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Leakage Current and Common Mode Voltage Issues in Modern AC Drive Systems

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Abstract-- Due to rapid developments of IGBT technology, switching time and frequency are dramatically increased. At higher carrier frequencies, IGBTs induce more capacitive coupled current into a rotor and a stator frame and lead to faster bearing damage. Common mode voltage enables motor to create shaft voltage through electrostatic couplings between the rotor and the stator windings and between the rotor and the frame, and it can caused bearing currents when the shaft voltage exceeds a breakdown voltage level of the bearing grease. Also, high frequency leakage current occurs through stray capacitors between stator winding and the motor frame due to a high rate of the common mode dv/dt at motor terminals which can produce induced shaft voltage. Conducted and radiated Electromagnetic Interference (EMI) emissions are major problems in recent motor drives that produce undesirable effects on electronic devices. In modern power electronic systems, increasing power density and decreasing cost and size of system are market requirements. Switching losses, Harmonics and EMI are the key factors which should be considered at the beginning stage of a design to optimize a drive system. In most of power electronic designs, EMI issues have not been taken into account as one of the main factors; and mitigation techniques for EMI are considered at the last stage of design. This paper also presents a relationship between these three factors and how a motor drive system can be optimised when EMI is taken into consideration with respect to leakage current, shaft voltage and bearing current.

***Index Terms*— Active filters, Bearing current, Common mode, EMI, Leakage current, Motor drive, Shaft voltage,**

INTRODUCTION

Nowadays, more than 60 percent of the world's energy is used to drive electric motors. Regarding to growing requirements of speed control, pulse width modulated inverters are used in adjustable speed drives. As shown in Fig.1, modern power electronic drives consist of a filter, a rectifier, a dc link capacitor, an inverter and an AC motor. Many small capacitive couplings exist in the motor drive systems which may be neglected in low frequency analysis but the conditions are completely different in high frequencies. In higher switching frequencies, a low impedance path is created for current to flow through these capacitors. Fig.2 shows the capacitive couplings of an induction motor and a view of stator slot, where C_{WR} is the capacitive coupling between the stator winding and rotor, C_{WS} is the capacitive coupling between the stator winding and stator, C_{SR} is the capacitive coupling between the rotor and stator frame. In a three phase power inverter, a DC voltage is converted to three phase voltages with 120^0 phase shift. Fig.3 shows a three phase voltage source inverter with a typical phase and neutral point voltages which is not zero and it is called common mode voltage.

Trend in increasing switching frequency improves the quality of current waveforms in motor drive systems but due to short switching time, a high dv/dt is produced across the motor terminal. Fig.4 shows an example of effects of high dv/dt and resultant leakage current. The leakage current is created by a high voltage stress during switching time.

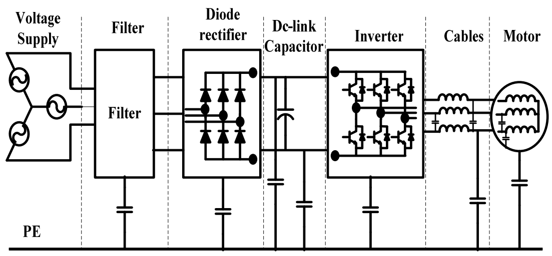

Fig.1. a power electronic motor drive system with capacitive couplings

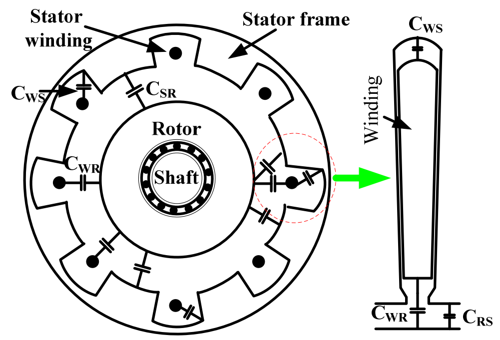

Fig.2. capacitance coupling in an induction motor and a view of stator slot

According to Fig.3, the output voltages of a power converter (V_a, V_b, V_c) are not the phase voltages. The load phase voltages and a common mode voltage (V_n) can be derived based on the power converter voltages. Each leg voltage of a three phase inverter is:

