Research Report

96-12

Neutral-to-Ground Voltage Minimization in a PWM-Rectifier/Inverter Configuration

A.M. De Broe, A.L. Julian, T.A. Lipo

Wisconsin Power Electronics Research Center
University of Wisconsin-Madison
Madison WI 53706-1691

Wisconsin
Electric
Machines &
Power
Electronics
Consortium

University of Wisconsin-Madison
College of Engineering
Wisconsin Power Electronics Research Center
2559D Engineering Hall
1415 Engineering Drive
Madison WI 53706-1691

NEUTRAL-TO-GROUND VOLTAGE MINIMIZATION IN A PWM-RECTIFIER/INVERTER CONFIGURATION

A.M. De Broe   A.L. Julian   T.A. Lipo

Department of Electrical & Computer Engineering
University of Wisconsin-Madison
1415 Engineering Drive
Madison, WI 53706 USA

ABSTRACT:

High frequency common mode voltage produced by power converters are a major cause of conducted EMI, creating motor ground currents, bearing currents and other harmful by-products. In this paper a control algorithm for an induction motor fed by a fully controlled rectifier and inverter is developed to reduce the common mode neutral-to-ground voltage of the induction motor. A bearing current model is used to evaluate the effects on the bearing currents of the double bridge modulation scheme when the new algorithm and conventional algorithms are used. Simulation results are shown to demonstrate the benefits of the new PWM approach.

1. INTRODUCTION

The high frequency common mode voltage produced by modern switching power converters has been recently found to cause failure modes in ac drives [1,2,3]. Since the stator windings of any machine are capacitively coupled to ground by means of the winding insulation, currents can flow to ground progressively deteriorating the insulation and causing conducted EMI ground currents. This capacitive current flows through the motor bearings and can ultimately cause their failure. In [1] the relationship between PWM switching and bearing currents has been clearly demonstrated. In general two components contribute to the bearing currents: those arising from *dv/dt* at the inverter switching instants and those which occur when the bearing-lubricant isolation breaks down, in which case the current is related to the instantaneous value (amplitude) of the neutral-to-ground voltage at the moment of breakdown. Since the destructive currents are mainly related to the isolation breakdown, it is important that the inverter and rectifier be controlled in such a manner that the neutral-to-ground voltage be minimized.

In this paper it is shown that by use of a suitable modulation strategy, the neutral-to-ground voltage of a typical PWM rectifier/inverter can be markedly reduced.

2. SPACE VECTOR MODULATION PRINCIPLES

A typical fully controlled PWM rectifier in combination with a DC voltage link and an inverter is shown in idealized fashion in Figure 1. While often not explicitly available, a DC link capacitor mid-point m is shown for convenience. It is assumed that both rectifier and inverter are space vector controlled. Eight possible switching states and corresponding voltage vectors V_k are shown in Figure 2.

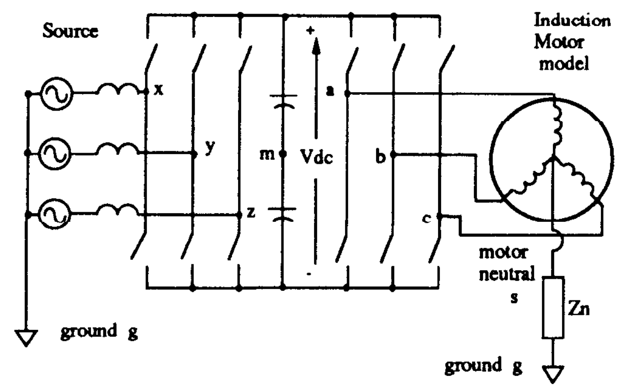

Figure 1: PWM Rectifier/PWM Inverter System

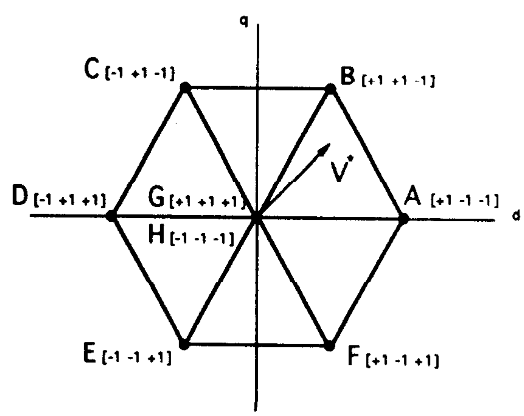

Figure 2: Possible Switching States for either Rectifier and Inverter in the *d,q* Plane

