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

Mesut Uur
Department of Electrical and Electronics Engineering
Middle East Technical University
Ankara, Turkey
Email: ugurm@metu.edu.tr

Ozan Keysan
Department of Electrical and Electronics Engineering
Middle East Technical University
Ankara, Turkey
Email: keysan@metu.edu.tr

***Abstract*—In this paper, a novel method is proposed to enhance the power density of integrated modular motor drive systems by reducing passive element sizes. A method is developed to eliminate the harmonic component on the DC bus which is six times the grid frequency. 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. A size reduction of %XXX and a cost reduction of %YYY is achieved on the DC bus capacitor. The possible adverse effects of third harmonic injection method are also discussed.**

Abstract'taki saylar gncellenecek.

I. Introduction

Introduction will be here.

Introduction tumuyle eksik

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 may be reflected to the other side, disrupting its operation. 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 filter components in case of passive rectifiers.

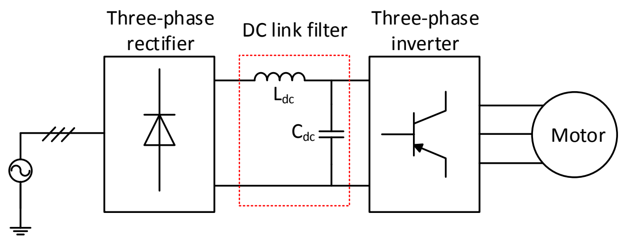

Fig. 1: A conventional motor drive system block diagram

The diode bridge rectifier is a natural-commutated converter, circuit schematic of which is shown in Fig. 8. A second order LC filter which is of low-pass type is usually utilized at the rectifier output for filtering. In this section, the harmonic content of the rectifier output voltage and the effect of filtering are shown analytically.

The supply voltages are shown in 1-3, where V_m is the RMS value of the supply voltage and f_s is the supply frequency.

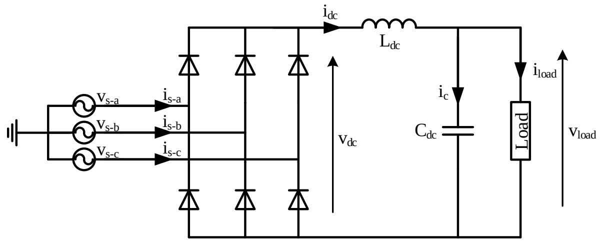

Fig. 2: Diode bridge rectifier circuit diagram

With this configuration, integer multiples of the harmonic component frequency of which is six times the grid frequency f_s are present on the rectifier output voltage in addition to the DC component as shown in 4.

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

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

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

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

The transfer function between v_{load} and v_{dc} is obtained to show the characteristics of the filter as in 5. Magnitude and phase of the harmonic components that are of interest are obtained from this model and they are later used in the implementation of the proposed method.

$$H(jw) = \frac{v_L(jw)}{v_{dc}(jw)} = \frac{R_L}{R_L(1 - w^2 L_{dc} C_{dc}) + jwL_{dc}} \tag{5}$$

A simulation is performed for the verification of these analytical models on MATLAB/Simulink, for 400V line-to-line grid voltage at 50 Hz, filter inductance of 1 mH, filter capacitance of 4 mF and load resistance of 10 Ω. In Fig. 3, the three-phase input voltages, the rectifier output voltage and the filtered load voltage waveforms are shown. In Fig. 4 and 5, the harmonic spectra of rectifier output voltage and load voltage are shown, respectively. A load voltage peak-to-peak ripple of 1% is usually aimed in case of motor drive inverter applications and the filter values are adjusted here such that a ripple of 0.9% is obtained. The inductance value is usually determined by the current ripple on this inductor and it has minor effect on the load voltage ripple. Capacitance values on the DC link are usually in a few hundred microfarad range when only high frequency fluctuations are considered, however in this case, capacitance values in milifarad range are needed.

In IMMD applications, decreasing the volume of the passive elements is a major challenge due to having small volume. Therefore, integration of the motor drive with passive rectifiers to the motor is a problem.

