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Impact of Stator Grounding in Low Power Single-Phase EC-Motors

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***Abstract*— Bearing currents cause a reduction of ball bearing's lifetime in electronically commutated permanent magnet motors. To compensate the lifetime decreasing factors, a tradeoff between special bearings and additional changes in the machine design have to be found. Stator grounding, for example, keeps the bearing voltage low and thus guarantees a long fan system's lifetime, however, results in a higher input filter effort. On the other hand, instead of reducing the bearing voltage, hybrid bearings could be deployed, which feature a high dielectric strength. The major disadvantage is that hybrid bearings are much more expensive than conventional metal bearings, thus the extra cost for the hybrid bearings has to be weighed up against the higher filter effort needed with stator grounding. In this paper bearing damage mechanisms are analyzed and the impact of stator grounding to avoid bearing currents in low power single-phase motors is presented. Based on the presented filter design procedure, the additional filter effort for stator grounded motors is determined, which shows that hybrid bearing are undesirable in mass application.**

I. Introduction

Typical drive units of today's fan systems for single-phase mains application are either induction motors (AC) or electronically commutated permanent magnet motors (EC). In general, AC-motors are simple, cost efficient and robust, but their efficiency is low, typically only around 60 %. In contrast, EC-motors show a better controllability and higher efficiencies around 80% [17], which results in a 50 % loss reduction between AC- and EC-motors, thus strongly influences the overall fan unit efficiency. However, the complexity and the need of control electronic increase the manufacturing costs of the EC-motor (cf. Tab. I).

The priorities of the motor type selection criteria are mainly influenced by customer needs and legal requirements, whereby the legal requirements of many countries set a focus on energy saving and reducing CO_2-emissions. Therefore, the European Union passed the energy related directive (ErP)

TABLE I
Qualitative comparison of AC- and EC-motors.

	AC	EC
Efficiency	-	+
Speed control	-	+
Noise	+	-
EMI-noise emissions	+	-
Lifetime and robustness	+	-
Costs	+	-

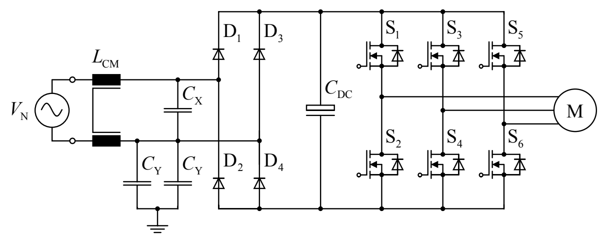

Fig. 1. Considered fan system consisting of a input filter, passive rectifier, inverter and EC-motor.

in 2009 [21]. This ecodesign requirement defines certain minimum efficiency in fan or pump units considering the whole system consisting of motor, electronic and blades for a rated power of 125 W-500 kW [22]. In 2015, the ErP is going to prescribe additional increases in efficiency. In order to be able to fulfill the given requirements in the future, the achievable efficiency will be one of the key criteria for the selection of the motor type. Nevertheless, increasing the efficiency of AC motors reduces the gap between AC and EC motors in terms of price and complexity, especially in the low power range. Consequently, the EC-motors become more and more attractive. However, the major technological difference between AC and EC-motors is found in the switched inverter. There, inverters with low switching frequencies cause harmonics in the motor windings and the iron losses as well as the acoustic noise are increased. Thus, generally an improvement is achieved with a PWM controlled inverter operating at higher switching frequencies above the audible range. Nevertheless, higher switching frequencies provoke bearing currents, which can drastically reduce the fan system's lifetime.

In this paper different methods to reduce bearing currents are presented and compared to each other, whereat the EMC directive still have to be fulfilled [19]. In Section II, the reason of bearing currents and the defect mechanisms are explained. In addition, possible arrangements to decrease the bearing currents are investigated based on a capacitive model of the motor. Afterwards, different feasible filter methods are analyzed and a simple filter design procedure is presented in Section III. Finally, in Section IV the input filter is designed for a motor with grounded stator and is compared to the filter effort which would result if hybrid bearings are deployed. The paper is concluded with experimental measurements concern-

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ing conducted EMI-noise emissions performed on a fan system consisting of a $170\,\mathrm{W}$ EC-motor.

II. Defect Mechanism of Isolated Bearings in Low Power Motors

Apart from mechanical and thermal stresses, the bearings of a fan system can be damaged by electrical currents flowing through the bearings. If the voltage across the bearing exceeds a critical bearing threshold voltage, mainly defined by the lubricant, a current flows through the bearing, which results in either a chemical change of the lubricant or in a higher surface roughness of the ball bearing races. Thus, the friction as well as the audible noise are increased resulting in shorter system lifetime and lower system performance.

The resulting bearing voltage can be attributed e.g. to induced shaft voltages due to small dissymmetries of the magnetic field in the motor's air gap [18], to electrostatic charging of rotor and frame caused by ionized air, to parasitic capacitive couplings where the bearing balls and races are charged, thus, leads to an insulation breakdown described as electrical discharge machining (EDM), or to rotor ground currents or high voltage transients ($\mathrm{d}V/\mathrm{d}t$) caused by the inverter, which results in circulating bearing currents [1], [2].

As shown in [2], for the investigated motor's size and power rating, the lifetime of the bearing is mainly decreased by capacitive coupling and EDM. Therefore, in order to analyze the bearing currents due to the capacitive coupling, based on the mechanical construction of the EC-motor, a model of the parasitic capacitances is deduced.

In Fig. 2 the cross sections in axial and radial direction of an EC-motor with a conducting stator bushing and the main parasitic capacitances C_{WS}, C_{WR} and C_{RS}, which describe the capacitive coupling between stator (S), rotor (R) and winding (W) are shown. The bearing's electrical behavior can be modeled with the capacitance C_{B}, since the lubricant isolates the bearing balls from the races. Typically, an impedance Z_{B} is added in parallel to the capacitance C_{B}, in order to be able to take mechanical and electrical abnormalities into account [18].

