Maximum Torque Minimum Peak Phase Current of a Dual Winding Interior Permanent Magnet Synchronous Motor

Takashi Suzuki*, ** a) Member, Shinji Doki** Senior Member
Hiroyasu Otake* Non-member

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This paper presents an analysis of the maximum torque minimum peak phase current of the dual winding interior permanent magnet motor. Reducing the current contributes to small motor size. The peak phase current to generate the torque is reduced by the cancelation of the torque ripple generated by the two windings. The high harmonic current that does not generate torque ripple in the dual winding motor is analyzed. With the high harmonic current, the minimum peak phase current to generate a predetermined torque is calculated. The experiments were conducted to confirm the reduction of the peak phase current without increasing the torque ripple.

Keywords : Dual Winding, Multi Winding, Interior Permanent Magnet Synchronous Motor

1. Introduction

The number of the automobile is growing and the sales volume reached 90 million in 2018 (1). With the convenience realized by the automobile, it is indispensable to life in many people. However, it has downside such as traffic accidents and environmental load that should be solved. Aiming to solve its downside, electrification of the automobile is advancing quickly in the recent years and many research efforts have been taken in the field (2). In the automotive application motors, large torque form 0 r/min to low speed, quietness, and small size to match the installation space in the automobile is required. Further, the components taking role of driving, turning, and stopping such as powertrain, steering, and brake are now electrified causing the needs of better reliability. The dual winding motor is important candidate for the automotive application motor since it contributes to smaller size and enhanced reliability.

In the motor drive of dual winding motor, current is applied to two windings in one stator with two respective inverters. The inverters may become smaller with parallelization. In addition, motor drive can be continued with the remaining inverter even if one of the inverter is stopped. The dual winding motor may be an old technology, but recently, the technology is in the spotlight again. There are researches such as control method (3)-(6) and motor drive in failure state (7)-(9). Furthermore, there are researches aiming to reduce the peak of the phase current to downsize the motor (10)-(12). The researches use the characteristics of dual winding motor with 6/π rad difference in the phase of the winding that torque ripple may be cancelled each other. In the researches (10) and (11), the fifth and seventh harmonics that reduce peak phase current without generating torque ripple in magnet torque is studied. Research (12) considers increased torque by the product of the high harmonics in the current and the high harmonics in the magnetic flux. It studied the optimization of reducing peak phase current and increasing maximum torque with the injection of the fifth and seventh harmonics to the phase current. In the application that requires large torque from 0 r/min to low speed, reducing the peak phase current reduces the temperature rise of the motor or switching devices. Reduced temperature rise contributes to the downsizing of motor or switching devices.

In this paper, maximum torque minimum peak current of motor with magnet torque and reluctance torque is analyzed. Former researches neglect or do not consider torque ripple generated in the reluctance torque. Difference between former researches and this paper is that this paper studies torque ripple generated by reluctance torque. The proposal in this paper is that this paper studies torque ripple generated in the reluctance torque. The targeting system in this paper is shown in Fig.1. The analysis is conducted in the dual winding motor with two sets of three phase winding connected at the neutral point and interior permanent magnet rotor which output magnet torque and reluctance torque.

In the next chapter, high harmonic current that does not cause torque ripple in dual winding interior permanent magnet synchronous motor (IPMSM) is derived. In chapter 3, reduction of peak phase current in d-axis current 0 A control is analyzed. Then in chapter 4, reduction of peak phase current in most torque per ampere (MTPA) control is analyzed. Following the analysis, temperature rise reduction with the motion of the peak phase current is discussed in chapter 5. The control block is shown in chapter 6. Finally, experimental result is shown in chapter 7.