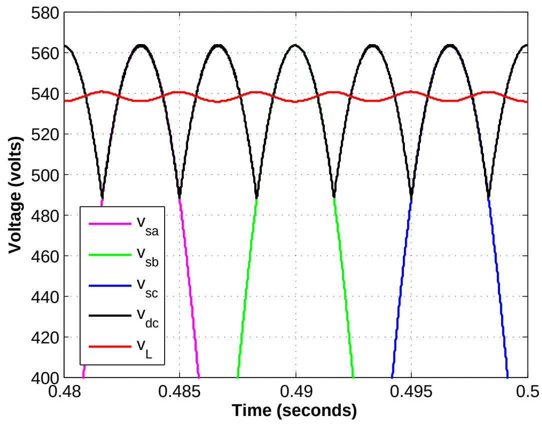

Fig. 3: Diode bridge rectifier input and output waveforms

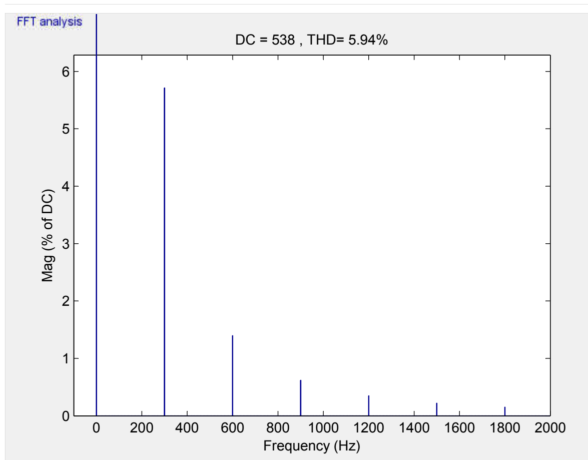

Fig. 4: Harmonic spectrum of rectifier output voltage

buraya % 30unu kaplyor gibi istatistikler gelebilir. IMMD ile ilgili olan kisim baglanacak. Harmonic spectrum lar duzenlenecek.

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, as shown in Fig. 6. 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.

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

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

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

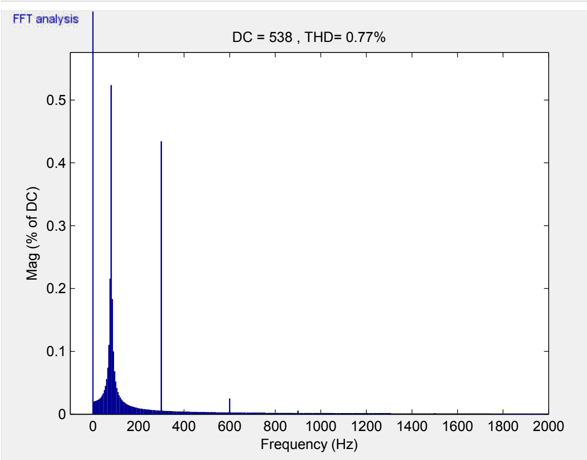

Fig. 5: Harmonic spectrum of load voltage

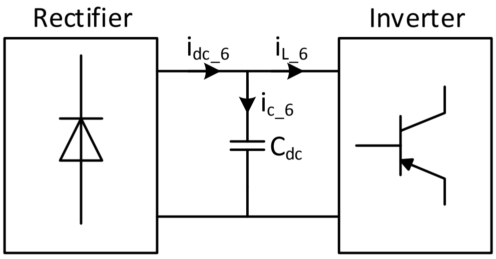

Fig. 6: The proposed method

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

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

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

Let us make the definitions shown in 12-**??**, where v denotes voltage, i denotes current, k denotes fundamental component and l denotes third harmonic component.

$$\phi_{kl-p} = \phi_{kv} + \phi_{li} \quad (12)$$

$$\phi_{kl-n} = \phi_{kv} + \phi_{li} \quad (13)$$

The instantaneous power expression for each phase are shown in 14-16.

$$\begin{aligned} p_a(t) = \frac{V_1 I_1}{2}&\Big[cos(\phi_{11n}) - cos(4\pi ft - \phi_{11p})\Big] \\ + \frac{V_1 I_3}{2}&\Big[cos(4\pi ft + \phi_{13n}) - cos(8\pi ft - \phi_{13p})\Big] \\ + \frac{V_3 I_1}{2}&\Big[cos(4\pi ft - \phi_{31n}) - cos(8\pi ft - \phi_{31p})\Big] \\ &+ \frac{V_3 I_3}{2}\Big[cos(\phi_{33n}) - cos(12\pi ft - \phi_{33p})\Big], \end{aligned} \quad (14)$$

$$\begin{aligned} p_b(t) = \frac{V_1 I_1}{2}&\Big[cos(\phi_{11n}) - cos(4\pi ft - 4\pi/3 - \phi_{11p})\Big] \\ + \frac{V_1 I_3}{2}&\Big[cos(4\pi ft + 2\pi/3 + \phi_{13n}) - cos(8\pi ft - 2\pi/3 - \phi_{13p})\Big] \\ + \frac{V_3 I_1}{2}&\Big[cos(4\pi ft + 2\pi/3 - \phi_{31n}) - cos(8\pi ft - 2\pi/3 - \phi_{31p})\Big] \\ &+ \frac{V_3 I_3}{2}\Big[cos(\phi_{33n}) - cos(12\pi ft - \phi_{33p})\Big], \end{aligned} \quad (15)$$

$$\begin{aligned} p_c(t) = \frac{V_1 I_1}{2}&\Big[cos(\phi_{11n}) - cos(4\pi ft - 8\pi/3 - \phi_{11p})\Big] \\ + \frac{V_1 I_3}{2}&\Big[cos(4\pi ft + 4\pi/3 + \phi_{13n}) - cos(8\pi ft - 4\pi/3 - \phi_{13p})\Big] \\ + \frac{V_3 I_1}{2}&\Big[cos(4\pi ft + 4\pi/3 - \phi_{31n}) - cos(8\pi ft - 4\pi/3 - \phi_{31p})\Big] \\ &+ \frac{V_3 I_3}{2}\Big[cos(\phi_{33n}) - cos(12\pi ft - \phi_{33p})\Big], \end{aligned} \quad (16)$$