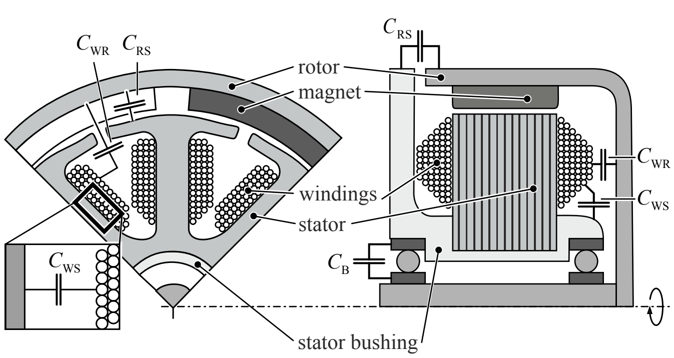

Fig. 2. Cross sections in axial and radial direction of an EC-motor with a conducting stator bushing and the parasitic capacitances C_{WS} (winding to stator capacitance), C_{WR} (winding to rotor capacitance) and C_{RS} (rotor to stator capacitance).

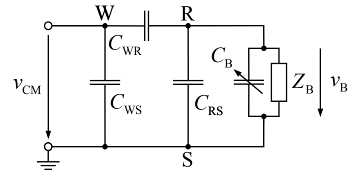

Fig. 3. Resulting capacitive model of the EC-motor describing the relation between common mode (CM) voltage v_{CM} and bearing voltage v_{B}.

In Fig. 3 the resulting capacitive model for one phase of the EC-motor is shown, which corresponds to the common mode (CM) models presented in the literature [3], [5], [18]. There, the bearing voltage v_{B} is defined by the common mode (CM) voltage v_{CM}, generated by the switching of the inverter stage, and the capacitive voltage divider consisting of C_{WR} and the parallel connected capacitances C_{RS} and C_{B}. Due to the smaller distance between winding and stator, C_{WS} is usually much larger than C_{WR} and for the same reason C_{RS} is larger than C_{WR}, thus only a part of the CM-voltage v_{CM} is accounted for the bearing voltage v_{B}. However, the maximum allowed bearing voltage $v_{\mathrm{B,lim}}$, which is in the range of $5\,\mathrm{V}-30\,\mathrm{V}$ for a conventional metallic ball bearing, can easily be exceeded [2].

In order to keep the bearing voltage and currents low - resulting in less abrasion and thus in longer lifetime - in the literature different concepts based on constructive arrangement or additional components are presented. One strategy to avoid bearing currents is to prevent the bearing capacitance C_{B} from being charged, which can be achieved by bypassing the CM-current through a low impedance or a short circuit connected in parallel to C_{B}, i.e. between rotor and stator (cf. Fig. 4 a)). This can be realized e.g. by microfiber rings [6], [7], by metallic springs or by the insertion of a dielectric material between stator and rotor, which increases the parasitic capacitance C_{RS} [4]. The major drawback of bypassing the bearing, however, is the lower CM impedance leading to higher CM-currents. In addition, the lifetime of the fan system is no more only limited by the damage of the bearings, but also by the abrasion of the sliding contacts or brushes between stator and the rotor.

Another option is to insert a shielding between winding and rotor (cf. Fig. 4 b)), which is splitting C_{WR} up into two parasitic capacitances $C_{\mathrm{WS,shield}}$ and $C_{\mathrm{RS,shield}}$, thus bypasses the CM-currents through the shielding directly to ground or to the stator potential respectively. In practice, the shielding is typically realized with a metallic layer consisting of an isolating and a grounded conducting painting of the stator, or with a grounded copper plated slot sticks [3], [5]. There, the increasing production costs can be considered as the major disadvantage of the inserted shielding or capacitive layers.

In contrast of providing a low impedance path which bypasses the bearings, there is also the possibility to increase the electrical impedance through the bearings. This can be achieved by either isolating the bearings from the conducting stator bushing - e.g. by resin insulators [16] (cf. Fig. 4 c)) - resulting in an additional parasitic capacitance C_{BS} which is connected in series to the bearing's impedance or to insert

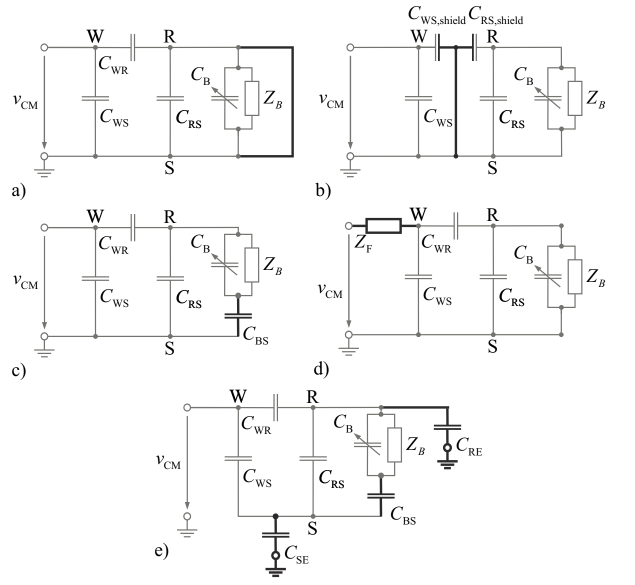

Fig. 4. Different concepts presented in the literature in order to keep the bearing voltage v_{B} low, a) insertion of a low impedance or a short circuit in parallel to C_{B}, b) insertion of a shielding between winding and rotor, c) increasing the electrical impedance through the bearing with isolated bearings, d) insertion of additional filter elements between inverter and motor or e) usage of an electrically isolating plastic stator bushing.

additional filter elements (cf. Fig. 4 d)) - e.g. CM-chokes - between the inverter and the EC-motor [13]. Hence, based on the capacitive voltage divider shown in Fig. 4 c), depending on the capacitance C_{BS}, the bearing voltage v_{B} can be strongly reduced. The isolation of the bearings, however, now inhibits the charge exchange between rotor and stator through Z_{B}, which means that the rotor's electrical potential could exceed the input CM-voltage v_{CM} and the critical bearing threshold voltage $v_{B,lim}$ due to electrostatic charging e.g. caused by ionized air. Consequently, this method can only be used in application with unionized air, which is fortunately the case in most applications.

