Elimination of the DC Bus Sixth Harmonic Component in Integrated Modular Motor Drives Using Third Harmonic Injection Method

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***Abstract*—In this paper, a novel method to eliminate the harmonic component occurring on the DC bus which is six times the grid frequency is proposed. This harmonic component is present due to natural commutation of the passive diode bridge rectifier in motor drive applications. In conventional drives, bulky LC filters are utilized to reduce the effect of this harmonic component to the motor drive inverter. With this method, DC bus capacitance requirement can be minimized which will enhance the power density and decrease the cost of the overall system. Third harmonic injection is used with modular inverters in an integrated modular motor drive application. Both rectifier and inverter side analytical models are presented, the elimination of the sixth harmonic component is described analytically, and verified by simulations performed on MATLAB/Simulink. The possible adverse effects of third harmonic injection method are also discussed.**

I. Introduction

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Most studies consider only one side for DC link characterisation or filter component optimization, although they should be considered simultaneously. This research aims at modeling the system as a whole, investigating the effect of harmonic components injected to the DC link from both sides and eliminating the low frequency harmonic due to the rectifier side by using the modular structure of the inverter side.

II. Problem definition

A conventional motor drive system block diagram is shown in Fig. 1. The rectifier and inverter are connected via the DC link, therefore a harmonic component injected from one side is reflected to the other side. For systems having two active converters on both sides such as back-to-back converters, the only fluctuations seen on the DC link voltage are high frequency components which are directly related to the switching frequencies of each side. On the other hand, in case of passive converters such as diode bridge rectifiers, low frequency components emerge on the DC link voltage which are related to the grid supply frequency. Since grid frequency is usually much smaller than the switching frequencies applied to active converters, filtering of fluctuations on the DC link requires much larger and more expensive components in case of passive rectifiers.

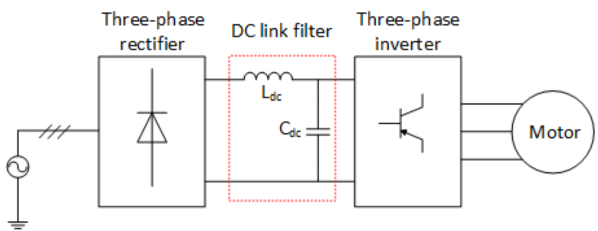

Fig. 1: A conventional motor drive block diagram

Diode bridge rectifier is a natural-commutated converter, circuit schematic of which is shown in Fig. 5. A second order LC filter which is low-pass type is usually utilized at the rectifier output for filtering.

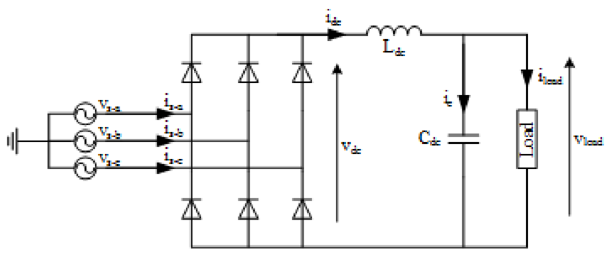

Fig. 2: Diode bridge rectifier circuit diagram

The supply voltages are shown in 6-8, where V_m is the RMS value of the supply voltage and f_s is the supply frequency.

$$v_{sa}(t) = \sqrt{2}V_m sin(2\pi f_s t) \tag{1}$$

$$v_{sb}(t) = \sqrt{2}V_m sin(2\pi f_s t - 2\pi/3) \quad (2)$$

$$v_{sc}(t) = \sqrt{2}V_m sin(2\pi f_s t - 4\pi/3) \quad (3)$$

With this configuration, integer multiples of sixth harmonic component are present on the rectifier output voltage in addition to the DC component as shown in 9.

$$v_{dc}(t) = \frac{3\sqrt{3}}{\pi}\left[1 - \sum_{k=1}^{\infty}\frac{2}{36k^2-1}cos(6k\omega_0 t)\right] \quad (4)$$

The transfer function of the DC link filter is shown in 10.

$$v_{dc}(t) = \frac{3\sqrt{3}}{\pi}\left[1 - \sum_{k=1}^{\infty}\frac{2}{36k^2-1}cos(6k\omega_0 t)\right] \quad (5)$$

Size of passives are very important for IMMD applications.

A set of voltage and current waveforms are shown in Fig. 3, for 400V line-to-line grid voltage at 50 Hz, filter inductance of 1 mH, filter capacitance of 3 mF and load resistance of 10 Ω. The three-phase rectifier output voltage and current has large harmonic components frequency of which is six times the grid frequency. This component is filtered by a second order LC filter resulting in a much smoother load voltage and current. Since the harmonic frequency is relatively low in comparison with conventional switching frequencies, large inductance and capacitance values are needed on the DC link filter. Those passive elements constitute a large portion of overall volume and cost, hence it is aimed to minimize their values.

