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Circulating Type Motor Bearing Current in Inverter Drives

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Abstract **- Motor bearing currents in inverter drives have become an important issue as very fast turn-off switching devices have become available for medium horsepower applications (10-100 HP). In previous work a non-circulating type of bearing current caused by parasitic capacitive coupling from stator windings to the rotor was identified. In this paper a new circulating inductive type of bearing current is reported. A theory for the existence of this new type of bearing currents in inverter-motor drives is proposed. It identifies the fact that unbalanced currents flow in the two coil sides of a motor winding due to distribution of capacitive coupling currents. The current unbalance produces a high frequency magnetic flux surrounding the motor shaft and thus causes a bearing current to circulate in the conductive loop formed by the stator case, rotor shaft and end bearings. The amplitude of the circulating bearing current depends on the common mode component of capacitive coupling currents. The analysis is verified by experimental measurement of bearing currents. The findings also provide insight to determining solutions for attenuating these destructive bearing currents.**

I. INTRODUCTION

PWM inverters have been associated with the generation of induction motor bearing currents and thus bearing damage in recent studies [1-4]. The high dv/dt common mode voltage excitation and the parasitic coupling capacitance in a drive system were found to account for the generation of these bearing currents. Based on a theory proposed in references [3,4], a small portion of common mode currents flow from the windings through parasitic capacitors to the rotor and then find their paths via the conductive bearings to the grounded motor case. Therefore, a type of bearing currents is recognized as the sum of those common mode currents which flow from the windings to the rotor, which is characterized by unidirectional, or non-circulating, flow from the rotor iron via bearings to the stator iron.

A new type of bearing current which can not be explained by the above theory has also been observed lately [6]. In contrast to the previous case, this type of bearing current circulates in a conductive loop formed by the motor stator case, rotor shaft and both end bearings. Its amplitude depends on all common mode currents including those flowing from the windings to both the stator and the rotor. Although both circulating and non-circulating types of bearing currents are attributed to common mode coupling currents, the circulating type bearing current is not simply the same as the common mode currents. It is actually induced by a high frequency flux produced by common mode currents which links the stator, rotor and bearing loop and hence is an inductive rather than capacitive effect.

To facilitate understanding of the difference between the two types of bearing currents, a review of the previous non-circulating type of bearing current theory is given. A brief introduction to the concept of coupling current in drive systems follows. This paper then proposes an explanation to the generation of a circulating type of bearing currents in inverter drives. An experiment has also been carried out to verify the analysis. The results provide new insights to solutions of bearing current problems in motor drives.

II. REVIEW OF NON-CIRCULATING TYPE BEARING CURRENT [4]

A simplified inverter-motor system with only phase 'a' winding 'a-N' shown is depicted in Fig. 1. The capacitance C_{ws} represents the per unit length parasitic capacitance from the winding to the stator and C_{wr} the value from the winding to the rotor. Voltage V_{ao} is the common mode voltage relative to the negative DC bus 'O' at motor phase 'a' input terminal which is defined as the voltage across the phase 'a' terminal and the negative rail of the inverter DC bus. Impedance Z_{in} is the common mode voltage internal impedance which usually consists of parasitic capacitance from the negative DC bus to the earth. The quantity C_g is the capacitance present across the bearings corresponding mainly to the motor air gap capacitance. A bearing current I_{brg} can then be easily identified as the sum of common mode currents flowing into all C_{wr}'s since it has to flow through bearings to the grounded stator iron. Although only the phase 'a' winding 'a-N' is shown in the figure, by similarity, common mode voltages V_{bo} and V_{co} of phases 'b' and 'c' also contribute to the bearing current I_{brg}.

As can be seen based on the above theory, this type of bearing currents is simply the sum of common mode currents to the rotor and it can only flow unidirectional from the windings to the rotor and then pass through bearings to the grounded stator. Due to this characteristic, it can be termed as non-circulating type bearing current.

