Methods for Minimizing Overvoltages and Electromagnetic Interference Effects in PWM Inverters - An Overview

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Abstract - This paper presents the principal methods discussed in the literature to minimize the coupling currents, the main cause of overvoltages and electromagnetic interference (EMI) problems that occur in PWM IGBT inverters, widely employed in AC induction motor drives. It is stressed that, by reducing the coupling currents, a decrease in overvoltages and EMI effects induced by inverters is achieved. The viewpoints of inverter design, induction motor structure modifications, as well as techniques applicable to the AC source and motor cable are discussed.

I. INTRODUCTION

The continuous increase in inverter application for motor drives in industrial areas, and the likelihood that they will soon find applications in residential use as well, poses a challenge to circumvent the interference problems that occurs with several communication equipment, electronic sensors, and other sensitive apparatus [6], [7] and [8]. It is now known that modern PWM inverters that utilizes fast IGBTs produce transient currents in induction motors whose frequencies lie in the MHz range, in addition to the more familiar carrier frequency related harmonics, typically in the lower kHz range [9], [10] and [12].

Parasitic capacitances occur in all drive system components, but those associated with the motor are of particular interest. In fact, the dominant capacitance is the stator winding-ground (or frame) capacitance (C_{sg}). The stator winding-rotor capacitance (C_{sr}) is much smaller, but of greater relevance, since it is directly related to the build-up of shaft voltage to ground (V_{rg}). When V_{rg} achieves the breakdown value of the bearing lubricating film, it causes a current discharge that has been identified as the source of mechanical damage that leads to bearing premature failure.

The undesired effects are caused by high voltage rate (dv/dt) imposed by fast IGBT switching, that excites the parasitic capacitances. In contrast to carrier frequency harmonics, the coupling currents are present only during the transitions (turn-on and turn-off), and circulate through the cable, motor windings, and inverter parasitic capacitances [11] and [13].

The switching states of a inverter bridge induce a voltage potential relative to a common reference, such as the negative DC bus. This voltage (V_{no}) is defined as common mode voltage, and is responsible for the generation of the currents between machine winding and ground, that are named common mode currents. These currents can overload the inverter, and are a source of EMI. For a Y connected motor, the neutral voltage with respect to the negative DC bus can be computed from the phase voltages with respect to the DC bus (V_{ao}, V_{bo}, and V_{co}) as:

$$\mathbf{V_{no} = (V_{ao} + V_{bo} + V_{co})/3} \quad \mathbf{(1)}$$

Other problems associated with the coupling currents include the reduction in insulation system life, in addition to the overvoltages and EMI effects already mentioned. It has been reported that traditionally, the solutions attempted by drives users and manufactures to prevent bearing failure includes: insulating the bearings, use of conductive grease, or the addition of slip rings connected to the shaft, and brushes, in order to provide a grounding path for the coupling currents [14] and [15]. All of them attain some degree of success, but also possess drawbacks. Bearing insulation results in a higher thermal resistance, leading to higher bearing and rotor temperature. Conductive grease is obtained by the inclusion of metallic particles in the grease, what increases abrasion and leads to a moderate reduction in bearing life. The brush and ring contact impedance is not so small, for the particular high frequency coupling currents, and do not completely prevents the flow of currents though the bearings.

The modern methods to minimize the damaging effects will be emphasize here, and consists in one of the following strategies: to reduce the parasitic capacitances between stator and ground, to provide paths for the coupling currents so that they are kept inside the inverter, and to cancel or reduce the common mode voltage generated by the switching states of the inverter.