If V_k and V_{k+1} are the two active voltage vectors adjacent to the desired reference voltage vector V^*, then V^* can be synthesized by using space vector PWM by averaging the time spent on the two adjacent states, that is

$$V^* = \frac{V_k T_k + V_{k+1} T_{k+1}}{T_s} \qquad \text{(Eq.1)}$$

where T_k and T_{k+1} are the time durations spent on states k and k+1 respectively. The remainder of the switching period T_s is spent on the two zero states.

The resulting neutral-to-ground voltage is clearly dependent on the combination of the two voltage vectors selected at the rectifier and the inverter. As a first approximation it can be assumed that the three phase-currents in the induction motor sum to zero. This assumption is clearly a reasonable approximation since the current flowing through the impedance Z_n from neutral to ground is very small compared to the phase currents in the induction motor. From Figure 1, the voltage V_{sm} is then equal to the sum of the phase voltages :

$$V_{sm} = \frac{V_{am} + V_{bm} + V_{cm}}{3}$$

The voltages are all referred to the fictitious midpoint m of the DC-bus. The voltages V_{am}, V_{bm} and V_{cm} can take on values of $\pm V_{dc}/2$.

Identical reasoning for the rectifier yields a similar equation for the voltage V_{gm}

$$V_{gm} = \frac{V_{xm} + V_{ym} + V_{zm}}{3}$$

where it is assumed again that the total input current is zero.

Finally, it can therefore be determined that

$$V_{sg} = V_{sm} - V_{gm}$$
$$= \frac{V_{am} + V_{bm} + V_{cm}}{3} - \frac{V_{xm} + V_{ym} + V_{zm}}{3}$$

Hence, both the switching state of the rectifier and the inverter determine the neutral-to-ground voltage of the induction motor. Table 1 summarizes the resulting voltages for possible combinations of rectifier and inverter switching states:

TABLE 1 - Neutral-to-ground voltage V_{sg} as determined by the switching states of rectifier and inverter

Rectifier switching states	Inverter switching states: A, C, E	B, D, F	G	H
A, C, E	0	$+V_{dc}/3$	$+2V_{dc}/3$	$-V_{dc}/3$
B, D, F	$-V_{dc}/3$	0	$+V_{dc}/3$	$-2V_{dc}/3$
G	$-2V_{dc}/3$	$-V_{dc}/3$	0	$-V_{dc}$
H	$+V_{dc}/3$	$+2V_{dc}/3$	$+V_{dc}$	0

It can be seen from Table 1 that the neutral-to-ground voltage of the induction motor can be as high as the total DC-link voltage when the opposite two zero states are selected by both the rectifier and inverter at the same instant.

3. CHOICE OF PWM SWITCHING SEQUENCE

In general, the control algorithm of the rectifier can be implemented for control of the input power factor, the DC voltage, the input currents or a combination of these requirements. The control of the inverter usually strives to generate phase currents in the induction motor with the least ripple and with a minimal harmonic content. The space vector control algorithm exemplified by Eq. 1 will synthesize a reference voltage vector V^* and then calculate the on-times for the adjacent voltage vectors. However, a degree of freedom remains in selecting the switching order of the different voltage vectors. In particular, any sequence that dwells the appropriate time on the two adjacent active voltage vectors and the remaining time of the switching period on one or both of the zero-voltage vectors will fulfill the requirements of the space vector algorithm and will synthesize the same reference voltage vector.

In this study, a switching sequence which serves to center the space vector pulses as shown in Figure 3 was selected because of its desirable properties in minimizing harmonics, current ripple and switching losses [4] (AB and BA pulses are centered in Ts/2). Centering the active space vectors causes an effective doubling in the switching frequency and a decrease in the switching frequency harmonics, compared to simple regular sampled PWM. This centering strategy also achieves an increase in modulation depth, known to be possible with third harmonic injection and space vector modulation techniques, by better allowing each half carrier period to be fully utilized over the fundamental output cycle.