In low power applications with unionized air, where typically the mechanical stresses are low, instead of isolated bearings an electrically isolating plastic stator bushing can be used as shown in Fig. 5. Beside a reduced system weight and lower material costs, the plastic stator bushing also features an electrical isolation between bearings and stator, which also results in an additional parasitic capacitance C_{BS} between bearing and stator. Due to the relatively thick plastic stator bushing the capacitance C_{BS} is typically small, thus the electrical impedance of the bearing is considerably increased and the bearing voltage as well as the bearing currents are strongly reduced. However, the bearing voltage and current can not be fully eliminated. As can be noticed, the bearing voltage v_{B} is reduced, if the capacitance of the plastic stator bushing C_{BS} is decreased. This can be achieved with a large isolation thickness and/or the usage of an isolating material with low permittivity. The thickness of the stator bushing, however, is usually limited by the overall motor dimensions.

Since the stator sheets are not grounded anymore, also

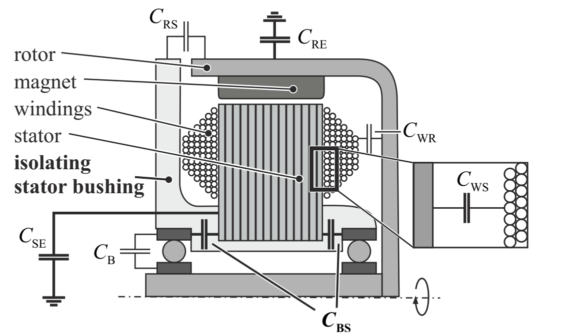

Fig. 5. Motor cross section with isolating plastic stator bushing and resulting parasitic capacitances C_{B}, C_{SE} and C_{RE}.

the parasitic capacitances C_{SE} between the stator sheets and ground and the capacitance C_{RE} between rotor and ground have to be considered (cf. Fig. 4 e)), which strongly influence the resulting bearing voltage. The resulting values of the two capacitances C_{SE} and C_{RE} are mainly defined by the motor's dimensions and the assembly of the fan system, i.e. the blades, housing and the installation situation of the fan, and thus can vary in a wide range.

Typically, the capacitance C_{WS} is much larger than C_{WR}, since on the one hand the windings are placed in the stator grooves and are directly wound around the stator sheets and on the other hand the windings are shielded from the rotor by the stator sheets (cf. Fig. 2). In addition, with external rotor motors the capacitance C_{SE} between stator and ground is small, since the rotor is almost fully enclosing the stator. However, due to the same reason, the capacitance C_{RE} may be large. Hence, at high frequencies the capacitance C_{WS} and C_{RE} are quasi shorting the stator potential S to the winding potential W and the rotor potential R to ground respectively. The largest possible bearing voltage with plastic stator bushing and isolated bearings appears with $C_{\mathrm{SE}} \to 0$ and $C_{\mathrm{RE}} \to \infty$ which is

$$v_{\mathrm{B,max,iso}} = \lim_{\substack{C_{\mathrm{RE}} \to \infty \\ C_{\mathrm{SE}} \to 0}} (v_{\mathrm{B}}) = \frac{C_{\mathrm{WS}} C_{\mathrm{BS}} \cdot v_{\mathrm{CM}}}{C_{\mathrm{RS}} C_{\mathrm{B}} + C_{\mathrm{RS}} C_{\mathrm{BS}} + C_{\mathrm{B}} C_{\mathrm{BS}} + C_{\mathrm{WS}} C_{\mathrm{B}} + C_{\mathrm{WS}} C_{\mathrm{BS}}}. \quad (1)$$

Depending on the capacitances C_{WS}, C_{B} and C_{BS} it is still possible that $v_{\mathrm{B,max,iso}}$ exceeds the maximum allowable bearing voltage $v_{\mathrm{B,lim}}$.

A further reduction of the bearing voltage, without changing the impedance through the ball bearings (i.e. C_{B} and C_{BS}), can be achieved if C_{SE} is shorted, which means that the stator S is grounded. Thus, based on the assumption that $C_{\mathrm{RE}} \to \infty$, the bearing voltage would be eliminated. As already mentioned, however, the capacitance C_{RE} is defined by the motor type and its dimensions, which can also result in small values. This would be detrimental if the stator is grounded. The maximum resulting bearing voltage $v_{\mathrm{B,max,gnd}}$ ($C_{\mathrm{RE}} \to 0$) is then given as

$$v_{\mathrm{B,max,gnd}} = \lim_{\substack{C_{\mathrm{SE}} \to \infty \\ C_{\mathrm{RE}} \to 0}} (v_B) = \frac{C_{\mathrm{WR}} C_{\mathrm{B}} \cdot v_{\mathrm{CM}}}{C_{\mathrm{RS}} C_{\mathrm{B}} + C_{\mathrm{RS}} C_{\mathrm{BS}} + C_{\mathrm{B}} C_{\mathrm{BS}} + C_{\mathrm{WR}} C_{\mathrm{B}} + C_{\mathrm{WR}} C_{\mathrm{BS}}}. \tag{2}$$

As already mentioned, however, since C_{WR} is much smaller than C_{WS}, the maximum resulting bearing voltage $v_{\mathrm{B,max,gnd}}$ is typically much lower than $v_{\mathrm{B,max,iso}}$.