II. METHODS FOR REDUCING THE EFFECTS OF OVERVOLTAGE AND EMI

II.1. Reducing the coupling currents – Electrostatic Shielded Induction Motor

The switching process of the PWM IGBT

inverters excite the parasitic capacitance existing between the stator and rotor motor winding and ground, as

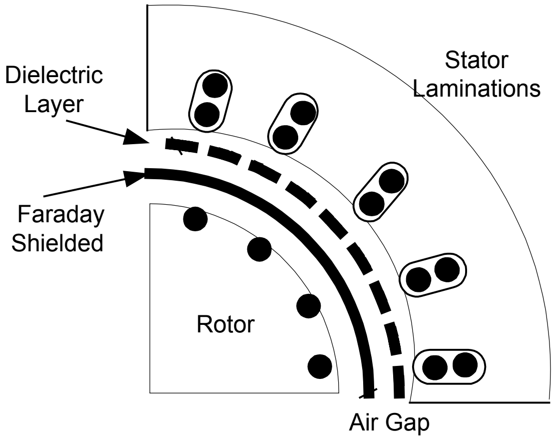

Fig. 1: ESIM construction using conductive tape or spray [2] .

previously discussed. The coupling currents are composed of common mode and differential mode currents. The paths of circulation define the type of interference, in particular when the AC source and the ground conductor are included in this path.

Proposed in [1], the Electrostatic Shielded Induction Motor (ESIM) utilizes a Faraday shield inserted into the air gap of a motor without short circuiting the stator laminations. The purpose is to decrease the capacitance between stator and rotor. The shielded construction techniques is composed of copper surface areas that collect and attenuate the electrostatically coupled voltage to ground. The different construction methods of the ESIM is show bellow [1]:

- Copper Foil Tape – a Faraday shield is construct, as show in Figure 1, installing copper foil tape and forming a continuous copper surface between the stator and rotor. The stator end windings were lined with copper foil tape and connected to ground.
- Copper Foil Tape on the Slot Stick Covers. – The shield is constructed using copper foil tape built into the slot stick covers, as show in Figure 2. The copper foils on each slot stick cover were single-point-connected to ground.
- Conductive Copper Paint Applied to the Stator Length – The Faraday shield is construct by spraying a conductive copper paint to the entire length of the stator, including end windings, and single-point-connected to ground. Before applying the conductive paint, an insulating varnish or insulation are applied to the stator laminations and end winding surface area. The shielded was evaluated through various tests and configuration, with load and no-load to analyze the effectiveness for shielding, thermal and electromechanical [1-2]. The copper foil tape shield reduced the rotor-ground voltage V_{rg} to about 5 to 10% of the value acquired without the Faraday shield. This demonstrates the universality of the ESIM as a solution to the electrostatic shaft voltage and bearing current problems [1]. The ESIM has a 29 to 1 reduction in dv/dt current and eliminates the discharge current when compared to a standard machine.

To examine the effectiveness of ESIM, tests were performed using typical system components and applications. Table 1 shows the reduction in the rotor voltage, dv/dt current, and discharge currents to motor stator shielded and motor stator with winding ends shielded in comparison to a standard 15 hp motor [2].

TABLE I:
EFFECTIVENESS OF ELECTROSTATIC SHIELDED INDUCTION MOTOR, VOLTAGE AND CURRENT COMPARISON [2].

Test Motor	Rotor Voltage (peak)	dv/dt Current (peak)	Discharge Current (peak)
Standard Machine	40 V	500 mA	3.5 A
ESIM with copper tape on the stator length	18 V	18 mA	None
ESIM with copper tape on stator and end winding	2.2 V	17 mA	None

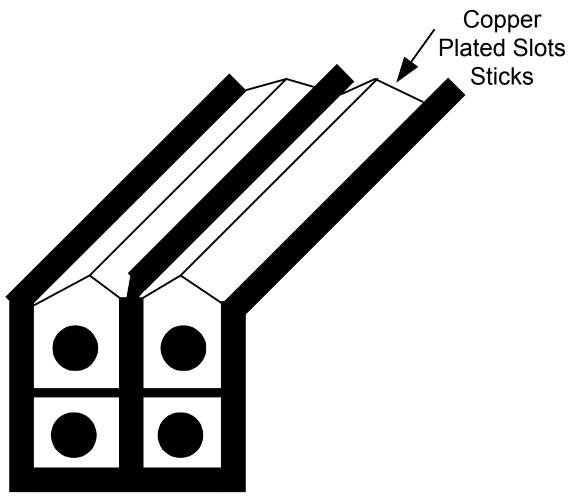

Fig. 2: ESIM construction using conductive slot stick covers [**2**].