$$V_a=V_{an}+V_n \quad V_b=V_{bn}+V_n \quad V_c=V_{cn}+V_n \qquad (1)$$

And then:

$$V_a+V_b+V_c=(V_{an}+V_{bn}+V_{cn})+3V_n \qquad (2)$$

It is clear that:

$$V_{an}+V_{bn}+V_{cn}=0 \qquad (3)$$

So, the common mode voltage can be calculated as:

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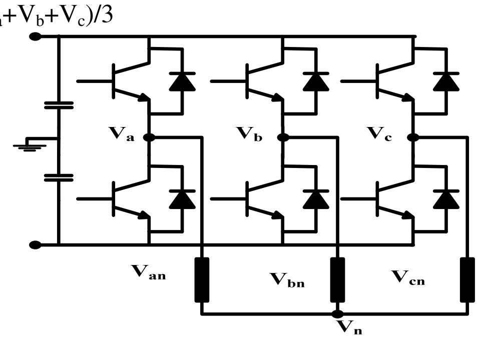
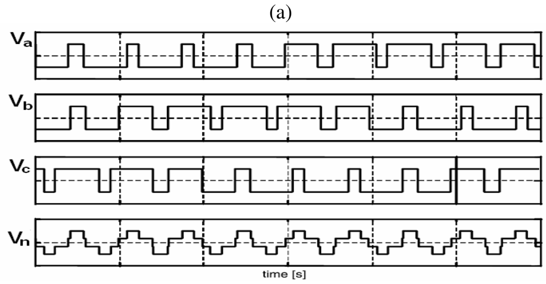
$V_n=(V_a+V_b+V_c)/3$ (4)



(a)



(b)

Fig.3. (a) three phase voltage source inverter (b) common mode voltage generation

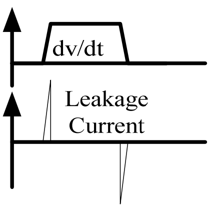


Fig.4. a typical example of high dv/dt and resultant leakage current

It can be analysed that high dv/dt and common mode voltage generated by PWM inverter in high frequency applications can causes some unwanted problems such as:

•Grounding current escaping to earth through stray capacitors inside a motor

•Shaft voltage and resultant bearing currents

•Conductive and radiated noises

•Motor terminal over voltages

I. SHAFT VOLTAGE AND BEARING CURRENTS

As discussed, a common mode voltage is present on the output of a three phase inverter. This voltage and fast switching transients (high dv/dt) may cause bearing currents in the motor. Another mechanism that causes bearing current is asymmetry in motor. Shaft currents can cause damages in rotating machinery such as: frosting, spark tracks at the surface of balls and races, pitting, welding [2]. Four potential sources of shaft voltage are: electromagnetic, electrostatic, external voltages supplied to the rotor windings, magnetic dissymmetry in an electrical winding. Fig.5 shows damages on the bearing.

Shaft voltage on an asynchronous motor is influenced by various factors such as:

•The design of the motor

•The capacitive couplings between stator windings and the rotor and between the rotor and the metal frame

•The configuration of the main supply

•Potential on the shaft voltage

•Voltage transient on the motor terminal

•The position of zero vectors in PWM pattern

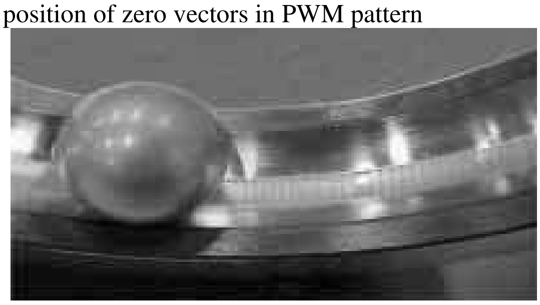


Fig.5. damages on the bearing (source: ABB technical guide)

