Circulating Type Motor Bearing Current in Inverter Drives

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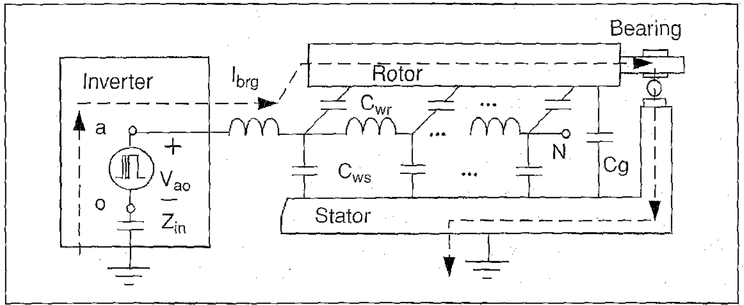

Fig. 1. Non-circulating type bearing current.

Pulse width modulated (PWM) inverters have been associated with induction motor bearing currents and thus bearing damage in recent studies [1-4]. The high dv/dt common mode voltages and parasitic capacitances in a drive system were found to account for the generation of motor shaft voltages and bearing currents. Based on a theory proposed in references [3, 4], the common mode voltages excite the parasitic capacitances of a drive system and produce the so-called common mode currents. A small portion of the common mode currents flows from the windings through parasitic capacitors to the rotor and then finds its path via the conductive bearings back to the grounded motor case. Therefore, a type of bearing current is recognized as being related to those common mode currents that flow from the windings to the rotor. Since this type of current passes through the bearings unidirectionally from the rotor iron to the stator iron, rather than circulating in the conductive loop formed by the stator case, rotor shaft, and bearings, it is termed the non-circulating type of bearing current.

A new type of bearing current that cannot 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 the 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 bearing currents of both circulating and non-circulating types can be simply attributed to common mode coupling currents, the generation of circulating type currents is a far more intricate process, which involves not only capacitive coupling but also inductive coupling or magnetic induction. In fact, the circulating type currents are related to an important characteristic inherent in coupling currents: the high-frequency capacitive coupling currents are always spatially distributed along a conductor. This characteristic states that currents in the two coil sides of a phase winding will never be equal. With unbalanced currents in the winding, a net flux with a high frequency will be produced surrounding the motor shaft. It is this flux that links the conductive loop formed by the stator case, rotor shaft, and bearings and induces the circulating currents.

The circulating-type bearing currents reported in this article are different in nature from those discovered about a century ago [7, 8]. Even before the invention of inverter drives, it was found that magnetic dissymmetries in electric machines can cause a net flux enclosing the motor shaft. This net flux induces a back EMF and causes a current to circulate in the conductive loop formed by the stator case, motor shaft, and bearings. Since this classical bearing current is related only to magnetic unbalance in motor magnetic circuitry, it can easily be distinguished from the inverter-induced circulating bearing current, even though they do share cer-

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The non-circulating type of bearing current includes the air-gap capacitor related discharge mode current and the dv/dt related conduction mode current.

tain similarity. To focus on the inverter-related bearing currents, throughout this article, it is assumed that dissymmetries in the motor magnetic circuit are negligible.

To facilitate understanding of the differences between the two types of inverter-induced 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 article then proposes an explanation to the generation of a circulating type of bearing current in inverter drives. The theory is backed up by experimental measurement of bearing currents. Finally, a solution to these bearing currents of both circulating and non-circulating types is also proposed.

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 phase winding to the stator and C_{wr} the value from the winding to the rotor. Voltage V_{ao} is the common mode voltage at motor phase "a" input terminal relative to the negative dc bus "O." It 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 total capacitance present across the bearings, corresponding mainly to the motor air-gap capacitance (may include bearing capacitance). In particular, if the bearings exhibit intermittent conductivity, the currents in C_{wr}'s will temporarily accumulate charges in the air-gap capacitor during the period when bearings are not conductive. The air-gap capacitor will then discharge to the bearings and produce a current spike, called the discharge mode bearing current, at the moment when the bearings suddenly resume conductivity. If the bearings exhibit continuous conductivity such that the air-gap capacitor is short-circuited, currents in C_{wr}'s will immediately pass through the bearings and become the dv/dt related conduction mode bearing currents. Nevertheless, the common mode currents flowing into the rotor will eventually find their paths through the bearings and create a bearing current I_{brg}. 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}. Based on this theory, the non-circulating type of bearing current includes the air-gap capacitor related discharge mode current and the dv/dt related conduction mode current.