II.2. Common mode voltage canceling or attenuation techniques

A totally different approach consists in eliminating or minimizing the origin of the problem, namely the common mode voltage V_{in}. To this end, three distinct circuits are next discussed, and shown in figures 3, 4 and 7.

Fig. 3 shows a cancellation method [3], where the common mode voltage is obtained from the inverter output by utilizing a RC network. This voltage is applied to the primary winding of a transformer, whose thee secondary windings are connected in series with the motor cable, between the inverter and the motor. The secondary common mode voltage is added to the inverter output voltage with apposite polarity, in order to cancel its common mode voltage. By properly selecting the turn ratio, the canceling of the motor-ground common mode voltage is achieved. As a consequence, the bearing currents, the shaft voltages, and the coupling currents can be reduced to a minimum value, thus eliminating the harmful effects on both the machine and the network. A disadvantage of this method is the additional losses in the RC network.

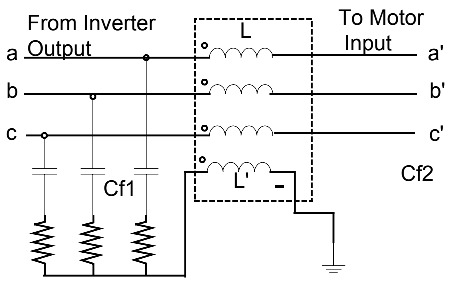

Fig. 3: R-C network and a three-phase common mode choke with a fourth winding [3].

Fig 4(a) illustrates a rectifier-inverter topology, where the rectifier is also PWM controlled. A special modulation algorithm is employed for both rectifier and inverter, such that at any given time, it is prevented that the three uppers switches in the inverter are "on", and simultaneously the three lower switches in the rectifier are also on". In such situation the machine neutral voltage with respect to ground world be the maximum value V_{dc}, i.e., the dc bus voltage.

Fig. 4(b) shows the voltage vectors associated with the PWM switching states, including the six active states (A to F) and the two "zero" states (G and H). The neutral to ground voltages obtainable from the switching states of rectifier and inverter are shown in Table 2. By preventing the zero states to occur simultaneously in the inverter and rectifier, it is possible to limit the neutral to ground voltage to 2/3 V_{dc}. As a consequence, the magnitude of the coupling currents is also reduced, minimizing the harmful effects on bearing currents and EMI problems [4]. Its worth saying that this method exhibits a limitation in current regulation.

TABLE 2:
NEUTRAL-TO-GROUND VOLTAGE 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

Figure 5 shows the neutral-ground voltage V_{sg} of the induction motor, the shaft voltage V_{shaft} and the bearing current I_{brg} when the switching algorithm proposed is applied. 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. 6). As a result, the current spike in I_{brg} at the instant of discharge due to bearing film breakdown is substantially lower in the synchronized case.

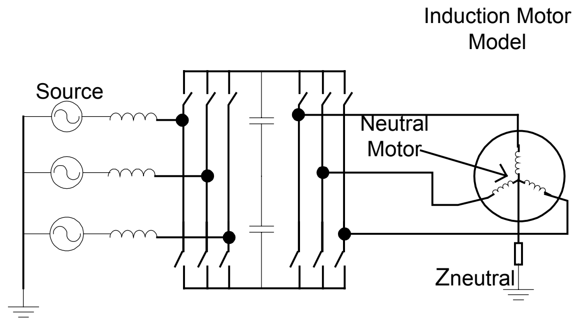

Fig. 4(a): PWM bridge topology for both Rectifier and Inverter [4].