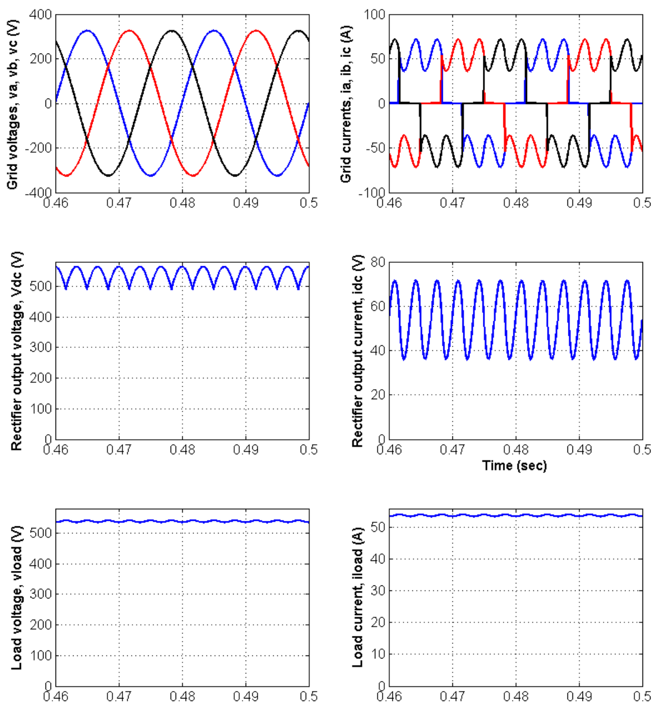

Fig. 3: Diode bridge rectifier input and output waveforms

III. Description of the Proposed Method

In the proposed method, a harmonic component which is six times the grid frequency is aimed to be created at the inverter DC input such that there will be no low order harmonic current flowing through the DC link capacitor. By doing so, the DC link capacitance requirement can be reduced significantly.

The harmonic component is created by injecting zero sequence third harmonic components at the motor side. Voltages and current expressions of one inverter module with zero sequence third harmonic injection are shown in 6-11.

$$v_a(t) = V_1 sin(2\pi ft - \phi_{1v}) + V_3 sin(6\pi ft - \phi_{3v}) \quad (6)$$

$$v_b(t) = V_1 sin(2\pi ft - 2\pi/3 - \phi_{1v}) + V_3 sin(6\pi ft - \phi_{3v}) \quad (7)$$

$$v_c(t) = V_1 sin(2\pi ft - 4\pi/3 - \phi_{1v}) + V_3 sin(6\pi ft - \phi_{3v}) \quad (8)$$

$$i_a(t) = I_1 sin(2\pi ft - \phi_{1i}) + I_3 sin(6\pi ft - \phi_{3i}) \quad (9)$$

$$i_b(t) = I_1 sin(2\pi ft - 2\pi/3 - \phi_{1i}) + I_3 sin(6\pi ft - \phi_{3i}) \quad (10)$$

$$i_c(t) = I_1 sin(2\pi ft - 4\pi/3 - \phi_{1i}) + I_3 sin(6\pi ft - \phi_{3i}) \quad (11)$$

Let us make the definitions shown in 12-19.

$$\phi_{11p} = \phi_{1v} + \phi_{1i} \quad (12)$$

$$\phi_{33p} = \phi_{3v} + \phi_{3i} \quad (13)$$

$$\phi_{13p} = \phi_{1v} + \phi_{3i} \quad (14)$$

$$\phi_{31p} = \phi_{3v} + \phi_{1i} \quad (15)$$

$$\phi_{11n} = \phi_{1v} - \phi_{1i} \quad (16)$$

$$\phi_{33n} = \phi_{3v} - \phi_{3i} \quad (17)$$

$$\phi_{13n} = \phi_{1v} - \phi_{3i} \quad (18)$$

$$\phi_{31n} = \phi_{3v} - \phi_{1i} \quad (19)$$

The instantaneous power expression for each phase are shown in 20-22.

$$\begin{aligned} p_a(t) = {} & \frac{V_1 I_1}{2}\left[cos(\phi_{11n}) - cos(4\pi ft - \phi_{11p})\right] \\ & + \frac{V_1 I_3}{2}\left[cos(4\pi ft + \phi_{13n}) - cos(8\pi ft - \phi_{13p})\right] \\ & + \frac{V_3 I_1}{2}\left[cos(4\pi ft - \phi_{31n}) - cos(8\pi ft - \phi_{31p})\right] \\ & + \frac{V_3 I_3}{2}\left[cos(\phi_{33n}) - cos(12\pi ft - \phi_{33p})\right], \end{aligned} \quad (20)$$

$$\begin{aligned} p_b(t) = {} & \frac{V_1 I_1}{2}\left[cos(\phi_{11n}) - cos(4\pi ft - 4\pi/3 - \phi_{11p})\right] \\ & + \frac{V_1 I_3}{2}\left[cos(4\pi ft + 2\pi/3 + \phi_{13n}) - cos(8\pi ft - 2\pi/3 - \phi_{13p})\right] \\ & + \frac{V_3 I_1}{2}\left[cos(4\pi ft + 2\pi/3 - \phi_{31n}) - cos(8\pi ft - 2\pi/3 - \phi_{31p})\right] \\ & + \frac{V_3 I_3}{2}\left[cos(\phi_{33n}) - cos(12\pi ft - \phi_{33p})\right], \end{aligned} \quad (21)$$

