Control Method that Reduces the High Harmonic in the Overmodulation Drive of the Dual Winding Motor during Voltage Supply Unbalance

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More reliable motor drive systems are expected in the realization of automated driving. The redundant motor drive system with two voltage supplies, two inverters, and a dual winding motor is one of the strong candidates since the two systems that construct the motor drive system are electrically independent. The dual winding motor has a characteristic of cancelling the 6th harmonic produced in the overmodulation drive. However, it loses its characteristic when there is a voltage difference in the two voltage supplies. In this paper, it is proposed to control only the sum of the current during the overmodulation to maintain the characteristic of cancellation even if there is voltage difference in the two voltage supplies. Furthermore, the current difference of the two windings is controlled in the sinusoidal wave region to suppress the deviation of currents and turned off during the overmodulation to reduce 6th harmonic. The maintained characteristic during voltage supply unbalance is confirmed with the experiment.

**Keywords**: Dual Winding, Overmodulation, Redundant Motor Drive, 6th Harmonic, Voltage Difference

1. Introduction

To decrease the environmental load and enhance the convenience of the automobile, expectation to the electrification and adoption of an automated drive technology is very high. At the introduction of new technology, new requirements and needs arise to the fundamental technology such as power electronics. Recently, the dual winding motor is attracting attention for its redundancy. In addition to studies on the basic control of the dual winding motor (1), there are studies on continuous drive in failure state (2), (3), and the utilization of redundancy to downsizing of the motor drive system (4), (5).

The motor drive system of electric power steering was conventionally a single system. It consists of a winding, an inverter and a voltage supply. However, with the start of the production of the system that consists of a dual winding motor and two inverters (6), the redundant motor drive system that consists of two voltage supplies are reported looking toward an automate driving (7).

Although the voltage of the battery is limited in the automobile auxiliary motors, enlarging the output of the motor is possible if more voltage is applied to the motor. In comparison with the sinusoidal wave drive, the overmodulation drive enlarges the applied voltage to the motor under the limited voltage supply. In the drive, a trapezoidal voltage is applied to the motor (8). The overmodulation drive has the advantage of increasing fundamental wave voltage, but it has the disadvantage of applying high harmonic to the motor, which may cause a vibration. In conventional studies, an optimum amount of the 3rd harmonic voltage injection that reduces the high harmonics (9) and the overmodulation for the motor with more than five phases (10) are studied. For the dual winding motor, modulation strategy with less high harmonics generation (11) and cancellation of the high harmonics with the two windings (12) are recently studied. However, conventional studies do not consider the motor drive system with the two voltage supplies or the unbalanced voltage in the two voltage supplies, although it is one of the strong candidates for the reliable motor drive system.

The motor drive system with the two voltage supplies is shown in Fig. 1. The windings in the dual winding motor are connected to the inverters with the respective voltage supply. We have been motivated by the characteristic of the two voltage supply system in which the two systems are electrically independent unlike the open winding motor drive system with two voltage supplies (3), we studied overmodulation in the two voltage supply system (14). In this paper, our former work is revised, and improved control is proposed. Firstly, the high harmonics produced in the overmodulation drive in the dual winding motor is explained. Secondly, the problem that arises under the condition of the voltage unbalance is analyzed. Thirdly, it is proposed to control the sum of the current during the overmodulation to maintain the characteristic of cancellation under voltage supply unbalance. Fourthly, to improve control, controlling the current difference in the sinusoidal wave region and turning off the control during the overmodulation drive are proposed to suppress the deviation of current in sinusoidal wave region. Finally, the effectiveness of the proposed control is confirmed with the conducted experiment. The proposed control is useful in applications like auxiliary motors in the vehicle since the voltage of the voltage supply fluctuates or drops as the other one of the multiple motors connected to the common battery pulls the electricity from the battery.