Instead of having either a isolated or grounded stator, it is also possible to adjust the stator and rotor potentials to each other, in order to totaly eliminate or to at least minimize the bearing voltage for each motor type or fan system assembly respectively. This can be illustrated rather easily by rearranging the components of the capacitive model found in Fig. 4 e) to the arrangement shown in Fig. 6, which is basically a Wheatstone bridge. As already shown, the bearing voltage v_{B} strongly depends on the potentials of the stator and rotor, which are defined by the voltage ratio of the two capacitive voltage dividers consisting of C_{WS} and C_{SE} or C_{WR} and C_{RE}. Consequently, the parasitic capacitances C_{RE} and C_{SE} could be adjusted in such a way that no current would flow through the bearing, which is achieved if the electrical potentials of the stator and rotor are equal. Therefore, either the fan system's dimensions would have to be adapted to the underlying applications, which in practice, especially in mass production, is not applicable. Therefore, an additional capacitance $C_{\mathrm{SE,add}}$, e.g. a SMD-capacitor, is placed in parallel to C_{SE}. The determination of the needed capacitance $C_{\mathrm{SE,add}}$ is extremely crucial, since on the one hand the measurements of the parasitic capacitances have to be performed during operation and on the other hand the small parasitic capacitances of the fan system are affected by the measurement itself. The small bearing voltage has to be measured with a differential probe, which typically features a high voltage divider and a input capacitance of a few picofarads. Consequently, the measurement could suffer from a bad resolution. Therefore, the bearing's outer race is connected to the stator sheets, i.e. the capacitance C_{BS} is shorted-out, thus a higher bearing voltage can be measured and a higher measurement accuracy is achieved. Due to the high bearing voltage and increased reproducibility of the measurements, hybrid bearings instead of conventional metal bearings were used in the measurement in order to find the optimal capacitor value $C_{\mathrm{SE,add}}$.

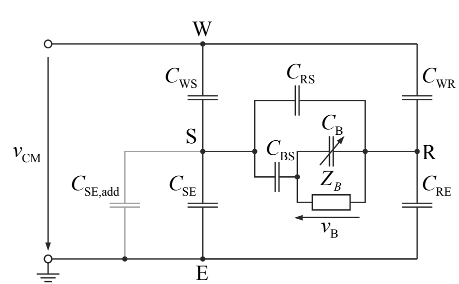

Fig. 6. Rearrangement of the capacitances according to a Wheatstone bridge.

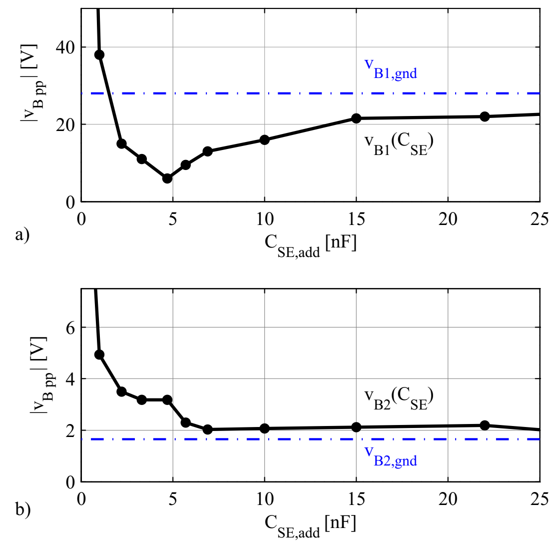

Fig. 7. Measured bearing voltage (HAMEG HZ115 differential probe) in a three phase motor with a DC-Link voltage of 325 V for a) non-isolated hybrid bearings (v_{B1}) and b) isolated hybrid bearings (v_{B2}).

In Fig. 7 a) the measured bearing voltage for different additional capacitances $C_{\mathrm{SE,add}}$ is shown. The minimum bearing voltage of $v_{\mathrm{B,adj}} = 6\,\mathrm{V}$ is achieved with an additional capacitance of approximately $C_{\mathrm{SE,add}} = 5\,\mathrm{nF}$. The highest bearing voltage of $v_{\mathrm{B,iso}} = 200\,\mathrm{V}$ was measured without any additional capacitance. In contrast, the bearing voltage with grounded stator can be reduced to $v_{\mathrm{B,gnd}} = 27\,\mathrm{V}$. However, it has to be mentioned that the system's behavior is negatively affected by the short circuit between bearing's outer race and stator sheets, i.e. much higher bearing voltages are provoked. Therefore, the bearing voltage was also measured without shoring-out the isolating plastic stator bushing. The resulting bearing voltage for different additional capacitances $C_{\mathrm{SE,add}}$ is shown in Fig. 7 b). As can be noticed, even if this measurement is extremely difficult, already with an additional capacitance $C_{\mathrm{SE,add}}$ of around $7\,\mathrm{nF}$ bearing voltages below critical voltage levels are obtained. The minimum bearing voltage of $v_{\mathrm{B,gnd}} = 1.7\,\mathrm{V}$ is achieved with a grounded stator, which is only slightly below the bearing voltage measured with $C_{\mathrm{SE,add}} = 7\,\mathrm{nF}$.

As a consequence, besides reducing the bearing voltage, the insertion of $C_{\mathrm{SE,add}}$ or grounding the stator results in higher EMI filter effort. A minimum bearing voltage, which is necessary to guarantee a long fan system's lifetime, comes along with a decrease of the impedance between the windings and ground. This results in an increase of the common mode currents thus in an increase of the filter volume. Due to the fact that for both capacitive voltage dividers $C_{\mathrm{SE,add}} \gg C_{\mathrm{WS}}$ and $C_{\mathrm{RE}} \gg C_{\mathrm{WR}}$, the impedance to ground is mainly defined by C_{WS} and C_{WR}. In addition, since $C_{\mathrm{WS}} \gg C_{\mathrm{WR}}$, the impedance to ground is dominated by C_{WS}. Consequently, the choice of whether to add a large capacitance $C_{\mathrm{SE,add}}$ or to ground the stator does not influence the needed common mode filter attenuation or filter volume respectively.