The placement of the active pulses within the carrier period also determines the current ripple component. If the two voltage pulses can be spaced equidistantly apart, the effective switching frequency of the line-to-line voltage is double that of the phase leg switching frequency and thus the current ripple reduces accordingly [4].

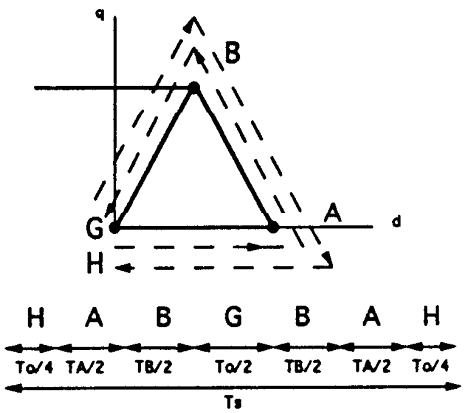

Figure 3: Symmetrical switching sequence pattern in the first 60° sector

4. MINIMIZATION OF THE NEUTRAL-TO-GROUND VOLTAGE

In order to minimize common mode voltage, the symmetrical switching sequence of Figure 3 can now be applied to both the rectifier and the inverter in a coordinated fashion. When the switching sequences of the rectifier and inverter are both synchronized to the centerpoint of the time-intervals Ts, their zero-voltage vector centerpoints coincide. An algorithm can then be developed to prevent the switching to different zero-voltage vectors in the inverter and rectifier at the same time. As a result the neutral-to-ground voltage of the induction motor always remains zero whenever both the rectifier and inverter select zero states and thus will never reach the value of V_{dc} and can be limited to $2V_{dc}/3$. Referring to Table 1, it is apparent that switching states combinations G-H and H-G are therefore inhibited.

To minimize the neutral-to-ground voltage the switching sequence of the active voltage-vectors must be reversed each time the reference voltage enters another sector. Table 2 summarizes the desirable switching sequences in each of the six different sectors defined by Figure 1. Table 1 reveals that selection of active voltage-vectors A, C and E in both the rectifier and inverter will yield a zero value of the neutral-to-ground voltage. The same is true for the voltage-vectors B, D and F. For example, referring to Table 2, if the reference voltage of the rectifier is in sector 1 and that of the inverter is in sector 2, switching states A and C have the possibility to overlap thereby causing a zero neutral-to-ground voltage to occur. One restriction that clearly applies is that the switching frequency of rectifier and inverter must be the same and synchronous to each other. Another limitation is that the current control capabilities of both the inverter and rectifier will be somewhat limited by the adoption of adjacent-state switching [5].

TABLE 2-Switching sequences in the different sectors

Sector	Switching Sequence
1st Sector (0°-60°)	H-A-B-G-B-A-H
2nd Sector (60°-120°)	H-C-B-G-B-C-H
3rd Sector (120°-180°)	H-C-D-G-D-C-H
4th Sector (180°-240°)	H-E-D-G-D-E-H
5th Sector (240°-300°)	H-E-F-G-F-E-H
6th Sector (300°-0°)	H-A-F-G-F-A-H

To illustrate the benefits that can be obtained by the new PWM switching algorithm, the system of Figure 1 has been simulated in the ACSL programming language. Parameters of the induction motor model and rectifier- and inverter-switching frequencies are given in the appendix. Figure 4 shows the neutral-to-ground voltage, V_{sg}, of the induction motor for the two different cases. The upper trace shows V_{sg} when the switching sequences in the rectifier and inverter are synchronized. The lower trace shows V_{sg} when the rectifier and inverter are switched at different frequencies and thus their switching sequences are not synchronized. It was determined that the rms value of V_{sg} decreased from 88 V to 35 V when applying the proposed switching algorithm which suggests a corresponding reduction in isolation breakdown ground currents.