2. Motor Drive of Dual Winding Motor

This paper studies the overmodulation of the dual winding motor that is connected to the inverters with the respective voltage supply as shown in the Fig. 1. The system studied in this paper has two

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The measured phase currents are translated to the d-axis and the q-axis currents with the equations (1) to (3).

\[
\begin{align*}
\begin{bmatrix} I_{d1} \\ I_{q1} \end{bmatrix} &= T(\theta) \begin{bmatrix} I_{d1} \\ I_{q1} \end{bmatrix} \quad \cdots \cdots \cdots \cdots \cdots \quad (1) \\
\begin{bmatrix} I_{d2} \\ I_{q2} \end{bmatrix} &= T(\theta - \pi/6) \begin{bmatrix} I_{u2} \\ I_{v2} \end{bmatrix} \quad \cdots \cdots \cdots \cdots \cdots \quad (2) \\
T(\theta) &= \begin{bmatrix} \cos(\theta) & \cos(\theta - \pi/3) & \cos(\theta + \pi/3) \\
\sqrt{2/3} & \sqrt{2/3} & \sqrt{2/3} \\
-\sin(\theta) & -\sin(\theta - \pi/3) & -\sin(\theta + \pi/3) \end{bmatrix} \quad \cdots \cdots \cdots \cdots \cdots \quad (3)
\end{align*}
\]

The controllers of the d-axis currents and q-axis currents calculates the d-axis and q-axis voltage references of each windings. The d-axis and q-axis voltage references are translated to the u-phase, v-phase, and w-phase voltage references with the equations (4) and (5).

\[
\begin{align*}
\begin{bmatrix} V_{u1,ref} \\ V_{v1,ref} \\ V_{w1,ref} \end{bmatrix} &= T^{-1}(\theta) \begin{bmatrix} V_{d1,ref} \\ V_{q1,ref} \end{bmatrix} \quad \cdots \cdots \cdots \cdots \cdots \quad (4) \\
\begin{bmatrix} V_{u2,ref} \\ V_{v2,ref} \\ V_{w2,ref} \end{bmatrix} &= T^{-1}(\theta - \pi/6) \begin{bmatrix} V_{d2,ref} \\ V_{q2,ref} \end{bmatrix} \quad \cdots \cdots \cdots \cdots \cdots \quad (5)
\end{align*}
\]

The amplitude and phase of the phase voltage references are obtained from the d-axis voltage and q-axis voltage with the equations (6) to (9).

\[
\begin{align*}
V_{amp1,ref} &= \sqrt{2/3} \sqrt{V_{d1,ref}^2 + V_{q1,ref}^2} \quad \cdots \cdots \cdots \cdots \cdots \quad (6) \\
V_{amp2,ref} &= \sqrt{2/3} \sqrt{V_{d2,ref}^2 + V_{q2,ref}^2} \quad \cdots \cdots \cdots \cdots \cdots \quad (7) \\
\theta_{\psi1} &= \tan^{-1} -\frac{V_{d1,ref}}{V_{q1,ref}} \quad \cdots \cdots \cdots \cdots \cdots \quad (8) \\
\theta_{\psi2} &= \tan^{-1} -\frac{V_{d2,ref}}{V_{q2,ref}} \quad \cdots \cdots \cdots \cdots \cdots \quad (9)
\end{align*}
\]

The modulations of u-phase, v-phase, and w-phase are calculated with the equations (10) and (11).

\[
\begin{align*}
\begin{bmatrix} M_{u1} \\ M_{v1} \\ M_{w1} \end{bmatrix} &= \frac{2}{V_{M1}} \begin{bmatrix} V_{u1,ref} \\ V_{v1,ref} \\ V_{w1,ref} \end{bmatrix} + \begin{bmatrix} 1/2 \\ 1/2 \\ 1/2 \end{bmatrix} \quad \cdots \cdots \cdots \cdots \cdots \quad (10)
\end{align*}
\]
The fundamental wave voltage and produced high harmonics are studied in this chapter.

3. The Overmodulation Drive in the Dual Winding Motor

The enlarged fundamental wave voltage and produced high harmonics are studied in this chapter.

The phase voltages when the supplied voltage is 10 V, the modulation index is 1.4, the phase of the phase voltage is 0 rad, and the frequency of the voltage is 100 Hz are shown in Fig. 3. The d-axis and q-axis voltages are shown in Fig. 4, and the spectrums are shown in Fig. 5. The spectrum of the dc component is not included in the figure. Since it is in the overmodulation drive and the peak of the phase voltage is limited at the supplied voltage, the high harmonics that are a multiple of six are produced. The major component of the generated high harmonics is the 6th harmonic.