For the sake of completeness, it has to be mentioned that without taking one of these two preventative measures keeping the bearing voltage low, the impedance between the windings and ground would be strongly increased since for external rotor motors C_{SE} is typically small. Hence, the filter effort would be comparably small. However, the high bearing voltages could only be handled by using hybrid bearings, which feature a higher dielectric strength but which are also much more expensive than conventional metal bearings. Thus, in financial terms, the extra cost for the hybrid bearings or for the higher filter effort have to be weighed up against each other, but typically the utilization of hybrid bearings is undesirable in mass application.

Thus, in financial terms, their utilization is undesirable in mass application. Nevertheless, the extra cost for the higher filter effort have to weighed up against each other, but typically In order to support the decision-making process, in the following the increase in filter effort is investigated.

III. EMI Filter Design

So far, the capacitive model of only one phase was considered (cf. Fig. 3). In Fig. 8 the motor's CM-model extended to three phases is shown. Based on the previous considerations ($C_{\mathrm{RE}} \gg C_{\mathrm{WR}}$) the capacitive model of the motor concerning the EMI-noise emissions between all windings $L_{1,2,3}$ connected together and stator can be simplified to one lumped capacitance $C_{\mathrm{M,CM}}$, which is mainly defined by C_{WS}. This actually equals to the parasitic CM-capacitance of the fan system, if either a large capacitance $C_{\mathrm{SE,add}}$ is added or the stator is grounded. For an isolated stator, i.e. if hybrid bearings are deployed, also the capacitance C_{SE} has to be considered. Then, the total CM-capacitance $C_{\mathrm{M,CM,tot}}$ of the motor is found by the series connection of $C_{\mathrm{M,CM}}$ and C_{SE} (cf. Fig. 8). The simplification of the motor's CM-model is verified with an impedance measurement between the phases L_1, L_2 and L_3 (all connected together) with and without a grounded stator for a $170\,\mathrm{W}$ stator EC-motor as shown in Fig. 9.

As can be noticed, the impedance measurement shows nearly a pure capacitive behavior with only some resonance effects between $80\,\mathrm{kHz}$ and $150\,\mathrm{kHz}$, which are irrelevant for the conducted EMI spectrum since the starting frequency of the CISPR directive is $150\,\mathrm{kHz}$. Hence, if the stator is grounded, the lumped equivalent capacitance $C_{\mathrm{M,CM}}$ of the

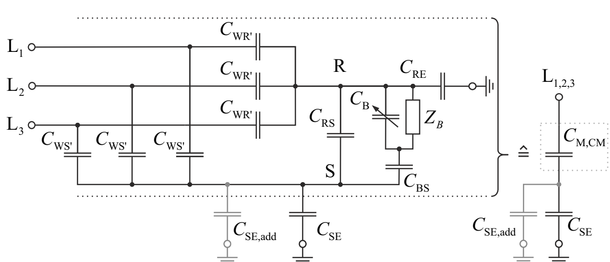

Fig. 8. Simplified capacitive model of a low power motor extended to three phases.

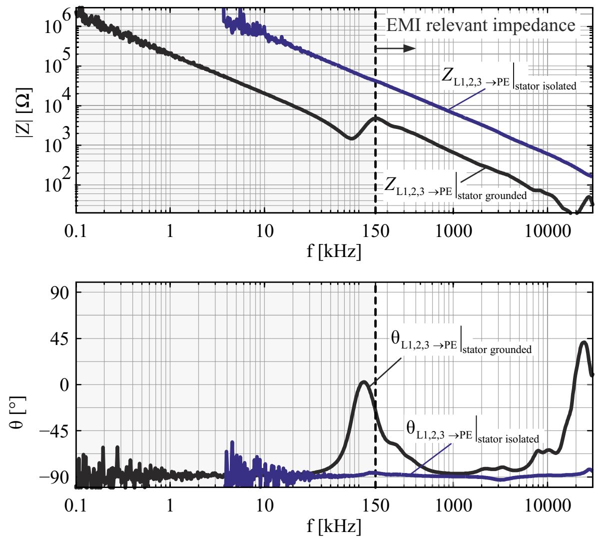

Fig. 9. Measured impedance between the windings (L_1, L_2 and L_3 connected together) and ground for grounded and isolated stator.

motor can be deduced for frequencies above $150\,\mathrm{kHz}$, which is $245\,\mathrm{pF}$. With an isolated stator, the total CM-capacitance $C_{\mathrm{M,CM,tot}}$ of the motor is measured to be $28\,\mathrm{pF}$. Based on these values a capacitance between stator and ground of around $C_{\mathrm{SE}} = 32\,\mathrm{pF}$ is calculated.

It has to be mentioned that the influence of winding and parasitic inductances can be accounted with more detailed and accurate models [11], [12]. However, for the considered frequency range above $150\,\mathrm{kHz}$ and the used motor type/size, the proposed capacitive model is sufficient.

In order to fulfill the EMC directive (CISPR, class B) concerning conducted EMI-distortions, the CM-noise emission caused by the inverter due to the motor's CM-capacitance $C_{\mathrm{M,CM,tot}}$, have to be filtered, whereat different filter approaches either at the fan system's input side or directly at the motor are applicable as shown Fig. 10. Instead of shorting the stator to ground, the simplest filter method would be to insert an CM-inductance $L_{\mathrm{CM\ a)}}$ between stator and ground, which is connected in series to $C_{\mathrm{M,CM}}$.

