Efficiency Improvement of Motor Drive System by using a GaN Three Phase Inverter

Yosuke Nakayama*, Yasuki Kanazawa†, Fumiya Kondo*, Masamichi Inoue*,
Kazuki Ohta*, Shinji Doki *and Koji Shiozaki‡
*Dept. of Electrical Engineering and Computer Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi, Japan
Email: y.nakayama@nagoya-u.jp, doki@nagoya-u.jp
†Naturanix Co., Ltd., Room 4, Center of Garage, 1-16-3, Yokokawa, Sumida-ku, Tokyo, Japan
Email: kanazawa@naturanix.co.jp
‡Institute of Materials and Systems for Sustainability, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi, Japan
Email: kshiozaki@imass.nagoya-u.ac.jp

***Abstract*—This paper shows the effectiveness for employing the GaN-FET inverter for operating the traction motor of a compact Electric Vehicle. Utilizing GaN-FET inverter can not only reduce the conduction loss, but also reduce the switching loss. Therefore GaN-FET inverter can operate motors in higher switching frequency compared with Si-IGBT inverters. It is effective to increase the switching frequency of the inverter to improve the motor efficiency because harmonic iron losses can be reduced dramatically by increasing the switching frequency, but the inverter loss becomes relatively large when the switching frequency is set too high. Therefore, optimized switching frequency should be obtained to maximize the total efficiency of the motor drive system. Experiments are carried out to compare efficiencies of motor drive system with Si-IGBT/GaN-FET inverter in several switching frequencies. Optimization of the switching frequency for maximizing the total efficiency is demonstrated to make effective use of the GaN-FET inverter in the motor drive system.**

***Keywords*—Wide bandgap, GaN, inverter, PMSM, Electric Vechicles**

I. Introduction

Permanent Magnet Synchronous Motors (PMSMs) are employed in various applications because of their high efficiency and high power density [1]–[3]. PMSMs are often utilized as the traction motor of pure electric vehicles, hybrid vehicles, and so on [4]–[6]. These applications require the drive system which includes the DC converter, the three phase inverter and the motor to improve the power density and the total efficiency [7] [8].

Wide bandgap (WBG) semiconductor devices such as Gallium Nitride (GaN) is extremely effective to improve the power density and the efficiency of the motor drive system [9]–[11]. These semiconductors have remarkable characteristics that low switching loss, low conduction loss and fast switching in wide temperature range [12]–[14]. Therefore, these semiconductors can develop the power density and total efficiency of the drive system at the same time. Numerical researchers applies these semiconductors in the applications field of converters, and they have indicated the impact of employing wide band gap semiconductors [15]–[18].

In the application field of motor drive system, switching frequency of the inverter is an important parameter to minimize the total efficiency of the inverter and the motor. Increasing of switching frequency results in decreasing of inverter efficiency. On the other hand, motor efficiency increases by operating in high switching frequency because harmonic iron losses can be reduced by increasing the switching frequency [19]. Recent motor is designed with very low impedance to operate until high speed region for developing the motor power density, therefore harmonic iron losses which are generated by switching of the inverter makes big influence to the total efficiency of the motor drive system [20].

Generally the inverter for the electric cars employs Si-IGBT for the switching device because Si-IGBT can achieve higher efficiency compared with Si-FET devices under high voltage and large current that are required for driving electric cars. However conventional Si-IGBT inverters are difficult to reduce the total loss of the motor drive system even if the switching frequency is optimized to achieve maximum efficiency, because the switching frequency cannot be increased enough for reducing harmonic iron losses of the motor due to increase of the switching loss of the inverter.

In this paper, GaN-FET inverter is employed to improve the total efficiency of the motor drive system. GaN semiconductors have much smaller conduction loss and they also achieve faster switching compared with Si semiconductors, therefore the GaN-FET inverter can achieve high efficiency even under high voltage and large current load without applying IGBT structure. Losses of each components of motor drive system with Si-IGBT/GaN-FET inverter with respected to the switching frequency are evaluated by simulations and experiments. The optimization of the inverter switching frequency for maximizing the total efficiency of the motor drive system is demonstrated experimentally.