In Fig. 6, the relation of the fundamental wave voltage and modulation index is shown. The vertical axis is the percentage of the fundamental wave voltage. It is 100 \% when the modulation index is 1. In the overmodulation drive when the modulation index is larger than 1, the slope decreases as the modulation index increases. The fundamental wave voltage when the modulation index is 1.4 is 1.155 times the fundamental wave voltage when the modulation index is 1. In Fig. 7, the relation of the 6th harmonic and fundamental wave voltage is shown. The 6th harmonic is calculated from the root mean square of the d-axis and q-axis voltages. The percentage of the 6th harmonic to the fundamental wave increases as the fundamental wave voltage increases.

The voltages of the dual winding motor when the supplied voltage is 10 V, modulation index is 1.4, phase of the phase voltage is 0 rad, and frequency of the voltage is 100 Hz are shown in Fig. 8 to Fig. 10. The d-axis and q-axis voltages of the two windings are shown in Fig. 8. The voltage sums of the two windings are shown in Fig. 9 and its spectrums are shown in Fig. 10. The spectrum of the dc component is not included in the figure. In the dual winding motor with the π/6 rad phase difference of the windings, the 6th harmonic

\[
\begin{align*}
    V_{M1} & = \frac{2}{V_{M2}} \left( \frac{V_{u2,\text{ref}}}{V_{w2,\text{ref}}} \right) + \left( \frac{1}{2} \right) \left( \frac{1}{2} \right) \left( \frac{1}{2} \right) \\
    V_{M2} & = \frac{2}{V_{M2}} \left( \frac{V_{u2,\text{ref}}}{V_{w2,\text{ref}}} \right) + \left( \frac{1}{2} \right) \left( \frac{1}{2} \right) \left( \frac{1}{2} \right)
\end{align*}
\]

\[m = \frac{2V_{\text{amp.ref}}}{V_{dc}}\]

\[m: \text{Modulation Index.}
\]

\[V_{\text{amp.ref}}: \text{Amplitude of the Phase Voltage Reference.}
\]

\[V_{dc}: \text{Supplied Voltage.}
\]

The relationship between the voltages and currents in the dual winding motor is shown in reference (13). In the dual winding motor, the flux produced by current in winding 1 will induce the voltage in winding 2 through the mutual inductance between the windings.

In this paper, the modulation index is defined in equation (14). It is calculated from the amplitude of the phase voltage reference.
is cancelled in the d-axis and q-axis voltage sums. In Fig. 11 the relation of the 6th harmonic and the fundamental wave voltage is shown. As for the voltage sum in the dual winding motor, the 6th harmonic is not produced at any modulation index.

4. High Harmonic under Voltage Supply Unbalance

In this chapter, high harmonics produced under voltage supply unbalance in the dual winding motor which is connected to the inverters with the respective voltage supply is explained. Then, the control method to reduce the produced high harmonics is proposed.

If the current of each windings is respectively controlled to output halves of the target torque under voltage supply unbalance, the modulation index of the inverter will be different since it is adjusted by the current controller. The d-axis and q-axis voltages when the supplied voltage is 10 V in voltage supply 1 and 11.5 V in voltage supply 2 (voltage difference 15 %), the amplitude of the fundamental wave voltage is 11.5 V each, and the phase of the phase voltage is 0 rad are shown in Fig. 12. The d-axis and q-axis voltage sums are shown in Fig. 13. Winding 1 is in the overmodulation but Winding 2 is not in the overmodulation. The modulation indexes are different if there is unbalance in the voltage supplies. If modulation indexes are different, the 6th harmonic is not cancelled.

In Fig. 14, the proposed control block is shown. To cancel the 6th harmonic with the two windings, it is preferable that the modulation indexes are the same. To keep the modulation indexes the same and control the output torque of the motor at the same time, the current sums of the two windings are controlled. In general, measured supplied voltage is set to $V_{M1}$ and $V_{M2}$ in the translation of phase voltage references to the modulations. For the proposed control, the voltage in voltage balanced state which is a fixed value is set to $V_{M1}$ and $V_{M2}$.