The total instantaneous power becomes as in 17. 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.

$$\begin{aligned} p_{total}(t) = \frac{V_1 I_1}{2}\Big[cos(\phi_{11n})\Big] + \frac{V_3 I_3}{2}\Big[cos(\phi_{33n})\Big] \\ + \frac{V_3 I_3}{2}\Big[cos(12\pi ft - \phi_{33p})\Big] \end{aligned} \quad (17)$$

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. 8.

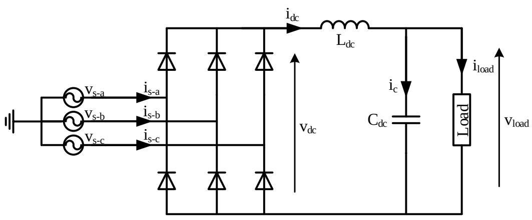

Fig. 7: IMMD scheme **cizilecek**

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. 8.

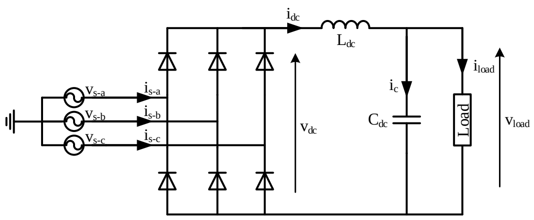

Fig. 8: Conventional connection and proposed connection **cizilecek**

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

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 are shown in Fig. 10. 2. DC link capacitor current in a separate figure, with the method and without the method are shown in Fig. 10. 3. The motor line currents, transistor currents The increase on the conduction losses of the switches and the copper losses of the windings

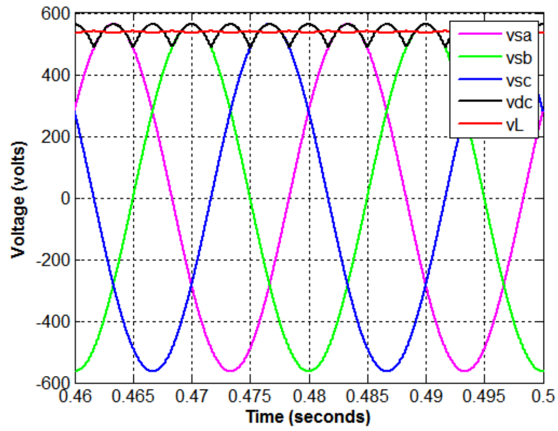

Fig. 9: The rectifier output current, the inverter input current, and DC link capacitor current **elde edilecek**

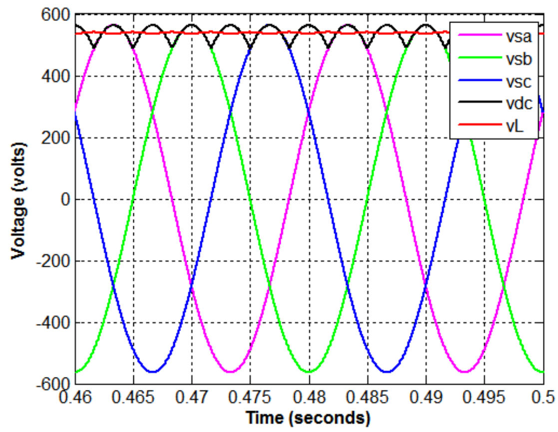

Fig. 10: DC link capacitor current in a separate figure, with the method and without the method **elde edilecek**

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

5. Discuss the variable frequency case: grid frequency and motor fundamental frequency are not the same.

6. Discuss the capacitor requirement. The percent decrease of the sixth harmonic current on the DC link capacitor, percent decrease of the overall capacitor RMS current.

7. Discuss quantitatively what it this reduction means (burada kapasitr rnekleri verilebilir)

DC bus capacitance requirement is directly related to the percent peak-to-peak voltage ripple constraint on the DC bus voltage. Therefore, application of the proposed method has no significant effect on the capacitance, however the RMS current requirement decreases significantly. Film capacitors has high RMS current ratings, but their capacitance per volume is low. On the contrary, aluminium electrolytic capacitors have low RMS current rating, but very high capacitance ratings per volume. Therefore, the proposed method will not have much effect when film capacitors are used, unless the switching frequency is higher than 150 kHz. On the other hand, overall cost and volume can be reduced significantly if aluminium electrolytic capacitors are used. 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.