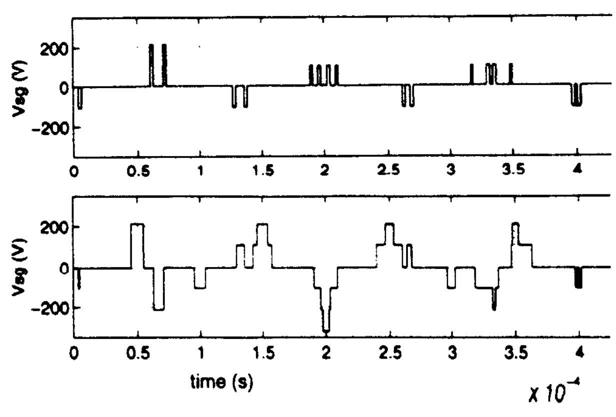

Figure 4: V_{sg} with switching sequences in rectifier and inverter synchronized (upper trace) and unsynchronized (lower trace)

5. EFFECT OF MINIMIZATION OF NEUTRAL-TO-GROUND VOLTAGE ON BEARING CURRENTS

The production of bearing currents by common mode voltages has recently been shown to be mainly a result of parasitic capacitive coupling between the stator windings and the rotor. In [2] a bearing current model is developed where the coupling path consists of a series inductance, resistance and capacitance (L', R', C'). The bearings are modeled as a switch with a certain internal inductance and resistance (Lb, R_b) (Fig. 5). Identification of the parameters of the bearing current model is based on the experimental measurements of the shaft voltage V_{shaft}, corresponding to the voltage across the bearings, and bearing current I_{brg} in response to the common mode excitation V_{sg}. The parameters used in the simulation are given in the appendix. In this model the switch is randomly opened and closed, modeling the sudden short circuit behavior which may be caused by lubricant film breakdown or ball and race contact [1].

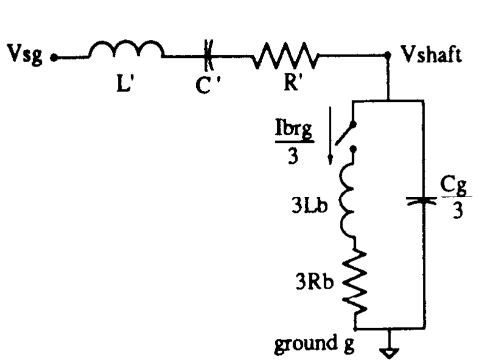

Figure 5: Bearing Current Model

In the simulation study the resulting neutral-to-ground voltage of the induction motor for a given PWM algorithm is calculated and applied as input voltage in the bearing current model based on the measured parameters of [1] and [2].

Figure 6 shows the neutral-to-ground voltage V_{sg} of the induction motor, the shaft voltage V_{shaft} and the bearing current I_{brg} when the switching algorithm of section 4 is applied. As predicted the voltage V_{sg} is limited to $2V_{dc}/3$ and this maximum value occurs infrequently. The rms value of the bearing current is calculated as 16 mA. As a comparison the same plots are made in a situation where the switching frequencies of rectifier and inverter are different and the algorithm independent (Fig. 7). The neutral-to-ground voltage now reaches its maximum value of V_{dc}; the rms value of the bearing current is 19 mA. It can be seen that the shaft voltage V_{shaft} does not charge up as high in the case of the synchronized switching sequence since V_{shaft} essentially follows V_{sg}. As a result the current spike in I_{brg} at the instant of discharge due to bearing film breakdown is substantially lower (note the different scale for the two bearing current plots).

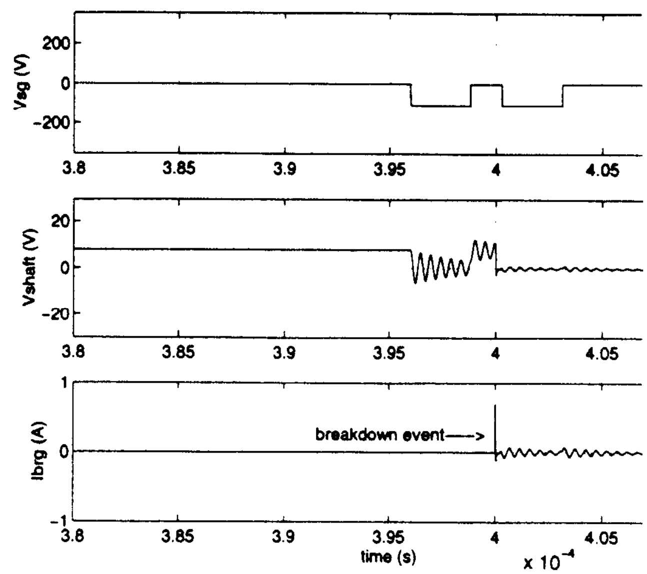

Figure 6: Common mode voltage, shaft voltage and bearing current (synchronized)