A. Several types of bearing currents

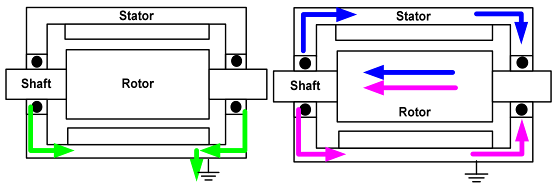
Bearing currents can be classified as following terms:

•Capacitive discharge current: it is related to a capacitive shaft voltage resulted by a high frequency common mode voltage between parasitic capacitances in the motor. If capacitive shaft voltage exceeds a critical bearing threshold voltage required to break down the insulating grease thin film, the charge accumulated in a rotor assembly is then unloaded through the bearing in the form of a discharging current (see Fig.6.a)

The following two types of bearing currents are related to interaction of common mode voltage with high dv/dt and the capacitance between stator winding and motor frame.

•Shaft grounding current: The common-mode voltage can also cause an increase in the stator frame voltage if the grounding is not satisfactory. The increase in motor frame voltage is seen from bearings. If this voltage exceeds the breakdown voltage of thin oil film, part of the current may flow through bearings.

•High frequency circulating bearing currents: high frequency common mode current forms a circular time varying magnetic flux caused around motor shaft. This flux is caused by a net asymmetry of capacitive current leaking from the winding into the stator frame along the stator circumference [98]. This flux induces a voltage which circulates the stator, rotor, and bearings. As shown in Fig.6.b, if proposed voltage exceeds the breakdown voltage of thin oil film, a circular high frequency current will be formed in motor bearings. This kind of shaft voltage is occurred in large motors.



(a) (b)

Fig.6. (a) capacitive discharge current (b) high frequency circulating bearing currents

B. Modelling

A per ball model of bearing is presented in [8], [15] (see Fig.7). This model consists of an inner and outer race resistance (R_{in} and R_{out}) in series with oil film capacitances ($C_{ball,i}$) from outer and inner races to ball and ball resistance($R_{ball,i}$). These series elements are then in parallel with a capacitance from the outer to inner races and a nonlinear element, which functions to randomly short the bearing outer and inner races replicating the balls penetrating the film layer.

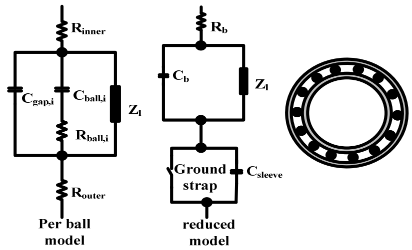


Fig.7.Motor bearing model

Models of parasitic couplings and high frequency components for an inverter fed induction motor drive system are investigated in [11-29] to determine suitable models to predict bearing currents and shaft voltage over a wide frequency range. Related issues to bearing currents in a doubly fed induction generator are presented in [20].

C. Bearing current reduction methods

Following methods are suggested in literature to mitigate bearing currents and shaft voltage [2-29]:

•Improve high frequency grounding connection from the motor to the drive and from the motor to the driven equipment [17]

•Install a grounded metallic foil tape to cover the stator slot and the end turns of the winding [2] [17] [21-22]

•Using a conductive grease to provide a lower impedance path through the bearing lubricant preventing excessive voltage build-up on the shaft [2] [3] [9] [21-22] [17]

•Insulate both motor and load bearing [2-3] [9] [21-22] [17]

•Establishing a low resistance current path to ground bypassing the bearings (shaft grounding brush) [2] [22] [17]

•Adding a common mode filter [2] [21-22] [17]

•Changing the cable to the proper installation type [2] [21-23]

•Use a potential transformer or coupling L-C filter [3] [21-22]

