fig.9 and Fig. 10.

| Teeth angle (degree) | Core length (mm) | Mode0,6f force(N) |
|----------------------|------------------|------------------|
| Teeth X 92           | 45               | 7.6              |
| Teeth Y 68           | 45               | 4                |
| Teeth X (reference)  | 77               | 0.8              |

| Teeth angle (degree) | Core length (mm) | Mode0,6f force(N) |
|----------------------|------------------|------------------|
| X' 68                | 31               | 2.4              |
| Y' 92                | 14               | 2.8              |
| Total (X'+Y')        | 45               | 0.34             |

Fig. 13. Torque and power comparison between single teeth stator (α = 92) and double teeth width stator (α = 68 and α = 92). Components are reduced to 42 % compared with the minimal point Z in fig. 9 and fig. 10, which has single teeth width of the α = 77 with the magnet width β = 138. The impact of this double teeth width design on the motor performance is also confirmed by FEA. The speed versus torque curve for both of the single teeth width design (α = 92) and the double teeth width design (α = 68 and α = 92) are compared in Fig. 13. As shown in the figure, the double teeth width design performs almost the same torque and power.
5. Performance of the developed ISG

The developed ISG outline and the speed-torque curve with the efficiency map are shown in Fig. 20 and Fig. 21 respectively. The maximum torque of 180 Nm can start up most of the internal combustion engines quickly and the generation power of 15 kW can cover most of the vehicle recuperation energy.

6. Conclusion

A design process and several technologies for a 48 V ISG motor are presented. The experimental results of the prototype machine are also validated. A compact position sensor with a newly invented topology is also presented which is also a key component to integrate the motor into the vehicle transmission gearbox. Finally, thanks to the combination of these technologies and items, the developed PMMSM achieved 180 Nm, 15 kW, respecting the vehicle requirements such as the layout space, NVH, the given inverter current, and so on.

Reference

(1) G. Archer: “2025 CO2: Regulation - The next step to tackling transport emissions”, TRANSPORT & ENVIRONMENT, pp.1-12, May (2015)
(2) G. Milton, P. Blone, K. Tufail, B. P. Coates, I. Newbigging, A. Cooper and P. J. Shaylor: “CO2 reduction through low cost electricification of the diesel powertrain at 48 V”, SAE Tech. Pap. Ser. (2017)
(3) Z. Liu, A. Ivanco, and Z. S. Filipi: “Impacts of Real-World Driving and Driver Aggressiveness on Fuel Consumption of 48 V Mild Hybrid Vehicle”, SAE Int. J. Altern. Powertrains, vol. 5, no. 2, pp.249-258 (2016)
(4) T. Teratani, K. Kuramochi, H. Nakao, T. Tachibana, K. Yagi, and S. Abou: “Development of Toyota Mild Hybrid System (THS-M) with 42V PowerNet”, in Proc. IEEE International Electric Machines and Drives Conference, vol. 1, pp. 3–10 (2003)
(5) C. Helbing, K. Bennewitz, and A. Mann: “The 48 V Mild Hybrid Drive System of the Volkswagen Golf 8”, MTZ Weltw. , vol. 81, no. 1, pp.18-25 (2020)
(6) F. B. Ekström, O. Rolandson, S. Eriksson, C. Odenmark, M. Svensson, A. Eriksson and H. Olsen: “A Mild Hybrid SIDI Turbo Passenger Car Engine with Organic Rankine Cycle Waste Heat Recovery”, in SAE Technical Papers 14th International Conference on Engines & Vehicles (2019)
(7) W. Lee, E. Schubert, Y. Li, S. Li, D. Bobba, and B. Sarlaugh: “Overview of Electric Turbocharger and Supercharger for Downsized Internal Combustion Engines,” IEEE Trans. Transp. Electrific., vol. 3, no. 1, pp.36–47 (2017)
(8) S. Ibaraki, Y. Yamashita, K. Sumida, H. Ogita, and Y. Jinnai: “Development of the ‘Hybrid Turbo’ an Electrically Assisted Turbocharger,” Mitsubishi Heavy Ind. Tech. Rev., vol. 43, no. 3, pp.1-5 (2006)
(9) Y. Liu, M. Canova, and Y. Y. Wang: “Distributed energy and thermal management of a 48 V diesel mild hybrid electric vehicle with electrically heated catalyst,” IEEE Trans. Control Syst. Technol., vol. 28, no. 5, pp.1-14 (2020)
Masaya Inoue
(Senior member) was in 1967. He received the B.E. and M.E. degrees from Hokkaido university in 1990, 1992 respectively. He joined Advanced Technology R&D Center, Mitsubishi Electric Corporation, where he has developed various kinds of electrical machines. In 2010, he joined Himeji Works, Mitsubishi Electric Corporation where he is conducting vehicle electrification projects. Mr. Inoue is a member of the IEEJ and IEE of Japan.

