Integrated Filters and Their Combined Effects in Matrix Converter

Tsuneo Kume, *Life Fellow, IEEE*, Kenji Yamada, Tsuyoshi Higuchi, Eiji Yamamoto,
Hidenori Hara, Toshihiro Sawa, and Mahesh M. Swamy, *Member, IEEE*

***Abstract*—A matrix converter has a topology that inherently exhibits sinusoidal input current waveforms and has small output voltage steps. This paper proposes to integrate the matrix converter with filters, which provide lower electromagnetic interference (EMI), lower common-mode current, lower shaft voltage, and sinusoidal output voltage waveforms. A salient aspect of the proposed integration is its ability to significantly reduce the value of the input EMI filter capacitors and still meet strict EMI regulations. This helps in reducing the ground leakage current, which in the past has been a serious limitation in applying EMI filters with low ground currents for human and cattle safety.**

***Index Terms*—AC/AC converter, common-mode voltage, electromagnetic compatibility/electromagnetic interference (EMC/EMI), harmonics, matrix converters, passive filter.**

I. Introduction

The voltage-source pulsewidth-modulation (PWM) inverter has been established as the major controller of motor drive systems. However, it is associated with issues pertaining to the output side or the motor side as well as the input side or the ac power system side [1], [2]. Typical problems in two-level voltage-source PWM inverters include the following:

1) high levels of input current harmonics, which have an unfavorable influence on the connected electrical system;
2) interference with other electrical equipment due to large common-mode current and conducted and radiated electromagnetic interference (EMI);
3) potential for motor insulation failure caused by surge voltage at the motor end;
4) premature bearing failure in motors due to shaft voltage and bearing currents.

Many authors have worked toward addressing the issues pertaining to two-level inverter drives, both on the input and output sides of the drives. Factors that contribute to power system pollution caused by power electronic converters and some effective mitigating methods have been addressed in the IEEE519 document [3]. Nonmandatory allowable level of current and voltage distortion for ensuring good power quality in an industrial plant is part of the IEEE519 document. However, the filters need to comply with IEEE519, either active type or passive type, add cost, and occupy space [4].

Some of the earliest work done in the area of recognizing the potential problems due to common-mode currents (ground leakage currents) in voltage-source PWM inverters and suggesting techniques of mitigating it is reported in [5]. The steep rising and falling voltage edges in conjunction with the parasitic capacitance between motor windings and motor frame have been recognized to be the prime reason for common-mode currents. The authors have discussed two different filtering techniques to reduce common-mode currents. The techniques are still valid, but they do not provide total cancellation of the common-mode voltage. Other solutions that address the aforementioned problem have been suggested in [6]–[10] by various authors. These passive techniques are still applicable but are costly and bulky.

Active circuits have also been proposed to cancel the common-mode currents in motors fed from two-level voltage-source PWM inverters. Two different techniques by different authors were proposed almost simultaneously [11], [12]. Authors in [11] have extended the concept of the common-mode transformer [7] and used it as part of an active circuit to apply a common-mode voltage across the fourth winding to cancel it out. A disadvantage of the circuit proposed in [11] is that the transistor used is hard to find in high voltage ratings needed for 460-V/575-V systems, where the common-mode voltage problems are more prevalent. A current injection circuit as opposed to the voltage cancellation circuit of [11] has been proposed in [12]. Similar to the results in [11], common-mode currents are actively canceled in [12]. Both techniques are limited to low-voltage applications.

When the cable between the inverter and motor is long, voltages at the motor terminals are higher than those at the inverter terminals due to the steep voltage gradient and distributed inductance–capacitance (LC) combination of the cable. High voltage appearing across the motor terminals may damage the insulation material of the windings. High rate of voltage change also creates nonuniform voltage distribution among winding turns, affecting the life of insulation material. Output dv/dt

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T. Kume, K. Yamada, T. Higuchi, and T. Sawa are with Yaskawa Electric Corporation, Kitakyushu 803-8530, Japan (e-mail: tjkume@yaskawa.co.jp; yamada@yaskawa.co.jp; hyuuma@yaskawa.co.jp; sawa@yaskawa.co.jp).