2. Torque of Dual Winding IPMSM

In this chapter, the torque equation of the dual winding IPMSM taking the high harmonic phase current in account is derived. With the equation, the high harmonic current that does not cause the torque ripple is analyzed.
In the former research (4), the torque equation of the dual winding IPMSM for the phase current without the high harmonic current is given. Based on the equation, the torque equation of the phase current with the basic wave and the high harmonics is calculated. Taking into account that it is not possible to apply third harmonics to the three phase motor with the neutral point, the torque equation when the fifth and the seventh harmonics are applied is calculated. The phase current of winding 1 and winding 2 which consist of the basic wave, the fifth harmonic, and the seventh harmonic are shown in equations (1) and (2). The d-axis and the q-axis currents of each winding as in equations (3) to (6) are derived from equations (1) and (2).

\[
I_{uw1} = \begin{pmatrix}
I_1 \sin(\theta - \alpha) \\
I_1 \sin(\theta - \frac{2\pi}{3} - \alpha) \\
I_1 \sin(\theta + \frac{2\pi}{3} - \alpha) \\
I_5 \sin(5\theta - \beta) \\
I_5 \sin\left(5\left(\theta - \frac{2\pi}{3}\right) - \beta\right) \\
I_5 \sin\left(5\left(\theta + \frac{2\pi}{3}\right) - \beta\right) \\
I_7 \sin\left(7\theta - \gamma\right) \\
I_7 \sin\left(7\left(\theta - \frac{2\pi}{3}\right) - \gamma\right) \\
I_7 \sin\left(7\left(\theta + \frac{2\pi}{3}\right) - \gamma\right)
\end{pmatrix}
\]

(1)

\[
I_{uw2} = \begin{pmatrix}
I_1 \sin\left(\theta - \frac{\pi}{6} - \alpha\right) \\
I_1 \sin\left(\theta + \frac{2\pi}{3} - \alpha\right) \\
I_1 \sin\left(\theta + \frac{2\pi}{3} - \alpha\right) \\
I_5 \sin\left(5\theta + \frac{\pi}{6} - \beta\right) \\
I_5 \sin\left(5\left(\theta + \frac{2\pi}{3}\right) - \beta\right) \\
I_5 \sin\left(5\theta + \frac{2\pi}{3} - \beta\right) \\
I_7 \sin\left(7\theta + \frac{\pi}{6} - \gamma\right) \\
I_7 \sin\left(7\left(\theta + \frac{2\pi}{3}\right) - \gamma\right) \\
I_7 \sin\left(7\left(\theta + \frac{2\pi}{3}\right) - \gamma\right)
\end{pmatrix}
\]

(2)

\[
I_{1d} = I_{d0} + I_{d6} \\
I_{1q} = I_{q0} + I_{q6} \\
I_{2d} = I_{d0} - I_{d6} \\
I_{2q} = I_{q0} - I_{q6}
\]

(3) to (6)

Torque equation of dual winding IPMSM from the former research (4) is shown in the equation (11). In the IPMSM, reluctance torque is generated with the product of d-axis current, q-axis current, and difference of the d-axis inductance and the q-axis inductance in addition to the magnet torque. The self-inductance and mutual inductance within one set of winding are contained in the d-axis inductance and the q-axis inductance. As for the dual winding IPMSM, mutual inductance between the two sets of winding also generates the reluctance torque.

\[
T = \varphi(L_{dq} + L_{dq}) + (L_d - L_q)(I_{1d}I_{1q} + I_{2d}I_{2q})
\]

(11)

\[
\varphi: \text{Magnetic Flux by the Magnet [V/(rad/s)]}, \\
L_d: \text{d-axis Inductance in Winding 1 or Winding 2 [H]}, \\
L_q: \text{q-axis Inductance in Winding 1 or Winding 2 [H]}, \\
M_d: \text{d-axis Mutual Inductance between Winding 1 and Winding 2 [H]}, \\
M_q: \text{q-axis Mutual Inductance between Winding 1 and Winding 2 [H]}
\]

From the equation (11) and equations (3) to (6), the torque equation taking the high harmonic phase current into account is derived as in equation (12).
3. Reduction of Peak Phase Current in d-axis Current 0A Control

The reduction of the peak phase current in d-axis current 0 A control, in other words, the phase of the basic wave in the phase current is 0 rad, is analyzed in this chapter.