$$p_c(t) = \frac{V_1 I_1}{2}\Big[cos(\phi_{11n}) - cos(4\pi f t - 8\pi/3 - \phi_{11p})\Big]$$
$$+ \frac{V_1 I_3}{2}\Big[cos(4\pi f t + 4\pi/3 + \phi_{13n}) - cos(8\pi f t - 4\pi/3 - \phi_{13p})\Big]$$
$$+ \frac{V_3 I_1}{2}\Big[cos(4\pi f t + 4\pi/3 - \phi_{31n}) - cos(8\pi f t - 4\pi/3 - \phi_{31p})\Big]$$
$$+ \frac{V_3 I_3}{2}\Big[cos(\phi_{33n}) - cos(12\pi f t - \phi_{33p})\Big], \quad (22)$$

The total instantaneous power becomes as in 23. As seen, all the frequency components which are two times and four times the fundamental frequency are cancelled, leaving two DC components and a component at six times the fundamental frequency. The last term will be used in this method for the cancellation of the sixth harmonic injected by the rectifier.

$$p_{total}(t) = \frac{V_1 I_1}{2}\Big[cos(\phi_{11n})\Big] + \frac{V_3 I_3}{2}\Big[cos(\phi_{33n})\Big] + \frac{V_3 I_3}{2}\Big[cos(12\pi f t - \phi_{33p})\Big] \quad (23)$$

IV. Implementation of the method and practical issues

This method is proposed for IMMD applications where selection of number of inverter modules, number of stator phases etc. are flexible. This makes the application of the method more convenient. In this paper, a six pole machine is considered. The schematic of the segmented stator and modular inverters is shown in Fig. 5.

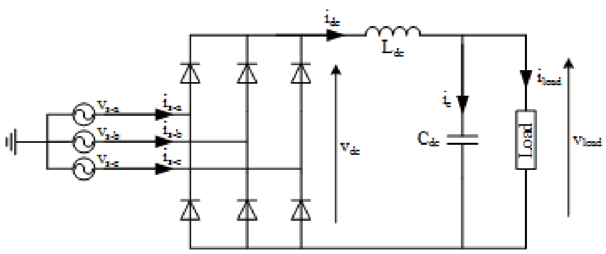

Fig. 4: IMMD scheme

It has been shown that, with conventional three-phase connection, injection of third harmonic is impossible, regardless of the winding connection being delta or wye, due to the nature of the three-phase. Therefore, in this paper, an IMMD scheme is proposed such that each stator coil is fed by a separate single-phase bridge inverter.

The conventional connection and the proposed connection are shown in Fig. 5.

The drawbacks of such a connection are as follows: bunlar akla

1) Increased number of switches: cost, akla
2) Conduction loss, switching loss
3) Copper loss, core loss
4) Torque ripple

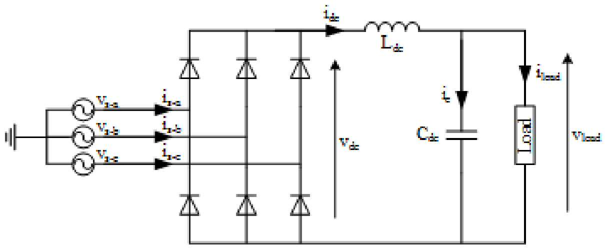

Fig. 5: Conventional connection and proposed connection

Additional advantages: bunlar akla

1) Increased modularity
2) Conduction loss, switching loss

New IMMD scheme for third harmonic injection, practical considerations

Give the block diagram and the modular structure with split windings at a separate diagram

DC linkte paralel balandn syle

Effect on torque ripple The discussion on the elimination of the harmonic when there is no third space harmonic A method can be developed to eliminate the third space harmonic

V. Results

Simulation results

Give the parameters, specifications Total output power Switching frequency Motor fundamental frequency Supply voltage, frequency Modulation index Number of modules Number of series and parallel connected modules Give the inductance capacitance, motor parameters etc.

1. The rectifier output current, the inverter input current, and DC link capacitor current at the same figure

2. DC link capacitor current in a separate figure The percent decrease of the sixth harmonic current on the DC link capacitor, percent decrease of the overall capacitor RMS current

3. The motor line currents, transistor currents The increase on the conduction losses of the switches and the copper losses of the windings

4. Current of the inverters separately, show how the sixth harmonic is created

5. Discuss the variable frequency case

6. Discuss the capacitor requirement There is no effect on the capacitance, but the RMS current rating decreases This will have no effect on film capacitors unless switching frequency is higher than 150 kHz But, the requirement on the RMS current will decrease significantly so that aluminium electrolytic capacitors can be made smaller now This will have the effects of: - Lower cost - Higher power density - Lifetime may be extended

VI. Conclusion

The conclusion goes here.

Acknowledgment

The authors would like to thank...

REFERENCES

[1] H. Kopka and P. W. Daly, *A Guide to LaTeX*, 3rd ed. Harlow, England: Addison-Wesley, 1999.