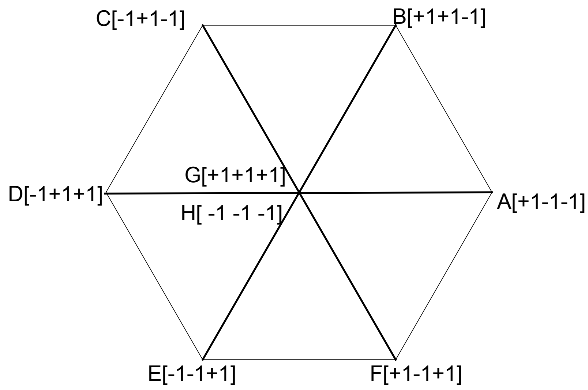

Fig. 4(b): Switching states of rectifier and inverter.

Fig. 7 shows an inverter topology where a fourth leg is added to the structure, with the objective of eliminating the common mode currents [5]. A modification in the modulation strategy can be implemented to obtain a zero neutral voltage at all times. The necessary condition to achieve this goal is to have $V_1+V_2+V_3+V_4=0$. Experimental measurements [5] demonstrated that this topology yields a reduction in the common mode voltage by a factor of five, when compared to a conventional three-leg inverter. However, due to the presence of energy storage elements, resonance problems were observed. The modulation index is also limited to 0.66.

A totally different solution was proposed in [6]. Figure 8 shows a topology where the inverter stage is implemented by two distinct bridges, enabling two independent circuits to feed the motor, while preserving essentially the same gate drive circuit.

This inverter is used to supply twelve terminal induction motors, that can be connected as show in Fig. 9,

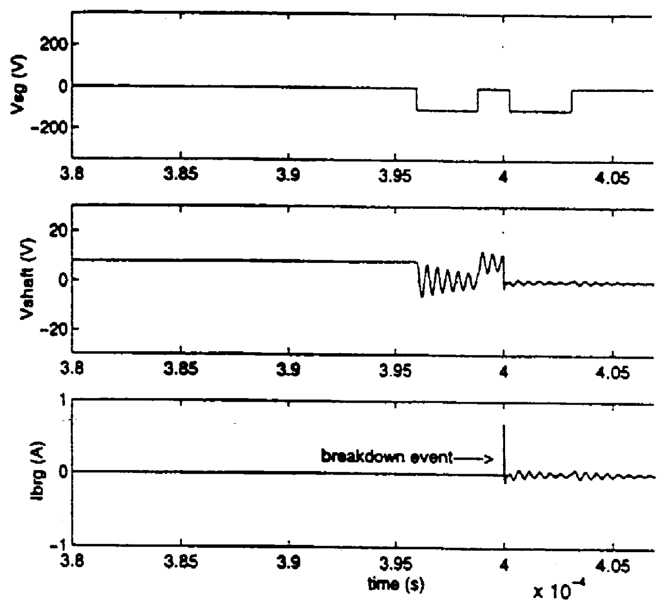

Fig. 5: Commom mode voltage, shaft voltage and bearing current (synchrononized) [4].

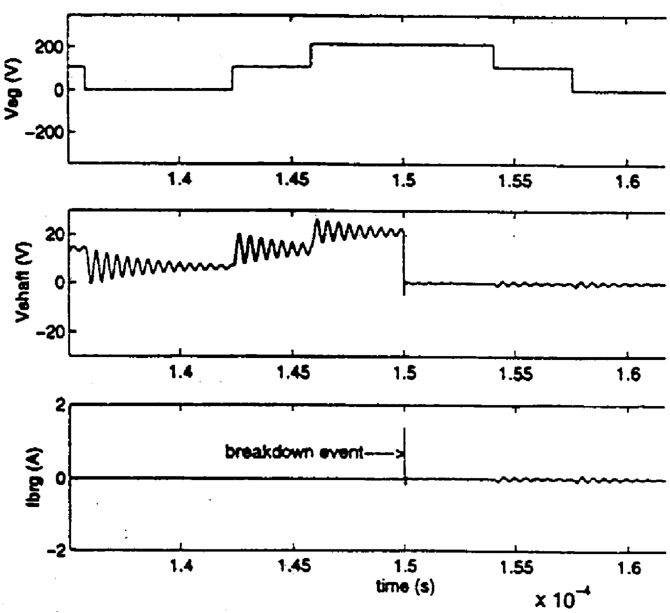

Fig. 6: Commom mode voltage, shaft voltage and bearing current (unsynchrononized) [4].