From the chapter 2, it is necessary that \( I_{ds} \) or \( I_{qs} \) is 0 A in order not to cause the twelfth harmonic torque ripple. Also, to reduce the peak of the phase current, the phase of the fifth harmonic, and the basic wave, it is necessary to keep the same. Taking these two matters in account, analytical searching in the two conditions was held. Firstly, searching amplitude of \( I_{qs} \) that reduces the peak of the phase current most in the condition when \( I_1 \) is 100 A, \( I_{ds} \) is 0 A, \( \beta \) is 0 rad, and \( \gamma \) is 0 rad is held. Secondly, searching amplitude of \( I_{qs} \) that reduces the peak of the phase current most in the condition when \( I_1 \) is 100 A, \( I_{ds} \) is 0 A, \( \beta \) is 0 rad, and \( \gamma \) is 0 rad is held. As \( I_{ds} \) and \( I_{qs} \) is sinusoidal wave, the amplitude of \( I_{ds} \) or \( I_{qs} \) is changed from -10 A to 10 A by step size 0.1 A in searching. The results of the searching are shown in Fig. 2 and Fig. 3. In the Fig. 2, the horizontal axis is amplitude of \( I_{ds} \) and the vertical line is the peak phase current reduced. In the result, the peak phase current reduced is negative when the peak of the phase current was increased. In the condition when \( I_{qs} \) is 0 A, the peak of the phase current is unable to reduce with \( I_{ds} \). However, in the condition when \( I_{ds} \) is 0 A, the peak of the phase current is reduced 3.41 % when the amplitude of \( I_{qs} \) is 5.3 A. The phase currents when \( I_{ds} \) is 0 A and the amplitude of \( I_{qs} \) is 5.3 A are shown in the Fig. 4.

4. Reduction of Peak Phase Current in MTPA Control

Reduction of the peak of the phase current when the phase of the basic wave is advanced is analyzed, in this chapter. When the phase of the basic wave is advanced, it is necessary to satisfy the equation (13) and (14) in order to match the phase of the fifth and the seventh harmonics to the basic wave.

\[
\beta = 5\alpha \\
\gamma = 7\alpha
\]

However, it is not possible to satisfy equation (13) and (14) as it is known from chapters 2 and 3 that \( I_{ds} \) is needed to be 0 A to reduce the peak of the phase current without causing the twelfth harmonic torque ripple. From the equation (9), \( \beta \) equals to \( \gamma \) when \( I_{ds} \) is 0 A. If \( \alpha \) is not equal to 0 rad, it is not possible to satisfy \( I_{ds} \) equal to 0 A, equation (13), and equation (14) at the same time. To reveal the phase current reduced in the MTPA control, analytical searching was held in the condition when \( I_1 \) is 100 A, \( I_{ds} \) is 0 A, and the amplitude of \( I_{qs} \) is 5.3 A, which is the condition when the peak of the phase current is reduced the most in the chapter 3. The difference from the searching in the chapter 3 is that phase of the basic wave is advanced 0.2 rad and \( \beta \) or \( \gamma \) is changed from 0 rad to 1.5 rad by step size of 0.01 rad. The result is shown in Fig. 5. The peak of the phase current is reduced the most at 1.2 rad. The reduced current is 3.38 %. The phase current, the basic wave of the phase current, the fifth harmonic, and the seventh harmonic when \( \beta \) and \( \gamma \) are 1.0 rad, 1.2 rad, and 1.4 rad are shown in Fig. 6 to Fig. 8. When \( \beta \) and \( \gamma \) is 1.0 rad, the peak phase of the basic wave and the fifth harmonic is matched, but the peak phase of the seventh harmonic is reduced.
harmonic is unmatched. When $\beta$ and $\gamma$ is 1.4 rad, the peak phase of the basic wave and the seventh harmonic is matched, but the peak phase of the fifth harmonic is unmatched. When $\beta$ and $\gamma$ are 1.2 rad, the peak phase of the fifth and the seventh harmonics are shifted almost the same amount but to the different direction. In Fig. 9, the phase currents when $I_{d6}$ is 0 A, the amplitude of $I_{q6}$ is 5.3 A, $\beta$ is 1.2 rad, and $\gamma$ is 1.2 rad are shown.