The d-axis and q-axis voltage references and the d-axis and q-axis voltages when the supplied voltage is 10 V in voltage supply 1 and 11.5 V in voltage supply 2 (voltage difference 15 %), the amplitude of the fundamental wave voltage is 11.5 V times two in
the sum of two windings, the modulation indexes are the same, and the phase of the phase voltage is 0 rad are shown in Fig. 15. The d-axis and q-axis voltage sums are shown in Fig. 16. The relation of the 6th harmonic and fundamental wave voltage is shown in Fig. 17. If the modulation indexes are kept the same, the 6th harmonic in the voltage sum is reduced. The small 6th harmonics produced even if the modulation indexes are the same is caused by the difference in the voltage of the voltage supplies. The proposed method in this paper tries to reduce the 6th harmonic by aligning the produced 6th harmonic in the voltages during the overmodulation. If the 6th harmonic in the voltages are aligned, the 6th harmonic in the currents are aligned when the parameters of the windings are the same. Therefore, the 6th harmonic voltages induced through the mutual inductance between the windings are aligned also.

If only the current sum is controlled, a difference in the amplitude of the fundamental voltage will occur, which will cause the difference in the d-axis and q-axis currents of the windings. It is alternative to the 6th harmonic generation in the overmodulation drive. However it is only downgrading in the sinusoidal wave drive region. To avoid the occurrence of the deviation in the current, the current difference controllers which work only in the sinusoidal wave region are added to the proposed control.

\[ \begin{align*}
I_{d_{\text{sum-ref}}} & : \text{d-axis Current Sum of Winding 1 and Winding 2.} \\
I_{q_{\text{sum-ref}}} & : \text{q-axis Current Sum of Winding 1 and Winding 2.} \\
I_{d_{\text{sum-ref}}, q_{\text{sum-ref}}} & : \text{d-axis and q-axis Current Sum References.}
\end{align*} \]

**5. Transition between the Sinusoidal Wave and Overmodulation Drive**

If the current sum is controlled, a difference in the amplitude of the fundamental voltage will occur, which will cause the difference in the d-axis and q-axis currents of the windings. It is alternative to the 6th harmonic generation in the overmodulation drive. However it is only downgrading in the sinusoidal wave drive region. To avoid the occurrence of the deviation in the current, the current difference controllers which work only in the sinusoidal wave region are added to the proposed control.

**Fig. 14. Proposed Control Block**

If the modulation indexes are kept the same, the 6th harmonic in the voltage sum is reduced. The small 6th harmonics produced even if the modulation indexes are the same is caused by the difference in the voltage of the voltage supplies. The proposed method in this paper tries to reduce the 6th harmonic by aligning the produced 6th harmonic in the voltages during the overmodulation.
Overmodulation Drive of Dual Winding Motor (Takashi Suzuki et al.)

6. Experimental Result

In this chapter, it is confirmed that the 6th harmonic is produced in the current sum of the two winding under voltage supply unbalance. Then, the reduction of the 6th harmonic with the proposed control is evaluated.

The currents of the windings are measured when the supplied voltage is 10 V in voltage supply 1 and 11.5 V in voltage supply 2. The measurement was conducted when the current of the windings are respectively controlled or the current sum is controlled. Also, the currents of the windings when supplied voltage is 10 V in both voltage supply and the current of the two windings are respectively controlled are measured for comparison. The d-axis current reference is -15 A and the q-axis current reference is 3.5 A for each windings. The reference of the current sum is two times the references for each winding. The reference of the current sum is two times the references for each winding. The phase currents were measured with the shunt resistors placed under the lower switching devices. To maintain the enough on time of the lower switching devices for the current acquisition, the PWM duties of each phases were limited at 90 % and 10 % (90 % - 10 % = 80 %). The rotational speed was adjusted so that the amplitude of the fundamental wave voltage is 8.8 V (80 % of 11 V). The measured currents are shown in Fig. 19 to Fig. 21. The experiment is also conducted when the amplitude of the fundamental wave voltage is 9.2 V (80 % of 11.5 V). The measured current is shown in Fig. 22 to Fig. 24. The parameter of the motor used in the experiment is shown in Table 1. From the experimental result, it is obvious that the 6th harmonic is produced in conventional control when there is voltage supply unbalance. Also, it is known that the 6th harmonic is less in the proposed control.