The resonant frequency of this series connection has to be lower than $150\,\mathrm{kHz}$, in order to properly attenuate the CM-current in the EMI spectrum of the CISPR directive. Then, for high frequencies the impedance between stator and ground is increased, i.e. the stator is decoupled from ground, and for low frequencies the stator is still grounded. Since the current through this inductance would be quite low, e.g. compared to the mains current in the input filter, and only one winding is needed, the inductor would feature a small size and could be realized e.g. as a SMD-component. However, due to the fact that the stator is no more grounded for higher frequency, this filter method results again in higher bearing voltages and in shorter lifetime of the fan system; thus is not applicable.

An other possibility is to increase the CM-impedance directly at the inverter output with a CM-choke $L_{\mathrm{CM\ b)}}$ along the motor cables. Hence, the CM-voltage v_{CM} between the

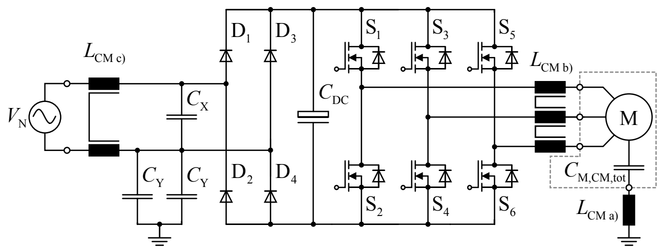

Fig. 10. Different filter approaches which are either applicable at the fan systems input side or directly at the motor.

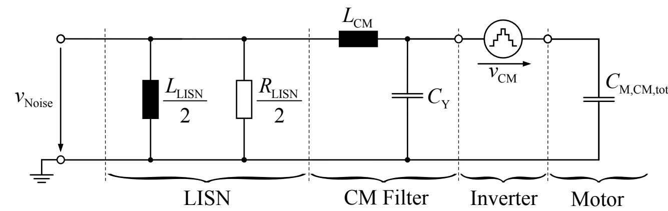

Fig. 11. CM-model of the fan system to calculate the needed filter attenuation.

motor phases and ground is decreased, as already shown in Fig. 4 d), and the EMI-noise emission is reduced, since the impedance to ground increased [13]. Compared to $L_{\text{CM a)}}$, the same inductance value is needed, however, for the coupled inductance $L_{\text{CM b)}}$ three windings are needed, which in addition have to conduct the full load current. Consequently, this results in a much larger filter volume.

In contrast to the filter methods $L_{\text{CM a)}}$ and $L_{\text{CM b)}}$, the CM-filtering can also be performed with a CM-choke $L_{\text{CM c)}}$ at the input of the fan system. Compared to $L_{\text{CM b)}}$, only two instead of three windings are needed and depending on the system design, the mains currents are lower than the phase currents of the motor. Moreover, in most rectifiers, a certain CM-choke is already used for the realization of the input filter. Thus, the existing CM-choke of the input filter only has to be adapted to the additional distortions caused by the stator grounding. Thus, for $L_{\text{CM c)}}$ a smaller volume than for $L_{\text{CM b)}}$ is expected and consequently this filter method is further pursued.

In order to calculate the filter attenuation, a CM-model of the whole fan system is needed as shown in Fig. 11. As stated above, the motor can be substituted by its CM-capacitance $C_{\text{M,CM,tot}}$ and the CM-input filter is given by L_{CM} and C_{Y}, whereas parasitic effects of the filter elements are neglected.

The CM voltage $v_{\text{CM}}(t)$, which is caused by the inverter, can be expressed by the switching state $\text{m}_{1\text{-}3}(t)$ of the three inverter branches and the DC-Link voltage V_{DC}

$$v_{\text{CM}}(t) = \frac{m_1(t) + m_2(t) + m_3(t)}{3} V_{\text{DC}}, \qquad (3)$$
$$m_{1-3}(t) = \begin{cases} 0 \text{ for closed switch} \\ 1 \text{ for opened switch} \end{cases}$$

where depending on the modulation scheme, the maximum peak to peak $v_{\text{CM,pp}}$ can be calculated for each switching cycle. For example, if a triangular carrier signal is used to generate the appropriate PWM-signal, $v_{\text{CM,pp}}$ is given by the two zero states with $\text{m}_{1\text{-}3}(t) = 1$ and $\text{m}_{1\text{-}3}(t) = 0$, which alternate every switching period. Thus, the resulting CM-voltage $v_{\text{CM,pp}}$ is equal to V_{DC}. However, for the calculation of the needed filter attenuation, only the harmonics in the EMI spectrum (150 kHz) have to be considered. The amplitude of the harmonics is calculated by the Fourier series of a rectangular signal with a constant duty cycle of 50 % and a peak to peak voltage of $v_{\text{CM,pp}}$, which is a worst case assumption of the EMI-noise emissions but which is typically in good agreement with measurements due to the measurement procedure of the quasi-peak detector performed in the EMI-receiver.

Finally, to complete the CM-model of the fan system, the Line Impedance Stabilization Network (LISN) with a terminating impedance of $L_{\text{LISN}} = 50\,\mu\text{H}/R_{\text{LISN}} = 50\,\Omega$ has to be taken into account [19].

It has to be mentioned that for the dimensioning of the EMI filter it is sufficient to only consider the amplitude of the first harmonics which is lying in the EMI spectrum, since with a square-wave CM-voltage the amplitude of the harmonics decreases with $1/n$ ($-20\,\text{dB/decade}$) and the filter attenuation of an LC-circuit increases with $40\,\text{dB/decade}$ (neglecting parasitic effects of the filter) the lowest harmonic in the conducted EMI spectrum is the most critical one. However, it has to be mentioned that due to the capacitive coupling between windings and ground the emitted noise increases with n ($20\,\text{dB/decade}$) thus the measured noise at the LISN only decreases with $-40\,\text{dB/decade}$. Furthermore, lower frequencies demand larger filter components and thus mainly determine the resulting filter volume.