E. Yamamoto and H. Hara are with Yaskawa Electric Corporation, Yukuhashi 824-8511, Japan (e-mail: yamamoto@yaskawa.co.jp; hhara@yaskawa.co.jp).

M. M. Swamy is with Yaskawa Electric America, Inc., Waukegan, IL 60085 USA (e-mail: mahesh_swamy@yaskawa.com).

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filters have been traditionally employed to address this problem. Rather than adding external filters, a totally different approach to address the winding stress in motors due to voltage reflection issues and bearing problems due to shaft voltage and bearing current is to use a neutral-point-clamped (NPC) three-level PWM general-purpose inverter [13]. In this circuit configuration, the NPC inverter has favorable features that include lower line-to-line and common-mode voltage steps, as well as lower ripple component in the output current for the same carrier frequency. These features lead to significant advantages for motor drives in the form of lower stresses to the motor windings and bearings, less influence of noise to the adjacent equipment, etc. However, the general-purpose NPC inverter still has a diode rectifier front end and, thus, has input current harmonic problems similar to conventional drive systems. Active front-end rectifier circuits for harmonic reduction can be employed, but it makes the system bulky and expensive.

EMI filters that attenuate the high-frequency normal-mode current and shunt the common-mode currents at the input side of the power converter have been a traditional solution of effectively reducing conducted EMI. However, large grounding capacitors are necessary to obtain lower common-mode impedance to shunt the common-mode current in order to meet strict EMI standards similar to the CISPR-11 standard. The need for large capacitance between line and ground increases ground leakage current that has power supply frequency components along with its harmonics. This can pose safety problems to human beings. Even farm animals on ranches that employ inverters for milk production are said to be vulnerable to ground current effects.

Common-mode filters (CMFs) are used for reducing common-mode voltage, shaft voltage, and bearing current. Reduction in common-mode voltage results in reduced common-mode current and, hence, lower conducted EMI. Employing CMF thus leads to minimization of input EMI filtering requirement. This can potentially reduce the value of the filter capacitor in the traditional input EMI filter, thereby improving safety levels.

In spite of the various advances made in addressing input and output power pollution caused by voltage-source PWM inverters, there is still a need for a converter that addresses both the input and output power pollution problems in an easier way without a need for large external peripheral equipment. Such a drive would then be able to achieve an environmentally harmonious system. One converter topology that shows promise in realizing this goal is the matrix converter [14].

II. ADVANTAGES OF MATRIX CONVERTER

A viable solution to address the problems listed in Section I is to employ a matrix converter. The output phase voltage in a matrix converter has three levels since it is constructed using the three available input phase voltages. Since the output voltage levels transit through the midlevel of the three available input voltages, the step change in the output voltage as well as in the common-mode voltage is generally lower than that in a conventional two-level voltage-source PWM inverters. One way of reducing the common-mode voltage in a matrix converter is to deliberately choose the input phase voltage with the median value to form the zero vector component, resulting in smaller step changes in the common-mode voltage as has been done in [15]. Although the selection is made such that the active voltage vector is not altered, the restrictions imposed on the choice of output vectors result in poorer output voltage waveform quality and increased harmonic flux in the machine [15]. Deliberately always choosing the median voltage to form the zero vector state introduces extra switching state and increases the effective switching frequency that is typically associated with higher loss in the converter. The strategy proposed in [15] does not eliminate the common-mode voltage—It only reduces the level by about 34% throughout the linear modulation range. Even without deliberately choosing the median voltage to form the zero vector state, the matrix converter exhibits lower voltage step size in the common-mode voltage waveform and enables easier filtering.