II. Evaluation of Loss Reduction of the Three Phase Inverter Using GaN-FETs by Simulations.

In this section, losses of 2 kinds of three phase inverters which are composed of Si-IGBTs or GaN-FETs are evaluated by performing the circuit simulator PLECS and Matlab-Simulink.

TABLE I: Specifications of semiconductors

Classification	Product name	Voltage	Current
Si-IGBTs	RGW60TS65D	650 V(25°C)	60 A(25°C)
GaN-FETs	GS66516T	650 V(25°C)	60 A(25°C)

TABLE II: Simulation setting for evaluation of inverter losses

Parameter	Symbol	Value
DC-link Voltage	V_{DC}	400 V
Load current	I_{load}	10 Arms to 30 Arms
Switching Frequency	F_{sw}	2 kHz to 40 kHz

Fig.1 shows the simulation block for evaluation of inverter loss of a PMSM drive system using PLECS and Matlab-Simulink. In the Matlab-Simulink Block, currents of the test PMSM are regulated by a current controller with an ideal inverter which outputs PWM phase voltage at switching frequency F_{sw}. PWM phase voltages and phase current signals calculated in Matlab-Simulink model are send in PLECS as gate signals of power devices and as references for current source, respectively. These phase voltages and phase currents refer the conduction loss and switching loss from loss table prepared in the PLECS. In the PLECS, power devices are defined by the device data which are obtained from data sheets and experiment results. From these device data, conduction loss and switching loss can be reffed according to the operation state as following equation:

$$E_{con} = \sum_{p=u,v,w} \frac{1}{\pi} \int_0^{\pi} E_p^{conT}(V_{DS}, i_p) d\theta \tag{1}$$

$$E_{on} = \sum_{p=u,v,w} \frac{1}{\pi} \int_0^{\pi} E_p^{onT}(V_{DS}, i_p, v_p) d\theta \tag{2}$$

$$E_{off} = \sum_{p=u,v,w} \frac{1}{\pi} \int_0^{\pi} E_p^{offT}(V_{DS}, i_p, v_p) d\theta \tag{3}$$

where θ is rotor position of PMSM, V_{DS} is Drain-Source voltage, i_p, v_p are phase current, phase voltage, respectively, E_p^{conT}, E_p^{onT} and E_p^{offT}, are conduction loss table, turn-on loss table and turn-off loss table in each phase, respectively.

These simulations can carry out loss evaluations with several table data, therefore they can simplify complex parameter identification and loss calculations of power devices for evaluation of inverter losses.

A. Comparison of switching losses and conduction losses

Table.I shows specifications of semiconductors which are employed in each three phase inverter in the simulator. Comparison of inverter losses are carried out according to the setting shown in Table.II.

Fig.2 shows conduction losses and switching losses of each inverter. GaN-FET inverter can reduce the conduction loss about 80% at 30 Arms in each carrier frequency because GaN-FET has much smaller on-state resistance. Similarly, GaN-FET inverter also can decrease the switching loss dramatically

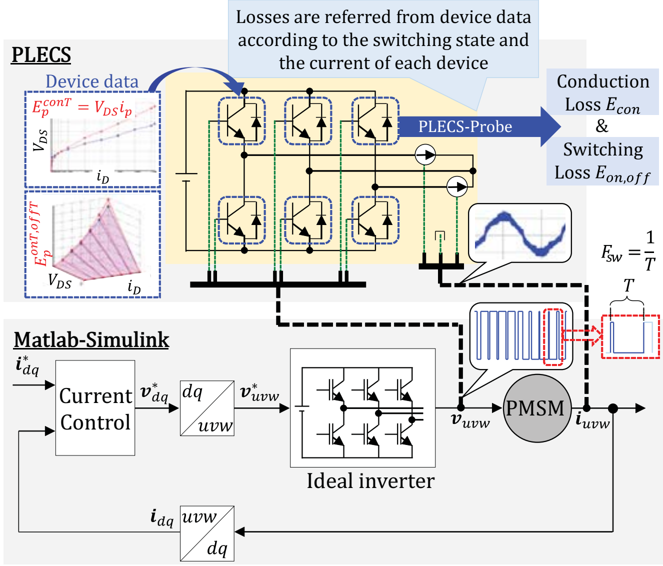


Fig. 1: Block diagram of vector control for PMSMs.

especially in high switching frequency region. The switching loss of GaN-FET inverter reduced about 63% at 30 Arms, 40 kHz compared with GaN-FET inverter. Inverter losses of the Si-IGBT inverter at 10 Arms in 2 kHz will be same level as the losses of the GaN-FET inverter at same current at 40 kHz; therefore GaN-FET inverter can boost the switching frequency about 20 times faster without increasing the loss compared with Si-IGBT inverter in some cases.