Concept of Coupling Current

To facilitate understanding of the circulating-type bearing current, the concept of parasitic capacitive coupling current in drive systems will be briefly

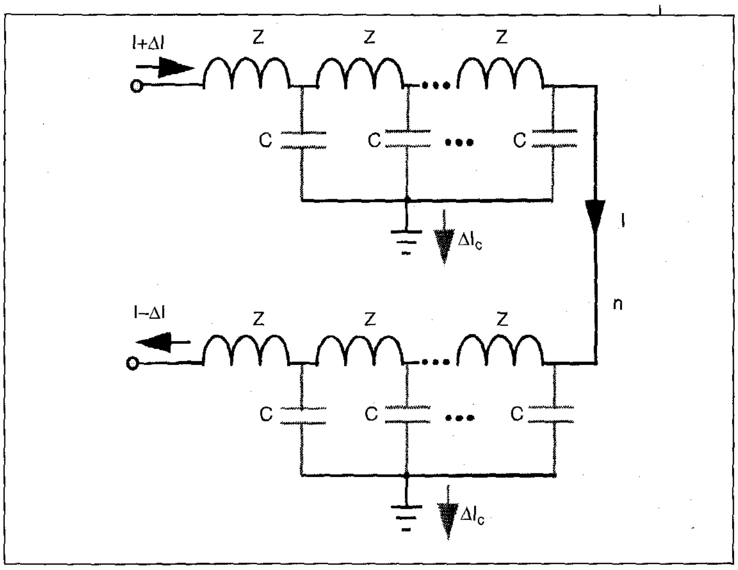

Fig. 2. Distributed circuit model of a motor phase winding.

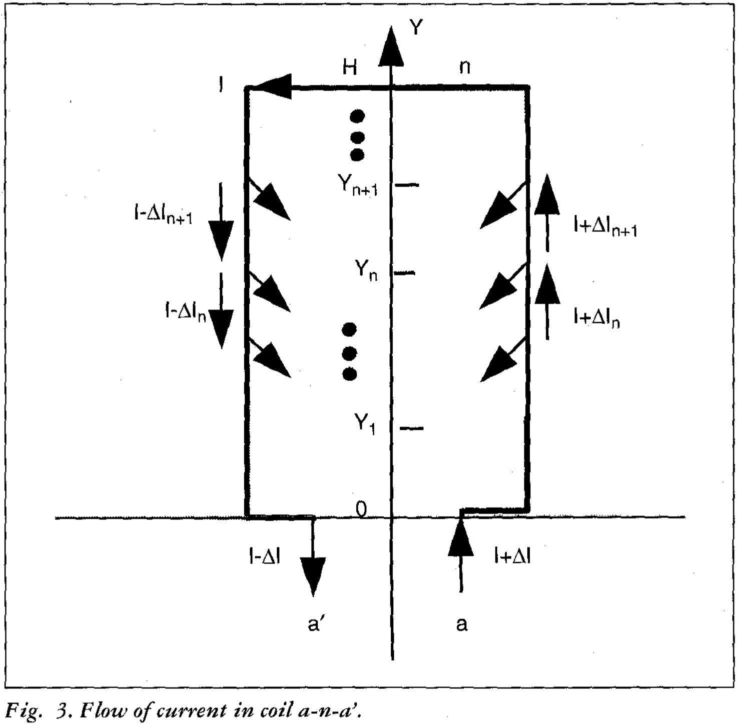

Fig. 3. Flow of current in coil a-n-a′.

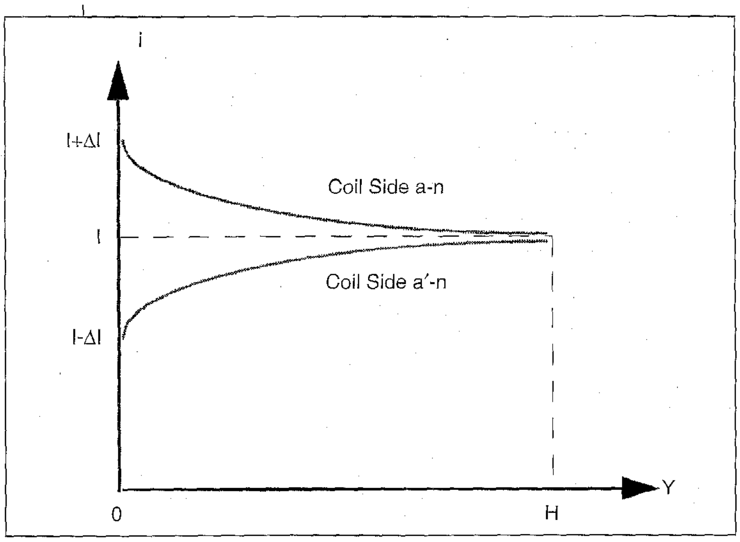

Fig. 4. Current distribution in coil a-n-a'.