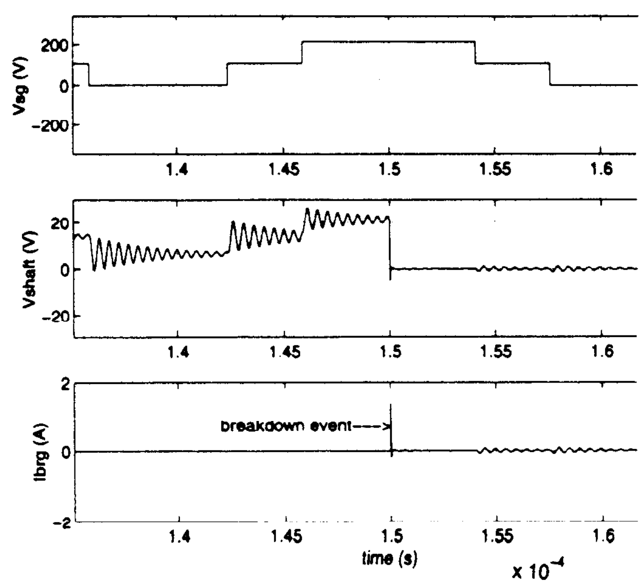

Figure 7: Common mode voltage, shaft voltage and bearing current (unsynchronized)

6. CONCLUSIONS

A proposed space vector algorithm for pulse width modulating the rectifier and inverter of an AC drive incorporates a switching sequence which minimizes the neutral-to-ground voltage of the motor stator winding. This algorithm reduces the amplitude of the bearing currents and serves to minimize other harmful effects such as conducted EMI and motor ground currents. Nonetheless, the basic pulse centering approach, previously reported in the literature as optimal in so far as current ripple, harmonics and switching losses are concerned [4], remains unchanged. Hence, the PWM approach illustrated in this paper preserves the beneficial properties of space vector PWM while minimizing its detrimental effects.

7. REFERENCES

[1] S. Chen , T. A. Lipo and D. Fitzgerald, "Measurement and Analysis of Induction Motor Bearing Currents in PWM Inverter Drives", IEEE PES Summer Meeting, July 24-27, 1995 (to appear in IEEE Trans. on Energy Conversion).

[2] S. Chen, T. A. Lipo, D. Fitzgerald, "Modeling of Motor Bearing Currents in PWM Inverter Drives", IEEE IAS Annual Meeting, Oct. 8-12, 1995, pp. 388-393.

[3] J. Erdman, R.J. Kerkman, D. Schegel, G. Skibinski, "Effect of PWM Inverters on AC Motor Bearing Currents and Shaft Voltages", APEC '95, March 5-9, 1995, vol. 1, pp. 24-33.

[4] D.G. Holmes, The Significance of Zero Space Vector Placement for Carrier Based PWM Schemes , IEEE-IAS 1995 Conference Record, pp. 2451-2458.

[5] A. Nabae, S. Ogasawara and H. Akagi, "A Novel Control Scheme for Current-Controlled PWEM Inverters", IEEE Trans. on Ind. Appl., vol. IA-22, no. 4, pp. 697-701, July/August 1986.

APPENDIX : SIMULATION MODEL PARAMETERS

Induction Motor Parameters:

R_s=0.4346 Ω	L_s=2.002 mH
R_r=0.8153 Ω	L_r=2.002 mH
L_m=69.3 mH	N_p=2

Rectifier Switching Frequency=7.5 kHz
Inverter Switching Frequency=7.5 kHz (when synchronized)
=10 kHz (when unsynchronized)

Bearing Currents Model Parameters:

L =300 μH	C =20 pF	R =200 Ω
L_b=150 nH	C_g=800 pF	R_b=15 Ω