From these results, it is evaluated that GaN-FET inverter has advantages that it can reduce the inverter loss even when the switching frequency is much faster than conventional Si-IGBT inverter.

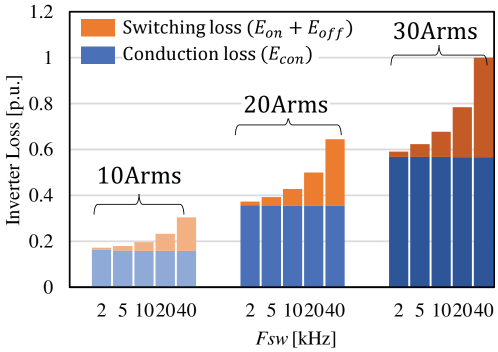
B. Loss reduction of motors by increasing the switching frequency of the inverter

As mentioned in previous section, utilizing the GaN-FET inverter can boost the switching frequency without large increase of inverter loss. Boosting of the switching frequency results in improving the total efficiency of the motor drive system because harmonic iron losses of the motor decreases in higher switching frequency.

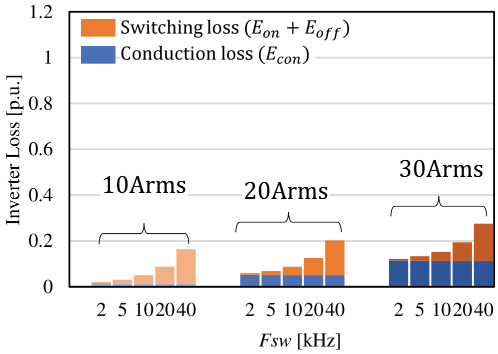
The motor efficiency is varied dramatically by the switching frequency of the inverter especially in low torque area in small output region. When the motor is operated by the inverter, each phase current of the motor contains the oscillation in the switching frequency. The oscillation of currents generates the harmonic iron losses.

Fig.3 shows the u-phase current waves in different condition of load and switching frequency at 0.5p.u. of rated rotation speed. The oscillation of u-phase current reduces dramatically by increasing the switching frequency.

The Total Harmonic Disturbance (THD) values of each u-phase current are compared in Fig.4. THD values of each current increase when the current amplitude or switching frequency is low. Increasing of THD values of phase current



(a) Si-IGBT inverter.



(b) GaN-FET inverter.

Fig. 2: Comparison of inverter losses.

induces generation of harmonic iron losses. Therefore, the motor efficiency tends to be low due to increase of the THD value of each phase current.

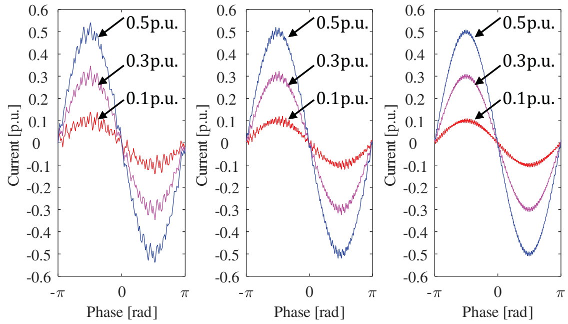
However, the accurate value of these losses are difficult to calculate theoretically. Therefore, we measured the motor efficiency for evaluation of the losses of each component of motor drive system.

III. Experimental Equipment

A test inverter and a test motor are selected to construct the multi purpose compact sport EV which is shown in Fig.5. This EV is designed to match urban lifestyles as a last mile transportation for people of all ages. Cruising distance and acceleration performance are must be improved to adopt to the traffic in a city. We employed the three phase GaN inverter and in-wheel motor which are suitable for the compact EV to increase the power density and to achieve high efficiency.