•Inserting a Faraday shield in to the air gap of a motor using a conductive copper surface to collect and attenuate the electrostatically coupled voltage to ground [3] [9] [21-22] [17]. There are several methods to shield the air-gap such as:

A. Copper Foil Tape

B. Copper Foil Tape on the Slot Stick Covers

C. Conductive copper paint applied to the stator

•Using R-L-C output filters or output line reactors [9] [21-22]

•Reduce drive input voltages [2][9] [21-22] [17]

•Hybrid ceramic bearing [9] [21-22] [17]

•Bearing insulation sleeve [9] [21-22] [17]

•Using shielded cable [21-22] [17]

•Common mode chokes between the PWM inverter and the induction motor [21-22]

•Dual bridge inverter to generate balanced excitation of the induction motor [22]

•Lowering of PWM frequency [2] [3] [9] [21-23]

•Use of an embedded circular comb-like coil in the stator slots to provide capacitance between the stator winding and the grounded coil and at the same time capacitance between the rotor shaft and the grounded coil . It provides a low impedance path for the high frequency common mode noise. Then, the peak voltage over the bearing capacitance will be reduced.

•Eliminate or reduce motor neutral voltage by redesigning common mode circuitry:

A novel space vector PWM strategy to reduce bearing currents in doubly fed induction generators in variable speed wind turbine applications is investigated in [27].

II. COMMON MODE CURRENT MITIGATION TECHNIQUES

A. PWM-based

Common mode currents must be eliminated in order to increase reliability and electromagnetic compatibility of electric drives. Several methods to mitigate common mode current are suggested in literature based on using active and passive circuit in inverter output. Several papers are presented pulse width modulation strategies to attenuate common mode voltage generating by zero switching vectors. By using of a suitable switching scheme, it is possible to control the fluctuation of common mode voltage in order to reduce the common mode current.

Space vector pulse width modulation strategy without zero vectors (states) is used in [30-32] which allows open loop voltage control and mitigation of common mode voltage by PWM modulation when the load is capacitive coupled to ground.

Random Pulse Width Modulation technique distributes the spectrum contents of load current without affecting the fundamental component and it may reduce the acoustic noise and mechanical vibration and electromagnetic interference of an inverter-fed induction motor drive when the amplitude of harmonics around side bands is decreased. [32] Involves switching patterns of random SVM techniques for common mode voltage mitigation.

Approaches to eliminate common mode voltages of multilevel inverters are presented in [49-52]. Two sinusoidal and space vector pulse width modulation techniques are discussed and applied to a three-level inverter. A simple closed loop hysteresis controller is used to balance the dc link capacitor voltages [52].

B. Active and Passive EMI Filters

Active EMI filters based on current injection is a proper solution to cancel the common mode high frequency currents. Fig.8 shows a block diagram of an active EMI filter and common mode transducer.

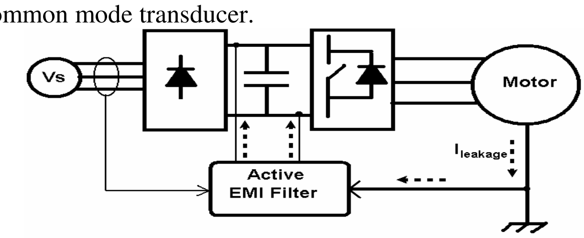


Fig.8 an active EMI filter

A survey of output filter topologies to minimize impact of PWM inverter fed induction motor is proposed in [53]. An active common mode noise canceller is presented in [35-36].
Proposed method is composed of an emitter follower using complementary transistors and a common mode transformer. An improved inverter output filter configuration to reduce both differential mode and common mode dv/dt at motor

terminals with one filter topology is suggested in [39] which consist of a three-phase RLC network. The filter star point is electrically connected to the dc-link midpoint. [39] presents a new common mode sinusoidal inverter output filter with variable inductances to achieve motor friendly performance of the PWM voltage source inverter. A passive common mode current attenuation technique for use with PWM drives is presented in [33].