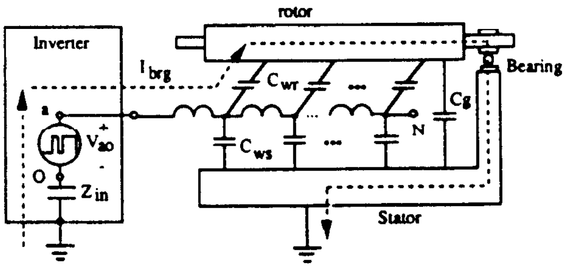


Figure 1. Non-Circulating Type Bearing Current

III. CONCEPT OF COUPLING CURRENT

To facilitate understanding of circulating type bearing currents, the concept of parasitic capacitive coupling current in drive systems will be briefly introduced. As is discussed, in a high dv/dt inverter drive, the lumped parameter circuit model of an induction motor can no longer be used to study such issues as bearing currents, surge voltage and electromagnetic interference (EMI). In particular, parasitic capacitance from the motor winding to the stator and the rotor must be taken into account.

To illustrate the concept of coupling current, consider only the parasitic capacitance between a phase winding and the stator iron. By motor symmetry it is reasonable to assume a uniform distribution of the parasitic capacitance along the phase winding conductor. A transmission line model as shown in Fig. 2 can then be used to describe the phenomenon based on results derived from [5]. In this model, Z represents the per unit length serial impedance of the phase winding which is motor parameter and operating condition dependent. The quantity C is the per unit length coupling capacitance from the phase winding to the stator, and the ground represents that the stator case is always connected to the earth.

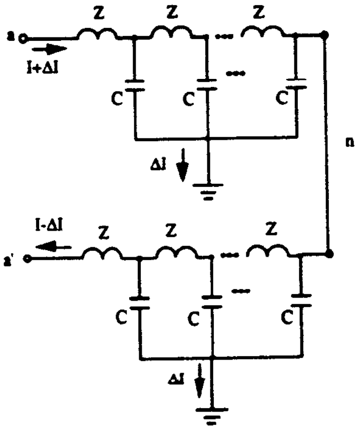


Figure 2. Distributed Circuit Model of A Motor Phase Winding

It can be seen that, due to the parasitic capacitances from the phase winding to the stator, a new type of current exists in the phase winding which flows into all parasitic capacitors. This current is different from the conventional fundamental and harmonic components. The sum of all currents in the parasitic capacitors is thus formally identified and defined for the first time as the coupling current in reference [6]. Therefore, based on the above simplified example, it is easy to see that the current in a motor winding of any drive systems will consist of not only the well-known fundamental plus harmonic component, I, but also those of the parasitic capacitors, or ΔI's.

In general, capacitive coupling is omnipresent between the winding and the stator and rotor, between the coils, as well as between the phases. Analysis in reference [6] shows that the coupling current in a three-phase system can always be decomposed into two components: the common mode and the differential mode. The differential mode coupling current flows between phases, while the common mode coupling current flows from phases to the earth ground. In a drive system, the common mode coupling current is physically present as the grounding (or leakage) current in the system. It can be divided into two different categories: the current from the winding to the rotor which is the source of the non-circulating type bearing current, and the current from the winding to the stator which is actually the main contributor of the motor and/or inverter grounding current.

Introduction of the concept of coupling current has also become invaluable for explanation of other unresolved issues such as EMI and voltage surge in drive systems. Although only the common mode component of a coupling current is able to be related to bearing currents, both common mode and differential mode components are found to be responsible for EMI emissions in a drive system. A further analysis of EMI mechanism in a drive system can be referred to reference [6].

IV. CIRCULATING TYPE BEARING CURRENT

By analyzing the means by which coupling currents flow in motor windings, a mechanism of circulating type bearing current generation can be proposed. The influence of parasitic coupling capacitance on winding current distribution in the space can be analyzed based on a single coil representation of the motor winding as shown in Fig. 3. Without loss of generality, a current can be assumed to be uniformly distributed in the plane perpendicular to the path of flow. Only the distribution along its direction of flow will be considered. Due to the parasitic capacitance, the current into the coil never equals that out of the same coil. This phenomenon can be described by a model which assumes that a current equal to I+ΔI flows into the terminal "a" while a current equal to I-ΔI flows out of the terminal "a' " of the coil. In other words, 'I' represents the fundamental component and the harmonics which passes through the whole coil, while ΔI's will be the coupling current which includes both common mode and differential mode components. Since the coupling current flows in parasitic capacitors, its distribution along the coil will vary spatially in the axial direction.

To simplify the analysis, it is assumed that the parasitic capacitance is uniformly distributed along the Y axis only, corresponding to the motor shaft axial direction. The current distribution in the coil becomes a function of Y as illustrated by Figs. 3 and 4, assuming a coil height equal to H. Therefore, it is evident that there is a current unbalance between the two coil sides or motor windings due to parasitic coupling even though the degree of unbalance varies spatially.