Fig. 5. Peak Phase Current Reduced and Phase of q-axis Sixth Harmonic Current.

Fig. 6. Phase Current when Phase of q-axis Sixth Harmonic is 1 rad. Basic Wave (Top: Gray Line), Phase Current (Top: Black Line), Fifth Harmonic (Middle), and Seventh Harmonic (Bottom).

Fig. 7. Phase Current when Phase of q-axis Sixth Harmonic is 1.2 rad. Basic Wave (Top: Gray Line), Phase Current (Top: Black Line), Fifth Harmonic (Middle), and Seventh Harmonic (Bottom).

5. **Reduced Temperature Rise with the Peak Phase Current Reduction**

In general, the motor temperature is mainly risen by the copper and the iron losses. The reduction of peak current contributes to less copper loss but may increase the iron loss if the frequency of fifth or seventh harmonics are high. The comparison of copper loss with the reduced peak phase current is calculated and compared in Fig. 10. At the 0 rpm to low speed, it was assumed that the rotor is stopped at the electrical angle of peak current for the worst case. The squared peak phase currents were calculated as the index of copper loss. For the mid to high speed, assuming that the frequency of the phase current is fast enough compared to the time constant of the temperature rise, integral of the squared current in one electrical cycle is calculated as the index of copper loss. From the calculation, it is known that the copper loss at 0 rpm to low speed is reduced with the reduction of the peak phase current, however, the copper loss at the mid to high speed increases when the peak of the phase current is reduced owing to the injected fifth and seventh harmonics. To avoid increasing the copper loss, the current injection is conducted only at 0 rpm to low speed and the injection should be turned off at mid to high speed. As the time constant of temperature rise is few seconds or more in most application, turning off the injection also contributes to avoiding the increase of the iron loss.
The reduction of peak phase current is effective in the application that requires large torque from 0 \( v/\min \) to low speed. With an extra room for the temperature rise limitation such as insulating coating, thinner wire may be applied to the winding and the size of the motor can be downsized. For the temperature rise limitation in the switching device, chip size of switching device can be reduced. Reducing the peak current is effective in the application whose worst case of the temperature rise is large torque from 0 \( v/\min \) to low speed such as electric power steering.

6. Control Block

The control block for the reduction of peak phase current is shown in Fig. 11. From the d-axis current reference \( I_{d0} \) * and q-axis current reference \( I_{q0} \) * calculated from the torque reference of the motor, the d-axis and q-axis current references for the each windings to reduce the peak phase current are calculated as in the equations (15) to (20).

\[
I_{1d} = I_{d0} + I_{d6}^* \tag{15}
\]

\[
I_{1q} = I_{q0} + I_{q6}^* \tag{16}
\]

\[
I_{2d} = I_{d0} - I_{q6}^* \tag{17}
\]

\[
I_{2q} = I_{q0} - I_{q6}^* \tag{18}
\]

\[
I_{6d}^* = 0 \tag{19}
\]

\[
I_{q6}^* = \frac{5.3}{100} \times \frac{2}{\sqrt{3}} \times \left[ I_{d0}^2 + I_{q0}^2 \cos \left( 6\theta - 6 \tan^{-1}\left( \frac{I_{d6}}{I_{q6}} \right) \right) \right] \tag{20}
\]

The first coefficient 5.3/100 in the equation (20) is from the analysis in the chapter 3. The coefficient 6 of the \( \tan^{-1} \) in the equation (20) is from the analysis in the chapter 4. It is derived by 1.2 rad divided by 0.2 rad.

7. Experiment

In this chapter, the reduction of the peak phase current and the twelfth harmonic torque ripple caused by the fifth and the seventh harmonics are confirmed with the experiment. In addition, temperature rise of switching device is evaluated to show the effectiveness of reducing the peak phase current.