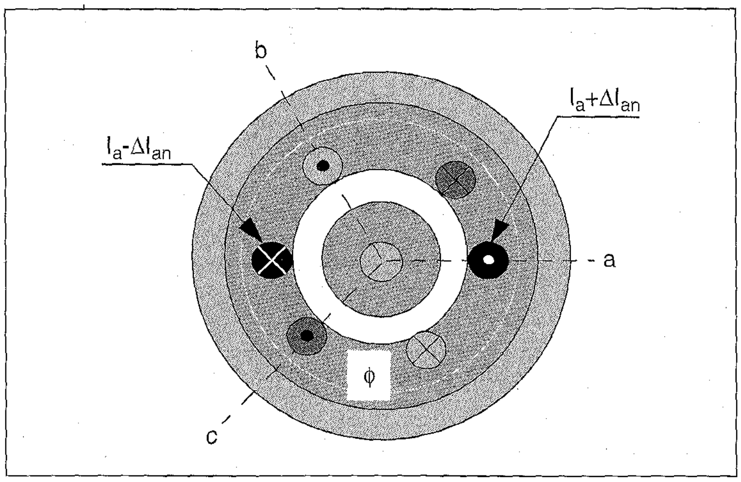

Fig. 5. Flux linkage enclosing the shaft of a three-phase motor.

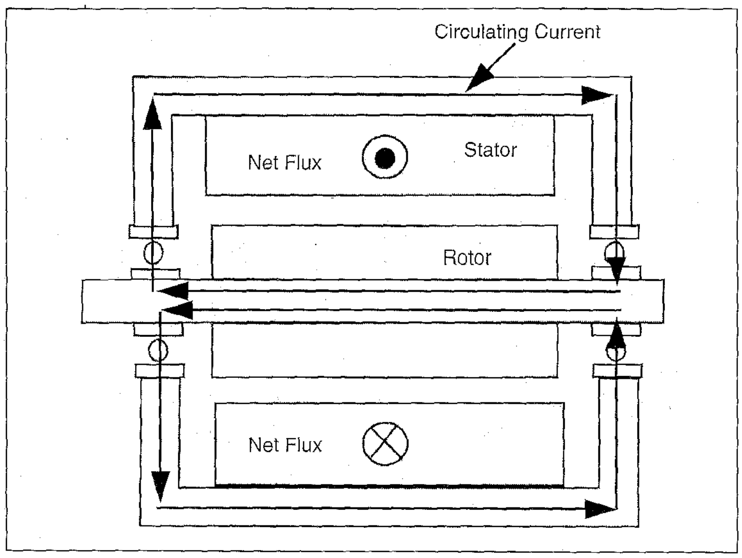

Fig. 6. Paths of circulating type bearing currents.

introduced. As is discussed in [3-4], 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, voltage surge, and electromagnetic interference (EMI). In particular, parasitic capacitances from the motor windings to the stator and the rotor must be taken into account.

To illustrate the concept of coupling current, it is sufficient to consider only the parasitic capacitances between a phase winding and the stator iron. By motor symmetry, it is reasonable to assume a uniform distribution of the parasitic capacitances 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 the stator case, which is normally connected to the earth.

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 evident 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 parasitic capacitors, or ΔI's. It is also noted that a part of the ΔI's flows into the earth ground as a common mode current indicated by ΔIc.

In general, capacitive coupling is omnipresent in a drive system. Parasitic capacitances exist between the windings and the stator, between the windings and rotor, as well as between the phases. Analysis shows that the coupling current in a three-phase system can always be decomposed into two components: the common mode and the differential mode [6]. 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

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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. An analysis of EMI mechanism based on the concept of coupling current can be found in reference [6].