A. Inverter specification

Table.III shows the target of the inverter specification. Test inverter includes the GaN transistor GS66516T produced by GaN Systems. To satisfy the target specification, 4 parallel drive technique is adopted in each phase of the inverter as shown in Fig.6. Pictures of an inverter module of each phase are shown in Fig.7. The power circuit wiring is simplified to reduce the influence on the signal circuit. The measurement



(a) F_{sw} = 5kHz (b) F_{sw} = 10kHz (c) F_{sw} = 20kHz

Fig. 3: u-phase current waves in each current amplitude and switching frequency.

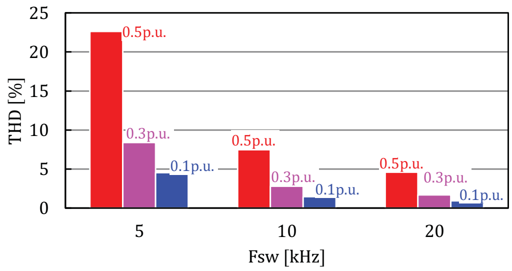


Fig. 4: THD value in each current amplitude and switching frequency.

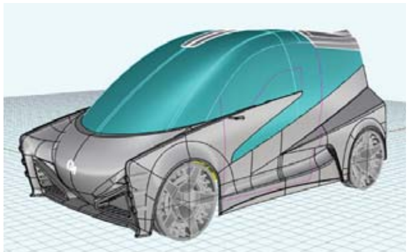


Fig. 5: Concept of the compact sport EV.

result of the module efficiency in the buck-boost converter within 90°C of package temperature without any cooling system is shown in Fig.8. The efficiency of the inverter module can be achieved over 99% both in buck and boost operation. The three phase inverter which consists of 3 inverter modules is shown in Fig.9.

B. Motor specification

Fig.10 shows the motor bench with the test motor and a load motor. We employed the in-wheel motor as a test motor which is suitable for compact EV to achieve high power density and high efficiency. The utilization of the in-wheel motor also have advantages that torque of each wheel of the car can be controlled in quick response. It helps turning action in narrow load, and it also helps to improve the driving performance and stability of the car by adopting the torque vectoring control.

The test motor utilizes the permanent magnet and the gear reduction system to realize high efficiency in a wide operation

TABLE III: Target specification of the inverter

Items	Values	Units
Input rated voltage	300	V
Operating voltage range	200-350	V
Input rated current	100	A
Output rated current	91	Arms
Output maximum current	200	A
Number of output phase	3	

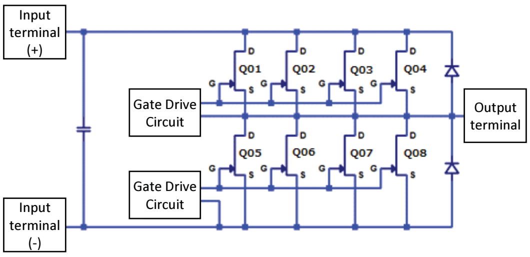
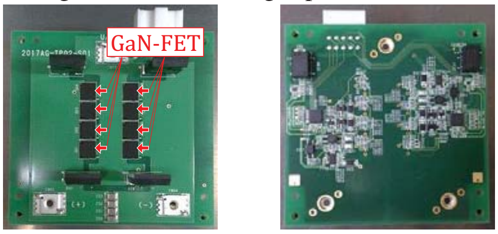


Fig. 6: Circuit of single phase inverter.



(a) Top. (b) Bottom.

Fig. 7: Single phase GaN inverter module.

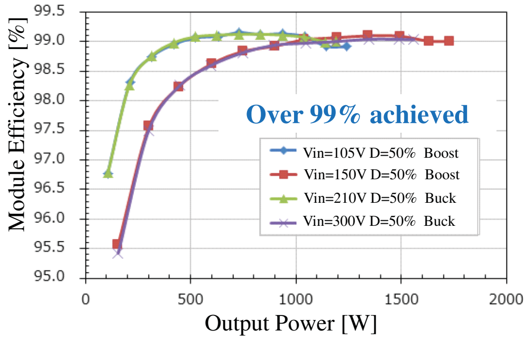


Fig. 8: GaN module efficiency in the buck-boost converter.