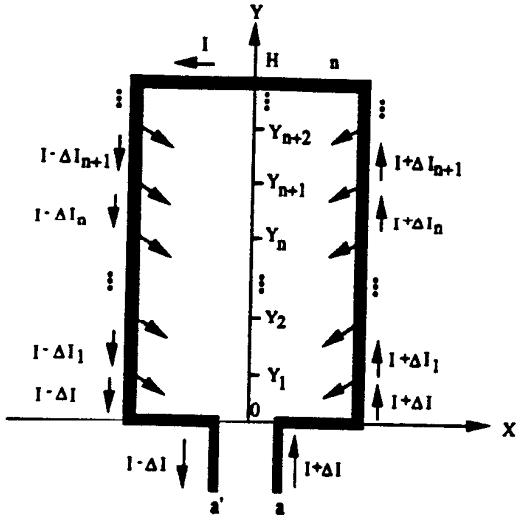


Figure 3. Flow of Current in Coil a-n-a'

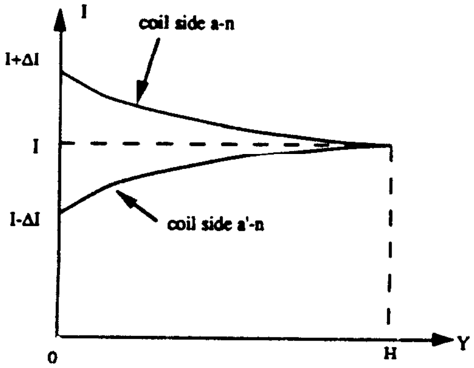


Figure 4. Current Distribution in Coil a-n-a'

For a simplified three-phase motor model with only three coils, it is instructive to take a cross section of the motor at location Y_n which is equivalent to a cylindrical section of the motor in the Y direction with a infinite small height from Y_n to Y_{n+1} as is shown in Fig. 5. The unbalanced currents at Y_n in the three phase windings are assumed to equal to $2\Delta I_{an}$, $2\Delta I_{bn}$ and $2\Delta I_{cn}$ respectively. By taking a Gauss surface ϕ inside the stator case which encloses all three phase windings as shown in the figure, the enclosed current will equal to

$$\begin{aligned} \Sigma I &= [(I_{an}+\Delta I_{an})-(I_{an}-\Delta I_{an})]+ \\ &\quad [(I_{bn}+\Delta I_{bn})-(I_{bn}-\Delta I_{bn})+ \\ &\quad [(I_{cn}+\Delta I_{cn})-(I_{cn}-I_{cn})] \\ &= 2\Delta I_{an}+2\Delta I_{bn}+2\Delta I_{cn} \qquad (1) \end{aligned}$$

As is known, the coupling currents ΔI_{an}, ΔI_{bn} and ΔI_{cn} contain both common mode and differential components. Although, just like the fundamental plus harmonics components, the three-phase differential mode coupling current components add to zero whereas the common mode components do not. Hence, there is a net current in the stator winding flowing axially. so that by Gauss' Law, there must thereby exist a net flux linkage surrounding the motor shaft existing primarily in the stator core. In other words, a flux produced by common mode coupling currents always links the closed-loop formed by the stator case, motor shaft and end bearings. Since common mode currents are pulses of very high frequency in a drive system, an EMF will be induced inside this loop, and a pulsating current will circulate as shown in Fig. 6 if the impedance of the loop is small.