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 capacitances 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, and only the current distribution along its direction of flow will be considered. To further simplify the analysis, it is assumed that the parasitic capacitances are uniformly distributed along the Y-axis or the motor shaft axial direction, and the parasitic capacitances along the X-axis or the radial direction will be neglected.

Due to the uniform distribution of the parasitic capacitances in the conductor, the current entering the coil may be dissipated partially into the capacitors along its way of travel. Therefore, the current into the coil may not equal that out of the same coil. This phenomenon can be described by a model that assumes that a current equal to $I+\Delta I$ flows into the terminal "a" while a current equal to $I-\Delta I$ flows out of the terminal "a'" of the coil shown in Fig. 3. In this model, "I" denotes the sum of the fundamental and all harmonic currents, and ΔI's represent the coupling currents, which include both common mode and differential mode components. Since the fundamental and harmonic currents pass through the whole coil, current "I" must be uniformly distributed along the direction of current flow. On the other hand, as the ΔI's are the currents flowing into parasitic capacitors, their distribution in the coil must vary spatially.

For any given position Y_n in the Y-axis, the same model applies to the sub-coil formed between positions Y_n and H, where H is the height of the coil. Therefore, the two coil-side currents at point Y_n can be expressed as $I+\Delta I_n$ and $I-\Delta I_n$, respectively, where ΔI_n must not be larger than ΔI. Based on this principle, the current distribution in the coil can then be determined as is illustrated in Figs. 3 and 4. It is evident that the currents of the two coil sides will not be equal to each other due to the existence of those parasitic coupling currents. Therefore, there is a current unbalance between the two coil sides of a motor winding and the degree of unbalance varies spatially.

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 an infinite small height from Y_n to Y_{n+1}, as is shown in Fig. 5. The unbalanced currents at Y_n of 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 be equal to

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

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, 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

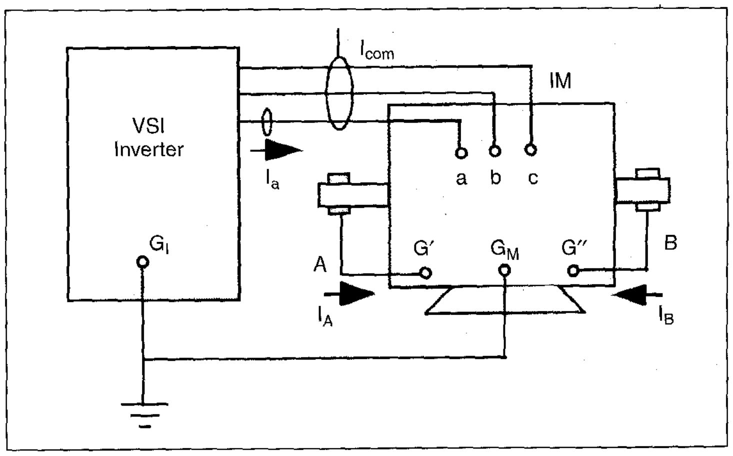
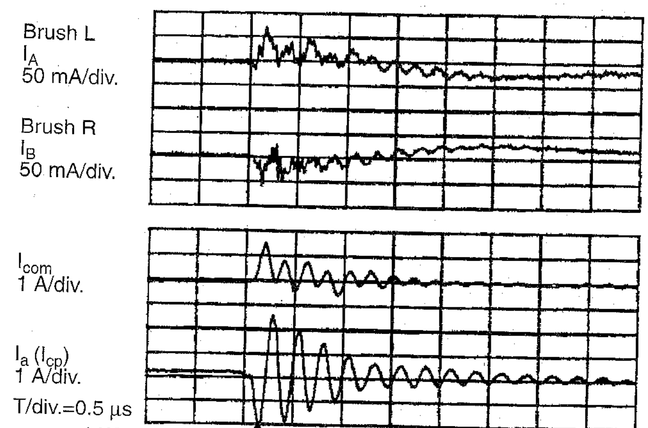
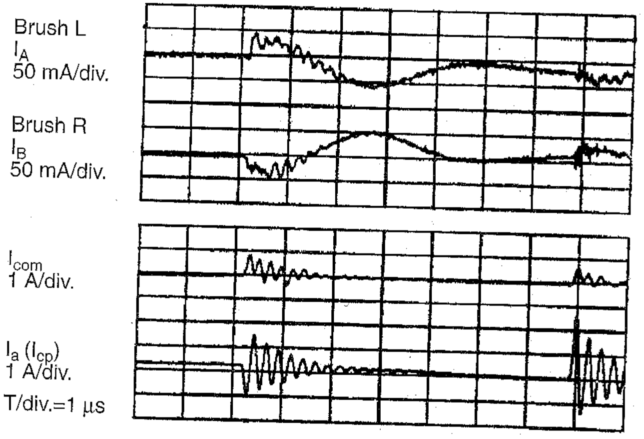


Fig. 7. Test setup for circulating type bearing currents.

exist a net flux linkage surrounding the motor shaft. 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 closed-loop is small.