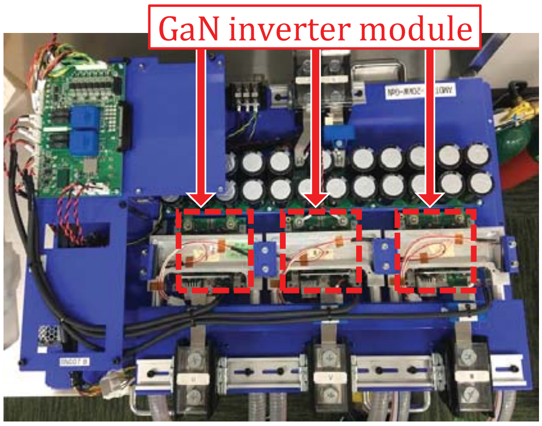


Fig. 9: Three phase inverter.

region as shown in Fig.11. Resolver signals can be obtained from the in-wheel motor for applying the vector control. Motor torque is obtained by flange torque sensor for accurate measurement.

IV. Experimental Results

Experiments are carried out to show the effectiveness of adjusting the switching frequency of the inverter. Inverter efficiency and motor efficiency are measured by using YOKOGAWA WY1804E. Test motor and load motor are driven by vector control.

A. Current distortion in each switching frequency.

Fig.12 shows each phase current with 0.1p.u. of rated torque. When the switching frequency is set 6.25 kHz, large current distortion can be observed. On the other hand, when the carrier frequency is set as 12.5 kHz or 20 kHz, disturbance components become small. From these results, it is evaluated that the increasing of the carrier frequency is effective to reduce THD values of each phase current. These results also indicate that the motor efficiency increases by setting the switching frequency of the inverter high.

As mentioned in the above, GaN inverter have a remarkable advantage that the inverter loss does not increase significantly by changing the carrier frequency. Therefore, the inverter efficiency and the motor efficiency in each switching frequency should be obtained to maximize the total efficiency of the inverter and the motor.

B. Efficiency variation due to shifting the switching frequency of the inverter.

In this section, difference of efficiency due to the switching frequency of the inverter is evaluated. Switching frequency is set as 6.25 kHz, 12.5 kHz and 20 kHz.

As shown in Fig.13, the inverter efficiency is reduced by increasing the switching frequency from 6.25 kHz to 12.5 kHz. On the other hand, motor efficiency increases significantly in the small torque region. As a result, total efficiency also increases almost of all region in measured range by shifting the switching frequency from 6.25 kHz to 12.5 kHz.

Similarly, inverter efficiency decreases and motor efficiency increases by shifting the switching frequency from 12.5 kHz to 20 kHz. Total efficiency also increased about a half area of measured range, on the other hand, the total efficiency reduced in some region mainly near high torque region. In these region, motor efficiency is almost same level in each switching frequency, because the difference of THD in each switching frequency becomes similar when the current amplitude becomes high.

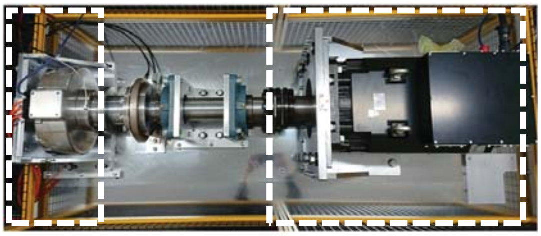


Fig. 10: Motor bench.

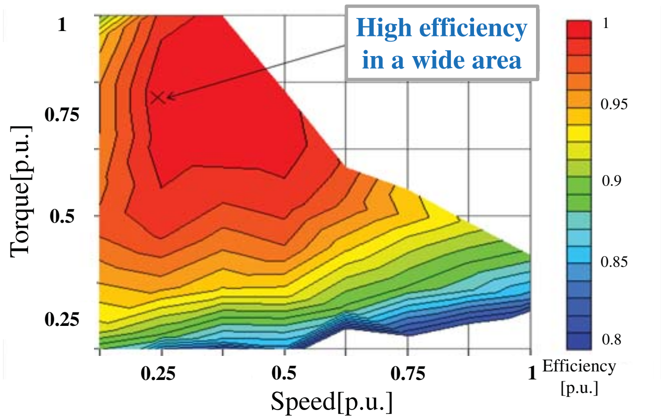


Fig. 11: Efficiency map of test in-wheel motor.