Junji Kitao
(Member) was born in 1988. He received the M. Eng. degree in Department of Electrical Engineering from Doshisha University, Kyoto, Japan, in 2013 and the D. Eng. degree in Graduate School of Science and Engineering from Doshisha University, Kyoto, Japan, in 2017. In 2013, he joined Advanced Technology R&D Center, Mitsubishi Electric Corporation, Hyogo, Japan, where he is involved in research and development of high-performance motor and its drive systems. Dr. Kitao is a member of the IEE of Japan.

Yoshihiro Miyama
(Member) was born in 1983. He received the M.Eng. degree in Department of Science and Engineering from Ritsumeikan University, Shiga, Japan, in 2009, and the D.Eng. degree in Graduate School of Functional Control Systems from Shibaura Institute of Technology, Tokyo, Japan, in 2019. In 2009, he joined Advanced Technology R&D Center, Mitsubishi Electric Corporation, Hyogo, Japan, where he was involved in research and development of high-performance motor and its drive systems. Since 2020, he transferred to the Himeji Works, Mitsubishi Electric Corporation, Himeji, Japan, where he is developing traction motors for automotive applications. Dr. Miyama is a member of the IEEE IAS, PELS, MS and the IEE and SAE of Japan.

Moriyuki Hazeyama
(Member) was born in Aichi, Japan in 1978. He received the M.E. and Ph.D. degrees in electrical engineering from Nagoya University in 2001, 2003. He is with the Advanced Technology R&D Center, Mitsubishi Electric Corporation, Amagasaki, Japan. His research interests are electromagnetic design of electrical motor and losses in electrical motor. Dr. Hazeyama is a member of the IEE of Japan.

Hitoshi Isoda
(Non member) was born in 1975. He received the M. Eng. degree in Department of Electrical engineering from Osaka University, Osaka, Japan, in 1999. He joined Mitsubishi Electric Corporation, Hyogo, Japan, in 1999. Currently he is involved in the development and design of the motor for EV and HEV in Electrical Machine Systems Dept.

Hideaki Arita
(Member) was born in Oita, Japan, in 1977. He received the B.Eng. and M.E. degrees in electrical and electronic engineering from Oita University, Oita, in 2000 and 2002, respectively. He joined the Advanced Technology R&D Center, Mitsubishi Electric Corporation, Hyogo, Japan.

Koji Nishizawa
(Non-member) He received his B.E., M.E., and Ph.D. degrees from University of Hyogo, Japan, in 2008, 2010, and 2015, respectively. Since 2015, he joined the Himeji Works, Mitsubishi Electric Corporation, Himeji, Japan, where he is developing rotor position sensor for hybrid electric vehicle motor.

Tatsuo Nishimura
(Member) was born in 1989. He received the M.Eng. degree in Department of Electrical Engineering from Kyoto University, Kyoto, Japan, in 2015. In 2015, he joined Advanced Technology R&D Center, Mitsubishi Electric Corporation, Hyogo, Japan. In 2021, he transferred to the Automotive Electronics Development Center, Mitsubishi Electric Corporation, Himeji, Japan. He has been involved in research and development of rotating machines.

Masatsugu Nakano
(Member) was born in 1972. He received the B.Eng., M.Eng. and Ph.D. degrees from Kyoto University, Kyoto, Japan, in 1996, 1998 and 2017 respectively. In 1998, he joined Advanced Technology R&D Center, Mitsubishi Electric Corporation, Hyogo, Japan, where he was engaged in the development of rotating machines. Currently, he has been with the Himeji Works, Mitsubishi Electric Corporation, Hyogo, Japan, where he is engaged in development and design of motors for automotive applications. Dr. Nakano is a member of the IEEE.