The current and speed were measured to confirm the smooth transition of the current difference control. The experiment was conducted when the supplied voltage is 10 V in voltage supply 1 and 11.5 V in voltage supply 2. The d-axis current reference is -15 A and the q-axis current reference is 3.5 A for each windings. The reference of the current sum is two times the references for each winding. The load of the test motor was controlled so that the region of the motor output changes from the sinusoidal wave region to the overmodulation drive region. The measured data is shown in Fig. 25 to Fig. 27. With the current difference control, the current deviation is suppressed in the sinusoidal wave region and the
control is turned off during the overmodulation reducing the 6th harmonic.

Fig. 19. Result in the Conventional Control at the Fundamental Wave Voltage 8.8 V when Both Voltage Supplies Are 10 V (Top Black Line: Winding 1 U-Phase PWM Duty, Top Gray Line: Winding 2 U-Phase PWM Duty, Middle: d-axis Current Sum, Bottom: q-axis Current Sum)

Fig. 20. Result in the Conventional Control at the Fundamental Wave Voltage 8.8 V when Voltage Supplies Are 10 and 11.5 V (Top Black Line: Winding 1 U-Phase PWM Duty, Top Gray Line: Winding 2 U-Phase PWM Duty, Middle: d-axis Current Sum, Bottom: q-axis Current Sum)

Fig. 21. Result in the Proposed Control at the Fundamental Wave Voltage 8.8 V when Voltage Supplies Are 10 and 11.5 V (Top Black Line: Winding 1 U-Phase PWM Duty, Top Gray Line: Winding 2 U-Phase PWM Duty, Middle: d-axis Current Sum, Bottom: q-axis Current Sum)

Fig. 22. Result in the Conventional Control at the Fundamental Wave Voltage 9.2 V when Both Voltage Supplies Are 10 V (Top Black Line: Winding 1 U-Phase PWM Duty, Top Gray Line: Winding 2 U-Phase PWM Duty, Middle: d-axis Current Sum, Bottom: q-axis Current Sum)

Fig. 23. Result in the Conventional Control at the Fundamental Wave Voltage 9.2 V when Voltage Supplies Are 10 and 11.5 V (Top Black Line: Winding 1 U-Phase PWM Duty, Top Gray Line: Winding 2 U-Phase PWM Duty, Middle: d-axis Current Sum, Bottom: q-axis Current Sum)

Fig. 24. Result in the Proposed Control at the Fundamental Wave Voltage 9.2 V when Voltage Supplies Are 10 and 11.5 V (Top Black Line: Winding 1 U-Phase PWM Duty, Top Gray Line: Winding 2 U-Phase PWM Duty, Middle: d-axis Current Sum, Bottom: q-axis Current Sum)
Table 1. Motor Parameter

| Parameter                                      | Value            |
|-----------------------------------------------|------------------|
| Back Electromotive Force                      | $0.6 \times 10^{-2}$ V / (rad/s) |
| Resistance                                    | 20 mΩ            |
| Inductance of Winding 1 and Winding 2         | 40 μH            |
| Mutual Inductance between Winding 1 and Winding 2 | 10 μH         |

7. Conclusion

In this paper, the overmodulation drive of the dual winding motor with two voltage supplies is studied. The motor drive system consists of the dual winding motor and two inverters with the respective voltage supply is one of strong candidates in reliability requiring application since the two systems are electrically independent. The dual winding motor has a characteristic of the low 6th harmonic since it is cancelled in the sum of two windings. In the one voltage supply system, the characteristic is effective in the overmodulation drive and the 6th harmonic produced in the overmodulation is reduced in the sum of two windings. However, the characteristic is lost when there is a voltage difference in the two voltage supplies. The 6th harmonic is produced in the sum of two winding. In this paper, it is proposed to control the sum of the current in two windings to maintain the characteristic of the low 6th harmonic. It is also proposed to control the current difference in the sinusoidal wave region to suppress the deviation of the current and turn off the control during the overmodulation drive to maintain the characteristic. With the proposed control, the modulation indexes are kept the same in the overmodulation and the 6th harmonic is reduced in the sum of the two windings even if there is a voltage difference in the two voltage supplies. The proposed control contributes to enhance the reliability of the motor drive system with more tolerance to the voltage supply unbalance.
Fig. 27. Result in the Proposed Control with the Current Difference Control when Voltage Supplies Are 10 and 11.5 V

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