C. Optimization of carrier frequency to maximize the total efficiency of the motor drive system.

From the above experiment results, in order to maximize the total efficiency of the motor drive system, the switching frequency should be adjusted due to operating point.

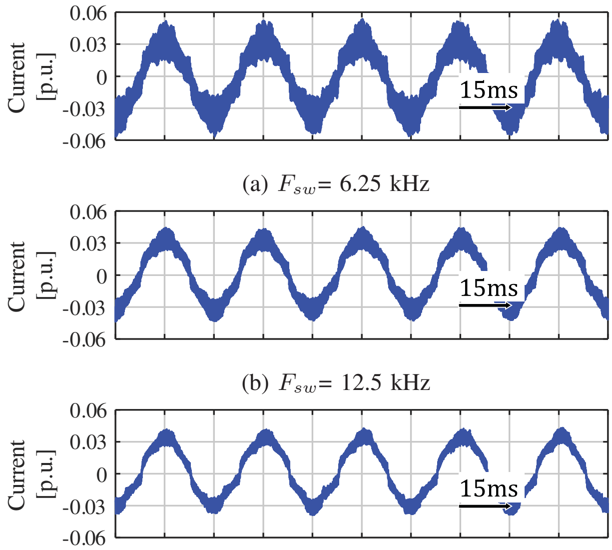
Fig.15 shows the switching frequency map which can maximize the total efficiency in each operating point. This map was obtained from the following steps:

(1) Measure the total efficiency with switching frequency at 6.25 kHz, 12.5 kHz and 20 kHz in several operating points.
(2) Find the optimized switching frequency which can maximize the total efficiency from 3 patterns of switching frequencies at each operating point.
(3) Linear interpolate the optimized switching frequency between each operating point.

From Fig.15, it is evaluated that the optimized switching frequency is higher than 10 kHz in most area of measured range. In the low torque area in low power region, optimized switching frequency tends to be higher than 10 kHz. On the other hand, in the low torque area in high power region, total efficiency is maximized near 10 kHz. Therefore, the switching frequency should be adjusted carefully due to operating point.

V. CONCLUSION

In this paper, the effectiveness for utilizing the GaN inverter was demonstrated. The advantages of employing the GaN inverter and in-wheel motor as the drive system of compact EV was discussed. The efficiency variations of each component due to shift of the switching frequency are experimentally evaluated, and optimized switching frequency of GaN inverter to maximize the total efficiency of motor drive system with GaN inverter was indicated.



(a) F_{sw}= 6.25 kHz

(b) F_{sw}= 12.5 kHz

(c) F_{sw}= 20 kHz

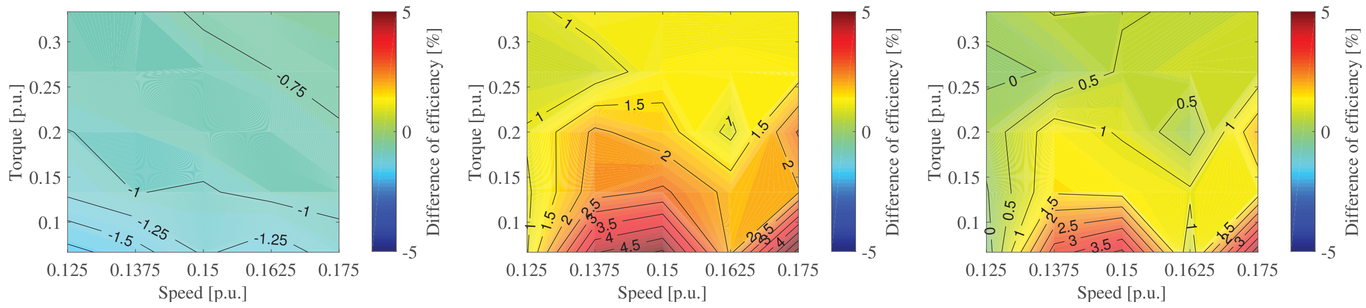
Fig. 12: Comparison of phase current at 0.1p.u. torque.

ACKNOWLEDGMENT

This project is supported by the Ministry of Environment, Japan through its "Development of GaN power/optical devices with extremely high efficiencies on high-quality GaN substrates and their applications to practical systems."