In Fig. 12, measured torque in d-axis current 0 A control in the condition when \( I_{d0} = 0 \), \( I_{q0} = 50 \) A, \( \beta = 0 \) rad, \( \gamma = 0 \) rad, the amplitude of \( I_{q6} \) is 2.2 A (\( = \frac{50}{\sqrt{3}} \times (5.3/100) \)), and the amplitude of \( I_{d6} \) is 0 A, 1.1 A, 2.2 A, 3.3 A, or 4.4 A are shown. In the measurement, the load motor was controlled to rotate at 5 \( v/\min \). The measurement target motor was controlled with the control block shown in the chapter 6. The parameter of the measured target motor is shown in Table 1. It was confirmed that the twelfth harmonic torque ripple is reduced when \( I_{d6} \) is 0 A and the twelfth harmonic torque ripple increases when the amplitude of \( I_{d6} \) is increased. In Fig. 13, the measured torque in the condition when \( I_{d0} = 0 \), \( I_{q0} = 50 \) A, \( \beta = 0 \) rad, \( \gamma = 0 \) rad, the amplitude of \( I_{q6} \) is 2.2 A, and the amplitude of \( I_{d6} \) is 0 A or 4.4 A are shown. Also in Fig. 13, the measured torque in the condition when \( I_{d0} = 0 \), \( I_{q0} = 50 \) A, the amplitude of \( I_{d6} \) is 0 A, and the amplitude of \( I_{q6} \) is 0 A is shown. In Fig. 14, measured phase currents in the condition where \( I_{d0} = 0 \), \( I_{q0} = 50 \) A, \( \beta = 0 \) rad, \( \gamma = 0 \) rad, the amplitude of \( I_{q6} \) is 2.2 A, and the amplitude of \( I_{d6} \) is 0 A is shown. The peak of the phase current is reduced.

In Fig. 15, the measured torque in MTP4 control is shown. In the condition when root mean square of \( I_{d0} \) and \( I_{q0} \) is 50 A, \( \alpha = 0.2 \) rad, \( \beta = 1.2 \) rad, \( \gamma = 1.2 \) rad, the amplitude of \( I_{q6} \) is 2.2 A, and the amplitude of \( I_{d6} \) is 0 A or 4.4 A are shown. Also in Fig. 16, the measured torque in the condition when root mean square of \( I_{q0} \) and \( I_{q0} \) is 50 A, \( \alpha = 0.2 \) rad, the amplitude of \( I_{q6} \) is 2.2 A, and the amplitude of \( I_{d6} \) is 0 A or 4.4 A are shown. Also in Fig. 16, the measured torque in the condition when root mean square of \( I_{q0} \) and \( I_{q0} \) is 50 A, \( \alpha = 0.2 \) rad, \( \beta = 1.2 \) rad, \( \gamma = 1.2 \) rad, the amplitude of \( I_{q6} \) is 2.2 A, and the amplitude of \( I_{d6} \) is 0 A is shown. The peak of the phase current is reduced.

The temperature rise of switching device with and without peak reduction is measured. In the measurement, the rotor is fixed at the electrical angle of the peak current in each cases. In Fig. 18, the temperature variation in d-axis current 0 A control is shown. In Fig. 19, the temperature variation in MTP4 control is shown. With the reduction of the peak phase current, temperature rise is lowered.
Table 1. Motor Parameter.

| Parameter                        | Value                      |
|----------------------------------|----------------------------|
| The Number of Pole Pairs         | 5                          |
| Resistance                       | 16 mΩ                      |
| Inductance: d-axis, q-axis       | 20 μH, 60 μH               |
| Back Electromotive Force Constant| $3.0 \times 10^{-2}$ V sec/rad |

Fig. 12. Twelfth Harmonic of Torque and Amplitude of $I_{d6}$ in d-axis Current 0 A Control.

Fig. 13. Measured Torque in d-axis Current 0 A Control. $(I_{d6}, I_{q6}) = (0 \, A, 0 \, A)$ (Left), $(I_{d6}, I_{q6}) = (0 \, A, 2.2 \, A)$ (Middle), and $(I_{d6}, I_{q6}) = (2.2 \, A, 4.4 \, A)$ (Right).