where two windings of the same phase are parallel connected, with the same polarity point together. To use the double bridge inverter, the windings of the motor must be connect as shown in Fig. 10. The double bridge topology utilizes three-phase bridges, so that the six IGBTs signal commands of the second bridge are inverted in sequence when compared to the first one. By this way, the currents circulates in opposite direction on same phase winding as show in Fig. 8, but the flux will be produced in the same direction because of inversion in the winding polarity. So, the magnetic fields are added resulting the complete magnetization, while the electric fields are cancelled, and the coupling capacitance greatly reduced. However, the electric field will be canceled and the capacitive effect will be virtually eliminated, resulting in a full torque without the common mode voltage [6]. The electrostatic coupling between the rotor shaft and case will be avoided without the common mode voltage.

This topology is applied to 460V rated voltage motors, with twelve terminals externally available. When it

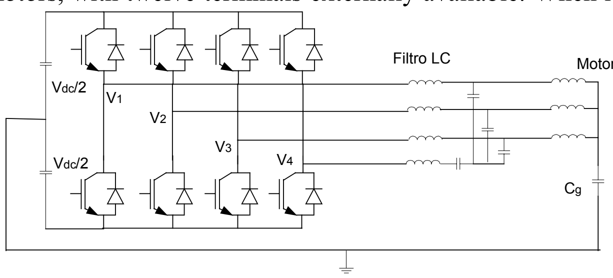

Fig. 7: Four leg inverter with second order filter and motor load.

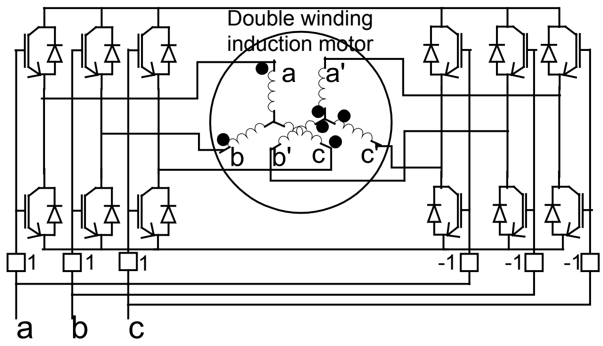

Fig. 8: Proposed PWM dual-bridge inverter drive. [6]

is not permissible, the connections could be redone, what do not represents a high cost. Experimental results shows a significant reduction in leakage currents, shaft voltage and bearing currents.

III. CONCLUSION

News techniques have been proposed and tested, as discussed in the literature, based on changes in inverter topologies and their operation, such as the use four winding transformer, the control of switching sequence, the inverter fourth leg, the double bridge inverter topology. These changes improve the performance of the drive system, decrease the common mode voltage and consequently the common mode current.

It is important to mention that changes in motor structure can be done to make it immune to capacitive coupling currents, and bearing currents. Among these techniques, the electrostatic shield which utilizes the

Faraday shield principle, decreases the capacitances between rotor and stator. A large reduction in rotor to ground voltage is reached, and consequently a decrease in the currents produced by dv/dt is obtained, when compared to conventional induction motors. The knowledge of such techniques is very important to those involved in the design and application of modern drive systems.

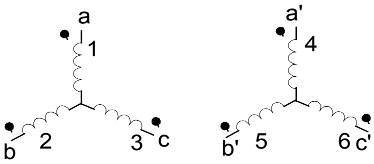

Fig. 9: Winding connection for a conventional dual-voltage motor [6].

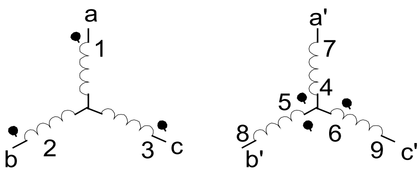

Fig. 10: Winding connection for the motor driven by the proposed dual bridge-inverter [6].

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