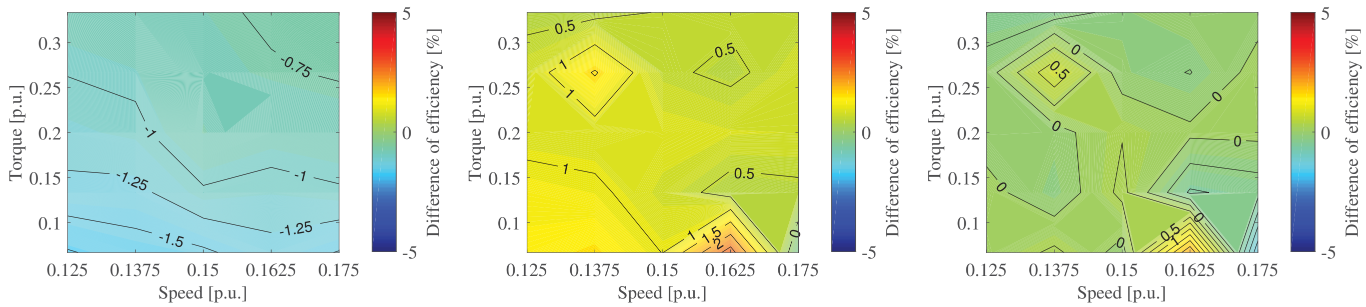
REFERENCES

[1] S. -K Sul and S. Kim, "Sensorless Control of IPMSM:Past, Present, and Future," IEEJ J. Industry Applications, vol.1, no.1, pp.15-23, 2012.
[2] M. Hasegawa and S. Doki, "Trends in Motor Drive Techniques in Japan," IEEJ J. Industry Applications, vol.1, no.3, pp.123-131, 2012.
[3] K. Yamano, S. Morimoto, M. Sanada, and Y. Inoue, "Design of Surface Permanent Magnet Synchronous Motor Using Design Assist System for PMSM," IEEJ J. Industry Applications, vol. 6, no. 6, pp. 409-415, 2017.
[4] K. Kondo and H. Kubota, " Innovative Application Technologies of AC Motor Drive Systems, " IEEJ J. Industry Applications, vol.1, no.3, pp.132-140, 2012.
[5] M. Arata, Y. Kurihara, D. Misu, and M. Matsubara, "EV and HEV Motor Development in TOSHIBA, IEEJ Journal of Industry Applications", vol.4, no.3, pp.152-157, 2015.
[6] Y. Nakayama, A. Matsumoto, and M. Hasegawa, "Position Sensorless Control System within Over-modulation Range Based on Mathematical Model Robust against Magnetic Saturation of IPMSMs," IEEJ J. Industry Applications, vol.6, no.1, pp.36-45, 2017.
[7] Y. Hosoyamada, M. Takeda, T. Nozaki, N. Motoi, and A. Kawamura, "High Efficiency Series Chopper Power Train for Electric Vehicles Using a Motor Test Bench," IEEJ J. Industry Applications, vol.4, no.4, pp.460-468, 2015.
[8] S. Kimura, K. Nanamori, T. Kawakami, J. Imaoka, and M. Yamamoto, "Allowable Power Analysis and Comparison of High Power Density DC-DC Converters with Integrated Magnetic Components," IEEJ J. Industry Applications, vol. 6, no. 6, pp. 463-472, 2017.



(a) Difference of inverter efficiency. (b) Difference of motor efficiency. (c) Difference of total efficiency.

Fig. 13: Efficiency difference between F_{sw}=6.25 kHz and 12.5 kHz (Efficiency at 12.5 kHz - Efficiency at 6.25 kHz).



(a) Difference of inverter efficiency. (b) Difference of motor efficiency. (c) Difference of total efficiency.

Fig. 14: Efficiency difference between F_{sw}=12.5 kHz and 20 kHz (Efficiency at 20 kHz - Efficiency at 12.5 kHz).