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.

Fig. 8. Measured circulating bearing/brush currents.

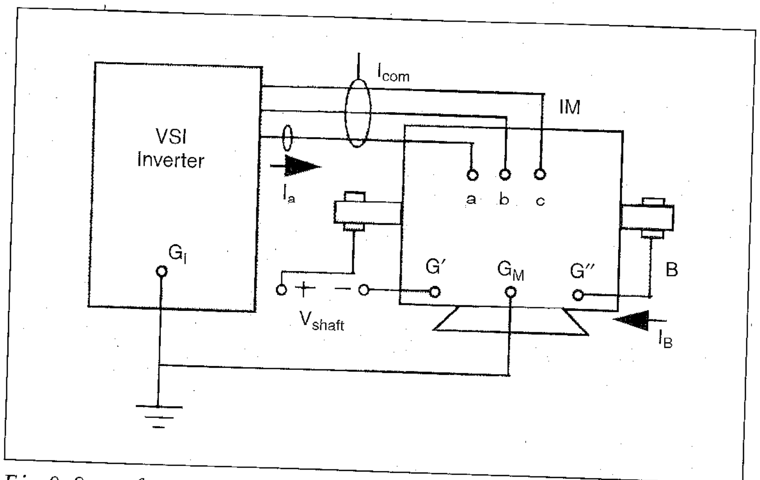


Fig. 9. Setup for measurement of the voltage (EMF) behind the circulating current.

A flux produced by common mode coupling currents always links the closed-loop formed by the stator case, motor shaft, and end bearings.

Experimental Verifications

Experiments have been performed to verify the above theoretical analysis. The test motor is a 230 V, 3 HP three-phase induction motor with both of its bearings insulated from the stator. The inverter used to drive this motor is operated with a constant volts/hertz with a sinusoidal PWM modulation and a switching frequency of 15 KHz. Two brushes (left L and right R) are installed to make contact, respectively, to the two ends of the motor shaft. The brush wires A and B can then be used to connect the brushes to the stator case via terminals G" and G', as is shown in Fig. 7. The terminal G_M is used to connect the stator case to the grounding conduit G, and G_I is the inverter case grounding point. This setup allows the use of brushes to simulate the electrical contact between the stator and the rotor produced by the bearings and to collect the possible bearing currents. The bearing currents will be detected by simply attaching a current probe to each of the wires A and B connected between the brushes and the stator. Those currents will be recorded as I_A and I_B. The total common mode current I_{com} of the drive system which flows into the earth ground is measured by another current probe enclosing all three motor input wires. The phase "a" current I_a is also measured and plotted as a reference to the total coupling current I_{cp} of this phase. As is pointed out above, I_a contains the fundamental current, the harmonic current as well as the coupling current. The coupling current component of I_a, denoted by I_{cp}, can be identified easily since it is a very high frequency ripple, usually in the megahertz range, superimposed on the I_a waveform.

The bearing/brush currents I_A and I_B are recorded as shown in Fig. 8. It is observed that there are three frequency components in I_A and I_B. The first component is a current ripple with a frequency of about 4 MHz and a peak-to-peak amplitude of about 50 mA, which can be recognized easily in Fig. 8a because its frequency is close to that of the common mode current I_{com}. The second component is a slow damping current with an amplitude of about 100 mA and a frequency of about 230

The experiments verify that a circulating bearing current will be produced if both ends of the motor shaft are connected to the stator case by low impedance paths.

KHz. This damping component can be clearly observed in the relatively large time scale of Fig. 8b. The third component is a very small current ripple with a frequency of about 12 MHz. With a very small amplitude and a high frequency, it looks just like an added thickness or a ripple carried over the 4 MHz waveforms of I_A and I_B shown in Fig. 8a. This 12 MHz ripple has be identified as the non-circulating bearing current or, specifically, the conduction mode bearing current as defined in references [4, 5]. Based on the definition of current probe directions, it is found 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.