A novel passive filter installed at PWM inverter output terminals is proposed in [44],[47] with an objective of eliminating the common-mode and differential-mode voltage generated by PWM inverter simultaneously. The proposed filter consists of three inductors, three capacitors, one resistor and a common-mode transformer. [45] Has extended the work of [36],[44],[47] by using a CM transformer with active circuitry using separate dc power supply for transistors. [48] Introduce a new passive filter consists of a common mode transformer and a conventional RLC filter. An active filter technique is presented in [54] to mitigate adverse effects of PWM inverter fed ac drives and reduce the size of EMI filter. Proposed common mode noise canceller is composed of a push-pull type emitter follower circuit using two complementary transistors, a common-mode transformer, three impedances for common-mode voltage detection, and two dc voltage sources, three capacitors, inductor, and resistor. Also passive EMI filter for proposed drive system tested and designed in [55-58]. Design and analysis of a current injection type active EMI filter for switching noise of high frequency inverters is described in [60]. It consists of two complementary transistors as active elements and a common mode current transformer. In [61] filter designing techniques are presented and compared with conventional LPF in order to analyse their effect on reducing EMI emissions.

III. Conducted and radiated EMI emissions

Conducted and radiated Electromagnetic interference emissions is a major problem with recent motor drives that produces undesirable effects on electronic devices such as AM radio receivers, medical equipments, communication systems and cause malfunctions and non-operations in control systems. A review on noise sources in electric machines and their mitigation techniques has proposed in [71]. [63] Provides a common understanding of the EMI issues such as generation of EMI, EMI modelling, mitigation of EMI, EMI coupling techniques and EMI standards and test method. According to [63] the various paths by which the noise frequency spectrum defined is coupled in to signals and equipment are:

- Conducted CM current inducing CM ground
- Critical distance vs. CM rise time
- CM current capacitive coupled to interface power
- Noisy shielded ground
- Noisy source ground
- Conducted CM current and radiated emissions
- Noise coupling paths in a drive system

[64-66],[73],[81],[90-93] Suggest several methods to measure and suppress conducted radio noise emissions. A comparison between EMI sources of a sinusoidal PWM hard and soft switching techniques were carried out in [67]. [85] Focuses on the review of conducted EMI modeling and filter design methods for inverter fed motor drive systems. Time domain and frequency domain models of differential and common mode conducted electromagnetic emission prediction for an induction motor drive system are presented in [69-70]. A comparative analysis between the standard PWM and a chaos-based PWM for DC/AC converters for electric drives is investigated in [72]. [75] Proposed a procedure to diagnosis the induction motor to predict the EMI. It is based on determining the resonance peaks of high frequency measurements. It can also, a filtering scheme slowing the removal of EMI from the data when the high frequency data affected by environmental EMI. In [77],[94] inverter switching related noises and switching characterization of the power MOSFET and its body diode reverse recovery characterization are evaluated for circuit modelling through simulation and measurements. The parasitic components and common mode path are identified and measured with the time-domain reflectometry method. A frequency domain approach to the prediction of differential mode (DM) conducted electromagnetic interference for a three-phase inverter is described in [84]. A mathematical model for the prediction of conducted EMI based on analytical disturbance-sources and propagation paths to estimate the common mode and differential mode is pointed out in [86]. [92] Identifies different noise modes for different front end diode rectifier conducting patterns based on the study of CM and DM propagation characteristics of diode front converter [93].

IV. Conclusiones

In this paper several aspects of high frequency related issues of modern AC motor drive system are such as common mode voltage, shaft voltage and resultant bearing current, leakage currents, modelling of the system have been discussed based on the literature. Conducted and radiated Electromagnetic Interference (EMI) emissions are major problems in recent motor drives that produce undesirable effects on electronic devices.

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