Fig. 14. Measured Phase Current of Winding 1 (Left) and Phase Current of Winding 2 (Right) in d-axis Current 0 A Control. Black Bold Line: U-Phase, Gray Bold Line: V-Phase, Black Thin Line: W-Phase.

Fig. 15. Twelfth Harmonic of Torque and Amplitude of $I_{d6}$ in MTPA Control.

Fig. 16. Measured Torque in MTPA Control. $(I_{d6}, I_{q6}) = (0 \, A, 0 \, A)$ (Left), $(I_{d6}, I_{q6}) = (0 \, A, 2.2 \, A)$ (Middle), and $(I_{d6}, I_{q6}) = (2.2 \, A, 4.4 \, A)$ (Right).

Fig. 17. Measured Phase Current of Winding 1 (Left) and Phase Current of Winding 2 (Right) in MTPA Control. Black Bold Line: U-Phase, Gray Bold Line: V-Phase, Black Thin Line: W-Phase.

Fig. 18. Measured temperature variation in d-axis Current 0 A Control. Without Peak Reduction (Left) and With Peak Reduction (Right).

Fig. 19. Measured temperature variation in MTPA Control. Without Peak Reduction (Left) and With Peak Reduction (Right).

8. Conclusion

In this paper, the reduction of the peak phase current in the dual winding IPMSM using the characteristics of the dual winding motor with $\pi/6$ rad phase difference is analyzed. With the characteristic of torque ripple cancelation, the sixth harmonic torque ripple in the magnet torque caused by the fifth and the seventh harmonics in the phase currents is cancelled, however, there is the twelfth torque ripple occurrence in the reluctance torque. It was shown in the paper...
that the occurrence of the twelfth harmonic torque ripple by injecting the fifth and the seventh harmonics is avoidable by constraints in injecting the fifth and the seventh harmonics that the sixth harmonic in the d-axis current is 0 A. With the analysis and the experiment, it was confirmed that the peak of the phase current is reduced avoiding the occurrence of twelfth harmonic torque ripple. The peak of the phase current is reduced by 3.41% in d-axis 0 A control and by 3.38% in the condition when the phase of the basic wave in the phase current is advanced 0.2 rad in $MTP_A$ control. With the reduction of the phase current, the temperature rise is reduced. Reduced temperature rise contributes to the downsizing of the motor and the chip size of switching device. This phase current injection technique reduces the temperature rise at 0 r/min to low speed, it is suitable to the application which requires large torque from 0 r/min to low speed such as electric power steering.

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**Takashi Suzuki** (Member) was born in Yokohama, Japan in 1980. He received the BS and MS degrees in mechanical engineering from Keio University, Japan, in 2003 and 2005, respectively. Since 2005, he has been with DENSO CORPORATION, Japan. He is currently working towards the PhD degree in the Nagoya University, Japan. His research interests include motor drive, power electronics and electric power steering.

**Hiroyasu Otake** (Non-member) was born in Nagoya, Japan in 1987. Received the BS degrees in electrical engineering and M.S. degrees in information technology from Nagoya Institute of Technology, Japan, in 2010 and 2012, respectively. Since 2012, he has been with DENSO CORPORATION, Japan. His research interests include motor drive, power electronics and electric power steering.

**Shinji Doki** (Senior Member) was born in Nagoya, Japan in 1966. He received the BE, ME and PhD degrees in Electronic-mechanical Engineering from Nagoya University, Japan in 1990, 1992 and 1995, respectively. Since 2012, He has been a Professor at Nagoya University, Japan. His research interests are in the area of control, modeling, signal/information processing and its application for a motor drive system. Dr. Doki received the IEEE IECON92 best paper award, the paper awards from the Institute of Electrical Engineers of Japan (2004, 20015) and Best Paper Award of The 20th IEEE International Conference on Electrical Machines and Systems 2017.

Mr. Suzuki is recipient of Best Presentation Recognition at IECON2015.