IV. Results

The filter design is performed for a fan system with a 170 W EC-motor, whose measured impedance to ground $Z_{\text{L1,2,3}\rightarrow\text{PE}}$ for grounded and isolated stator have already been shown in Fig. 9. The drive unit is connected to the European mains voltage (230 V/50 Hz), which results in a maximum DC link voltage of 325 V. The switching frequency of the inverter is selected above the audible frequency range at 16 kHz. The first harmonic in the EMI spectrum is located at 160 kHz, which means a reduction of the harmonic's amplitude by $-20\,\text{dB}$.

According to the EMC directive (CISPR, class B/EN5022B), the conducted EMI-noise emissions should be below $63\,\text{dB}\mu\text{V}$ for QP at 160 kHz. Thus, including some margin due to component tolerances and additional parasitics of the inverter and diode rectifier, the input filter should show an attenuation of around 87 dB at 160 kHz.

The design of the CM-filter provides one degree of freedom, i.e. the ratio between L_{CM} and C_{Y}, which can be used to optimize the filter in terms of minimum overall filter volume or minimum costs. However, the design space is limited by other requirements, like the ground currents, which have to be limited below 3.5 mA [20]. Consequently, for the given specifications, the filter capacitance C_{Y} has to be smaller

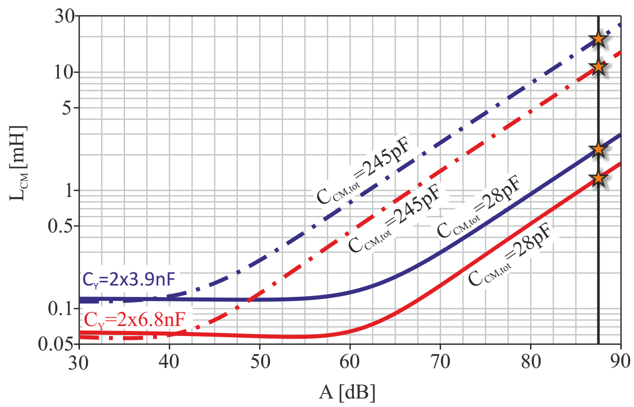

Fig. 12. Filter damping for grounded (dashed) and isolated (solid) stator and markers for the needed filter damping.

than 2 x17 nF. In order to still allow a parallel connection of several drive units without exceeding the maximum allowed ground currents, a CM-filter capacitance of $C_{\mathrm{Y}} = 3.9\,\mathrm{nF}$ and $C_{\mathrm{Y}} = 6.8\,\mathrm{nF}$ was selected. Based on these capacitor values and the needed attenuation of around 87 dB, the CM-filter inductance L_{CM} for a grounded ($C_{\mathrm{M,CM,tot}} = 245\,\mathrm{pF}$) and isolated stator ($C_{\mathrm{M,CM,tot}} = 28\,\mathrm{pF}$) can be determined from Fig. 12. Consequently, since the motor CM-inductance $C_{\mathrm{M,CM,tot}}$ with a grounded stator is approximately ten times higher than with an isolated stator, also the needed CM-filter inductance value L_{CM} is increased by the same factor.

As shown in Fig. 12, for the design with grounded stator and $C_{\mathrm{Y}} = 2\,\mathrm{x}3.9\,\mathrm{nF}$, a CM-inductance of $L_{\mathrm{CM}} = 20\,\mathrm{mH}$ would be needed. Since such a high CM-inductance requires a high number of turns and/or a large core size, the parasitic capacitance of the CM-inductance is strongly increased, which leads to a poor EMI behavior in the upper frequency range; hence, this design is omitted. Thus, increasing the CM-capacitors to $C_{\mathrm{Y}} = 2\,\mathrm{x}6.8\,\mathrm{nF}$ results in a more feasible CM-inductance value of $L_{\mathrm{CM}} = 10\,\mathrm{mH}$, which shows a much better EMI behavior due to the lower parasitic capacitance. The characteristic values of the selected CM inductance based on a ring core with outer diameter d_{a}, inner diameter d_{i}, height h and number of turns N as well as the dimensions of the corresponding CM-capacitor with length l, width w and height h are given in Tab. II. In Fig. 13 the corresponding EMI measurements (measured with a ESCI7 from Rohde&Schwarz) are shown. It can be noticed, that the CM-filter design perfectly fulfills the EMI standard over the whole measuring range.

Without stator grounding, the needed CM-filter inductance can be reduced to $L_{\mathrm{CM}} = 1\,\mathrm{mH}$, if the CM-capacitors values are not changed ($C_{\mathrm{Y}} = 2\,\mathrm{x}6.8\,\mathrm{nF}$). Consequently, also the total CM-filter volume is reduced, in this case by $50\,\%$ (cf. Tab. II).

The resulting EMI-measurements are shown in Fig. 14. As can be noticed, up to approximately $2-5\,\mathrm{MHz}$ the measured EMI spectrum of the fan system with isolated stator is similar to the one with grounded stator. Around $9\,\mathrm{MHz}$, however, with the isolated stator a resonance is measured, which is determined as a CM resonance by the separation of the noise

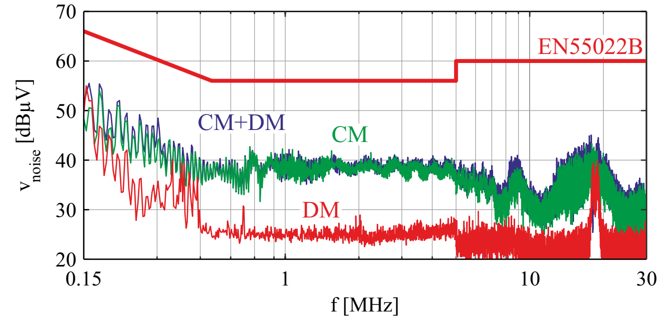

Fig. 13. Measured EMI spectrum for a CM-filter design of L_{CM}=10mH, C_{Y}=2x6.8nF and grounded stator.