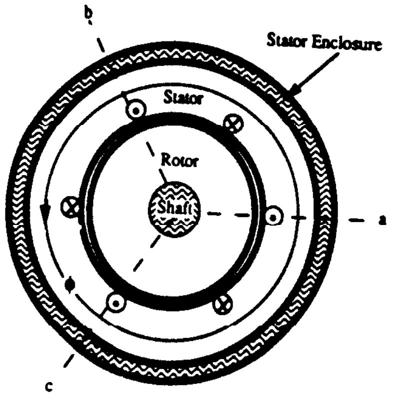


Figure 5. Flux Linkage Enclosing The Shaft of A Three-Phase Motor

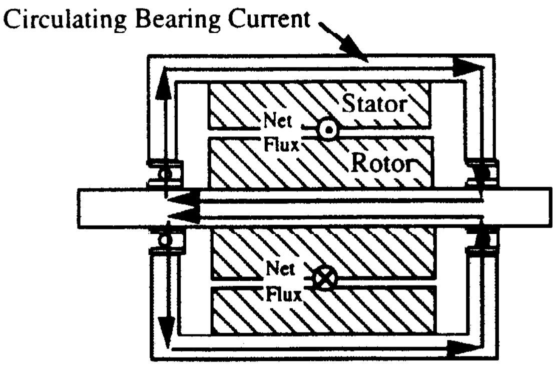


Figure 6. Path of Circulating Bearing Current

V. EXPERIMENTAL VERIFICATIONS

Experiments have been performed on several induction motors to verify the above theoretical analysis. The test motor is a 230 V, 3 HP three-phase induction motor with its bearings insulated from the stator. By connecting two wires A and B from the stator case through brushes to both ends of the shaft as shown in Fig. 7, the circulating bearing current can be detected by simply attaching a current probe to each wire. The terminals G_M, G' and G" are all grounding points on the stator case. The total common mode current I_{com} of the drive system which flows into the earth ground is measured by a probe enclosing all three motor input wires. The inverter uses a sinusoidal PWM modulation with a switching frequency of 15 KHz.

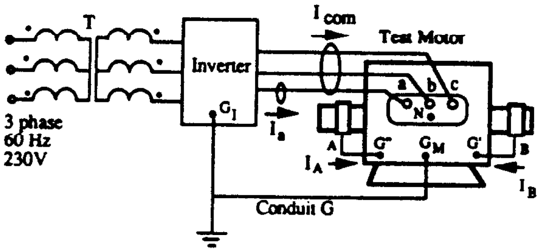
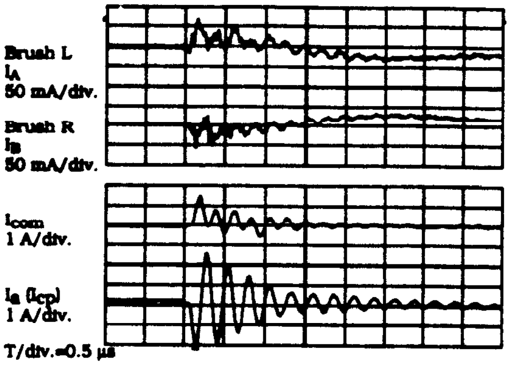
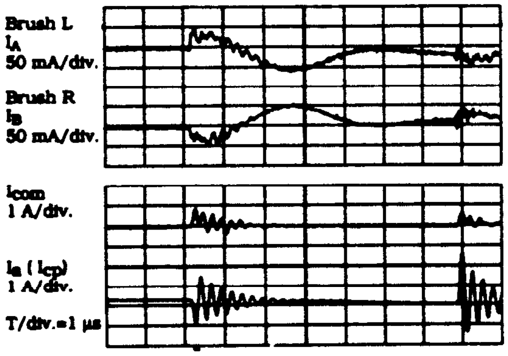


Figure 7. Test Setup for Circulating Type Bearing Current

The circulating bearing current is recorded as shown in Fig. 8. The current in brush wires A and B are labeled as I_A and I_B respectively. It is observed that there are three frequency components in I_A and I_B. The first component is a very small current ripple with the highest frequency of about 12 MHz which can be seen clearly in a relatively small time scale as that of Fig. 8a. The ripple can be identified as the non-circulating bearing current or, specifically, the conduction mode bearing current as defined in references [4, 5]. The second component is another current ripple with a frequency of about 4 MHz and a peak-to-peak amplitude of about 50 mA which can be recognized easily because its frequency is close to that of the common mode current I_{com}. The third component is a slow damping current with an amplitude of about 100 mA and a frequency of about 230 KHz. This damping component can be clearly observed in the relatively large time scale of Fig. 8b. Based on the definition of probe current directions, it is seen that the 4 MHz components in I_A and I_B are 180 degrees out of phase as well as the 230 KHz components. Therefore, the 4 MHz and 230 KHz components constitute the circulating bearing current.