The EMF causing the circulating currents is also observable by using the test setup shown in Fig. 9. By disconnecting one brush from the stator, the loop for the circulating currents becomes open-circuited and the EMF in the loop can be observed as the shaft voltage V_{shaft}. The measured shaft voltage V_{shaft} together with other important reference signals is plotted in Fig. 10. In this figure, the 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 have to flow into brush wire B. The 4 MHz and 230 KHz components similar to that of the circulating currents are seen to be present in the shaft voltage waveform. These two components are clearly the EMF associated with the circulating currents. The maximum peak amplitude of the back EMF is measured to be about 100 mV. It is interesting to notice that 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 ideal zero impedance between the stator and the rotor. Thus, it is reasonable to see this 12 MHz frequency in the voltage signal.

Finally, it is should be pointed out that the current in the shorted brush wire B also contains some 4 MHz component, as does that of the EMF or V_{shaft}. This can be explained by the fact that the open circuit of left brush cannot 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 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 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 from the stator. However, 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.

This paper proposes a theory for the existence of a new type of circulating bearing current in inverter-motor drives. It identifies that unbalanced currents flow in motor windings due to parasitic capacitances to the ground and between adjacent turns which become a significant factor in today's high dv/dt IGBT inverters. The unbalanced currents in the windings produce a net flux surrounding the motor shaft. It is this flux that links the conductive loop formed by the stator case, rotor shaft, and bearings and induces the circulating currents. The circulating bearing current is also proved to be related only to the common mode currents. The analysis is

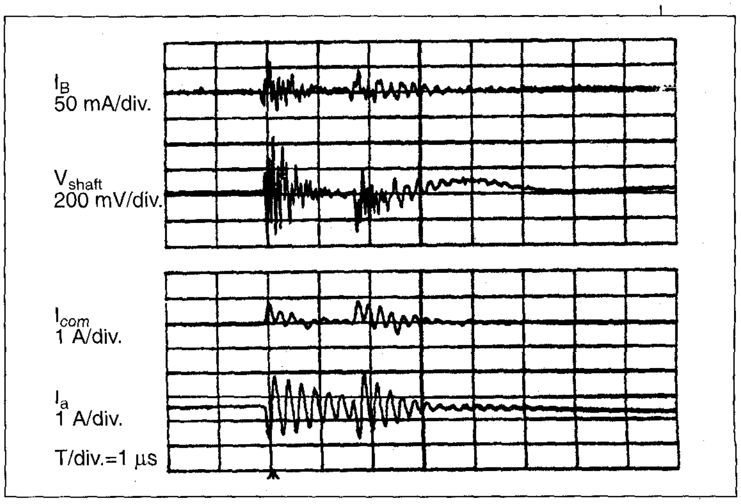


Fig. 10. Measured voltage (EMF) behind the circulating current.

verified by experimental measurement of bearing currents. The findings provide additional insight to the problems imposed by bearing currents in ac motor drives. A solution to eliminate bearing currents of both circulating and non-circulating types is also proposed.

Discussion

The circulating type bearing current is an addition to the previously recognized bearing currents of non-circulating type: the dv/dt related conduction mode bearing current and the air-gap capacitor related discharge mode bearing current. Therefore, there are at least three different formats of bearing currents: the circulating currents, the dv/dt currents, and the discharge currents. Each of those formats happens under certain conditions. Questions remain to be answered regarding which format(s) will be encountered mostly in normal drive applications.

The relative importance of the constituent components of bearing currents and their relationship to the reduced bearing life also remain as an interesting and challenging topic. Studies of this problem based on the non-circulating type of bearing current, i.e., the dv/dt current and the discharge current, have been published in [9]. However, a complete study may need to include the newly defined circulating current. This topic obviously does not fall into the scope of this article.

A question of great importance is whether it is possible to eliminate or reduce all bearing currents and, if so, how many methods will be available. The solution to bearing currents proposed in this article has helped answer part of the question. Methods for bearing current reduction using common mode filters are also possible. Another promising method is based on the concept of common mode voltage cancellation. This idea is based on the fact that common mode voltages input to the motor are the origin of all common mode currents and, thus, all bearing currents as well as common-mode EMIs. If the total effect of the common-mode voltages can be eliminated, the bearing currents and EMI will be both reduced. A technique of common cancellation has been proposed in [6]. This concept has recently gained more and more attention as is evidenced by references [10, 11].

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