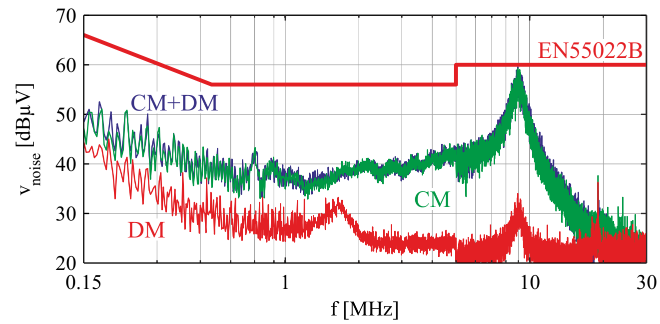

Fig. 14. Measured EMI spectrum for a CM-filter design of L_{CM}=1mH, C_{Y}=2x6.8nF and isolated stator.

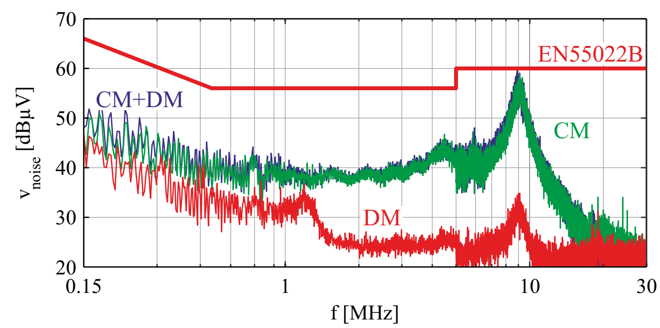

Fig. 15. Measured EMI spectrum for a CM-filter design of L_{CM}=2mH, C_{Y}=2x3.9nF and isolated stator.

signal in CM and DM. Since the peak of this resonance is still below the limit, additional damping elements to attenuate the resonance peak are not needed.

In order to reduce the ground currents, with the isolated stator the CM-capacitors can be further decreased to $C_{\mathrm{Y}} = 2\,\mathrm{x}3.9\,\mathrm{nF}$, which results in a needed CM-inductance of $L_{\mathrm{CM}} = 2\,\mathrm{mH}$.

As shown in Fig. 15, the EMI-spectrum stays almost unchanged with nearly the same damping and the same resonance behavior. Compared to the design with $C_{\mathrm{Y}} = 2\,\mathrm{x}6.8\,\mathrm{nF}$, the ground currents are reduced by $43\,\%$, however, the filter volume is again increased by $54\,\%$.

In Table II the three different filter designs are summarized

TABLE II
IMPACT ON REDUCING BEARING CURRENTS FOR THE PRESENTED MOTOR.

		Stator isolated		Stator grounded
L_{CM}	inductance	1 mH	2 mH	10 mH
	outer diameter d_{a}	9 mm	14 mm	14 mm
	inner diameter d_{i}	4 mm	9 mm	6.5 mm
	height h	4.5 mm	5 mm	9.5 mm
	number of turns N	2 x16	2 x26	2 x31
C_{Y}	capacitance	2 x6.8 nF	2 x3.9 nF	2 x6.8 nF
	length l	5 mm	5 mm	5 mm
	width w	13 mm	10 mm	13 mm
	height h	11 mm	10.5 mm	11 mm
Volume	CM-filter	2465 mm^3	3804 mm^3	4950 mm^3
	total electronic	100 %	ca. 104 %	ca. 106 %

again. As already mentioned, the total CM-filter volume for a grounded stator and conventional bearing ($L_{\mathrm{CM}} = 10\,\mathrm{mH}$) is twice as big as for an isolated stator and hybrid bearing ($L_{\mathrm{CM}} = 1\,\mathrm{mH}$), which is $4950\,\mathrm{mm}^3$ compared to $2465\,\mathrm{mm}^3$. Nevertheless, since the total volume of the electronics, consisting of passive rectifier and inverter stage, is around $42\,\mathrm{cm}^3$, the CM-filter volume is only slightly influencing the total electronics volume. On the one hand, if the stator is isolated, a reduction of the ground currents by increasing the CM-inductance and decreasing the CM-capacitors results in a total volume increase of $4\,\%$. On the other hand, if the stator is grounded, the total volume increases by $6\,\%$ compared to the smallest CM-filter design. Thus, even with stator grounding - which enables the deployment of conventional bearings - the change in total volume and thus also in costs is negligible. In contrast, even if hybrid bearings result in smallest CM-filter the costs are strongly increased. Due to the fact, that the price of hybrid bearings is more than ten times higher than for conventional metal bearings, the additional filter costs for a grounded stator (which in this case increase by around $30\,\%$) are more than compensated, thus not applicable in mass production.

V. CONCLUSION

In fan systems with EC-motors, the CM-voltage caused by the inverter results in bearing voltages/currents, which drastically reduce the fan system's lifetime. Therefore, in this paper different methods to avoid bearing voltages are presented. In low power applications, where typically electrically isolating plastic stator bushing are used, the lowest bearing voltages are achieved if either the stator potential is adjusted to the rotor potential by adding a separate capacitor between stator and ground or the stator is shorted to ground. These preventative measures, however, come along with a reduction of the impedance between the windings and ground, which results in a higher input filter effort. Instead of reducing the bearing voltage, hybrid bearings could be deployed, which feature a high dielectric strength. However, hybrid bearings are much more expensive than conventional metal bearings, thus the extra cost for the hybrid bearings has to be weighed up against the higher filter effort. As shown in this paper, the additional filter effort is relatively small which makes the hybrid bearing undesirable in mass application.

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