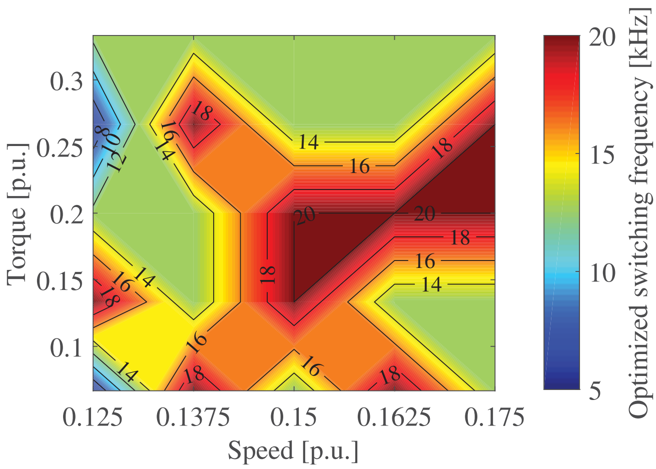


Fig. 15: Switching frequency map for maximize the total efficiency of the motor drive system.

[9] J. Wang, Y. Li, and Y. Han, "Integrated Modular Motor Drive Design WithGaNPowerFETs," IEEE Transactions on Industry Applications, vol. 51, no. 4, pp. 3198-3207, July-Aug. 2015.

[10] K. Kumar, "Efficiency improvement of three phase traction inverter through GaN devices for PMSM," in Proc. 2016 IEEE International Conference on Power Electronics Drives and Energy Systems, pp. 1-6, 2016.

[11] T. M. Jahns, and H. Dai, "The past, present, and future of power electronics integration technology in motor drives, " CPSS Transactions on Power Electronics and Applications, vol. 2, no. 3, pp. 197-216, 2017.

[12] H. Umegami, F. Hattori, Y. Nozaki, M. Yamamoto, and O. Machida, "A Novel High-Efficiency Gate Drive Circuit for Normally Off-Type GaN FET," IEEE Transactions on Industry Applications, vol. 50, no. 1, pp. 593-599, Jan.-Feb. 2014.

[13] X. Wen, T. Fan, P. Ning, and Q. Guo, "Technical approaches towards ultra-high power density SiC inverter in electric vehicle applications," CES Transactions on Electrical Machines and Systems, vol. 1, no. 3, pp. 231-237, 2017.

[14] K. Li, P. Evans and M. Johnson, "SiC/GaN power semiconductor devices: a theoretical comparison and experimental evaluation under different switching conditions," IET Electrical Systems in Transportation, vol. 8, no. 1, pp. 3-11, 2018.

[15] T. Morita, S. Tamura, Y. Anda, M. Ishida, Y. Uemoto, T. Tanaka, and D. Ueda, "99.3% Efficiency of three-phase inverter for motor drive using GaN-based Gate Injection Transistors," in Proc. 2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition, pp. 481-484, 2011.

[16] Y. Shi, L. Wang, R. Xie, Y. Shi, and H. Li,"A 60-kW 3-kW/kg Five-Level T-Type SiC PV Inverter With 99.2% Peak Efficiency," IEEE Transactions on Industrial Electronics, vol. 64, no. 11, pp. 9144-9154, 2017.

[17] T. Miyazaki, H. Otake, Y. Nakakohara, M. Tsuruya, and K. Nakahara, "A Fanless Operating Trans-Linked Interleaved 5 kW Inverter Using SiC MOSFETs to Achieve 99% Power Conversion Efficiency," IEEE Transactions on Industrial Electronics, vol. 65, no. 12, pp. 9429-9437, 2018.

[18] K. Yamaguchi, K. Katsura, T. Yamada, and Y. Sato, "Comprehensive Study on Gate Driver for SiC-MOSFETs with Gate Boost," IEEJ J.Industry Applications, vol. 7,no .3, pp. 218-228, 2018.

[19] Y. Yoshida, K. Nakamura, O. Ichinokura and K. Tajima, "Efficiency Optimization of SPM Motor Considering Carrier Harmonics Based on Electric and Magnetic Networks," IEEJ J.Industry Applications, vol.3, no.6, pp. 422-427, 2014.

[20] Y. Miyama, M. Hazeyama, S. Hanioka, N. Watanabe, A. Daikoku, and M. Inoue, "PWM Carrier Harmonic Iron Loss Reduction Technique of Permanent-Magnet Motors for Electric Vehicles," IEEE Transactions on Industry Applications, vol. 52, no. 4, pp. 2865-2871, 2016.