a) With a time scale of 0.5μs/div., the highest frequency is identified as conduction mode bearing current



b) Showing a whole low frequency damping cycle

Figure. 8 Measured Circulating Bearing/ Brush Current

The EMF causing the circulating current is also observable by using the test setup shown in Fig. 9. The measured shaft voltage V_{shaft} together with other important reference signals is plotted in Fig. 10. In this figure, current I_B in the shorted brush shows a short burst of high frequency current at about 12 MHz corresponding to each PWM switching instant. Based on the theory of the non-circulating bearing current, this 12 MHz frequency current is expected because the non-circulating bearing currents all flow into brush wire B. The shaft voltage V_{shaft} contains the back EMF voltage in the loop. The 4 MHz and 230 KHz components similar to that of the circulating current are seen to be present in the shaft voltage waveform. These two components are clearly the EMF associated with the circulating current. The maximum peak amplitude of the back EMF is measured to be about 100 mV. However, a 12 MHz component is also present in the voltage waveform. Theoretically, the short-circuit from the right end of the shaft to the stator should have made this voltage disappear. However, with a high frequency signal at 12 MHz, the brush apparently can not provide an sufficiently small impedance between the stator and the rotor. Thus, it is reasonable to observe this 12 MHz frequency in the voltage signal.

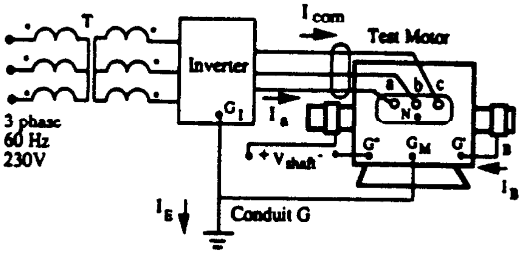


Figure 9. Setup for Measurement of the Voltage (EMF) Behind the Circulating Current

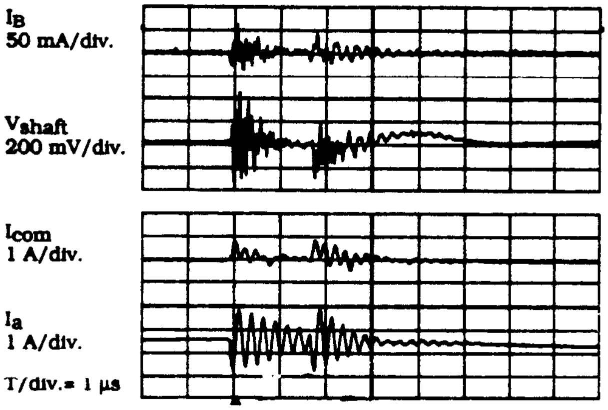


Figure 10. Measured Voltage(EMF) Behind the Circulating Current

Finally, it is should be pointed out that the current in the shorted brush wire B also contains a 4 MHz component as does that of the EMF or V_{shaft}. This is can be explained by the fact that the open-circuit of left brush can not prevent the loop from being closed by parasitic capacitances especially the air-gap capacitor which is present across the open shaft end. Therefore, the 4 MHz EMF component can still pass through the air-gap capacitor and produce a small circulating current in the right hand brush, while the 230 KHz EMF component is apparently more difficult to pass through the air-gap capacitor due to the small capacitance so that almost no 230 KHz current can be seen.

In conclusion, the experiments verify that a substantial circulating bearing current will be produced if both ends of the motor shaft are connected to the stator case by low impedance paths, such as the two end bearings with low impedances. Therefore, one solution to this problem can be easily implemented by insulating one or both bearings to the stator. Since an effective solution to the non-circulating type bearing current requires a short-circuit from the stator to the rotor using a brush, it is obvious that an optimal solution to both circulating and non-circulating bearing currents is to use one brush connecting one end of the shaft to the stator and, at the same time, insulate the bearing which locates on the other end of the shaft.

VI. CONCLUSIONS

This paper propose a theory for the existence of a new type of circulating bearing currents in inverter-motor drives. It identifies that unbalanced current flow in motor windings due to parasitic capacitance to ground and adjacent turns becomes a significant factor in today's high dv/dt IGBT inverters. A component of bearing current is found to circulate in a conductive loop formed by stator case, rotor shaft and end bearings. The circulating bearing current results from a high frequency flux produced by common mode currents. The analysis is verified by experimental measurement of bearing current. The findings also provide additional insight to the problems imposed by bearing currents in ac motor drives.

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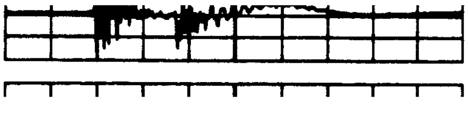
200 mV/div.



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