TABLE I
COMPARISON OF FEATURES BETWEEN TWO-LEVEL INVERTER AND MATRIX CONVERTER

Performance Parameter	Two-level Inverter	Matrix Converter
Input Current THD	high	low
Common mode voltage step	large	small
Common mode current	high	low
Shaft voltage step	large	small
Bearing current	high	low
EMI at 150kHz	Fails CISPR 11	Fails CISPR 11

The input to the matrix converter is an ac voltage source, whereas the load on the matrix converter is an induction motor, which is inductive in nature. Since the current into the inductive load is switched from one phase to the other, it can create interference and can stress the input ac source. To prevent this, ac capacitors are used at the input of the matrix converter, which then absorb the switching ripple current component. In order to prevent import of harmonics from external sources into the input capacitor, an inductor is used, the addition of which forms a low-pass input filter. The components of the input LC filter are chosen to filter the carrier-frequency components of the matrix converter. The operation of the matrix converter in conjunction with the low-pass input LC filter results in a sinusoidal input ac current. The presence of an input LC filter provides a stable neutral point and facilitates further filter integration. A summary of the advantages of a matrix converter over two-level voltage-source inverter is given in Table I.

Fig. 1 compares the common-mode voltage in a matrix converter with that in a conventional two-level inverter. The common-mode voltage steps are much smaller in the matrix converter, resulting in potentially lower common-mode current, shaft voltage, and bearing current. Thus, the matrix converter topology lends itself to easier filtering. Integration of different filters to achieve a low-noise drive that has lower ground current and higher safety margin is the thrust of this paper.

From the explanations provided thus far on the operation of the matrix converter, it can be said that the performance of the matrix converter is similar to a three-level inverter. Since the

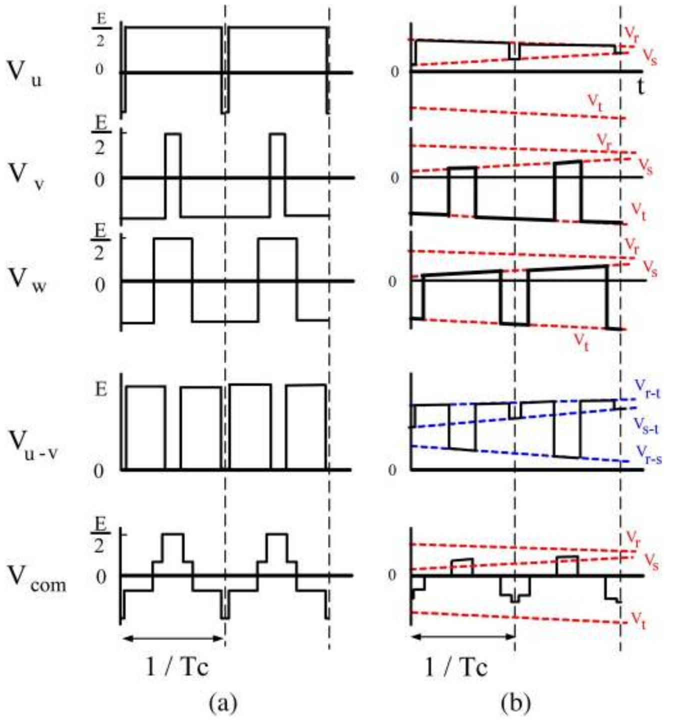


Fig. 1. Common-mode voltage in two different types of motor controllers, both employing three-phase modulation. (a) Two-level inverter. (b) Matrix converter.

matrix converter is an inherently regenerative drive, it is fair to compare it with a back-to-back three-level voltage-source inverter. Salient comparison points are briefly discussed as follows.

1) A matrix converter uses 18 semiconductor switching devices, whereas a comparable three-level back-to-back voltage-source inverter employs 24 devices.
2) A matrix converter does not need smoothing dc bus capacitor and the associated soft-charge circuit.
3) In the case of a back-to-back voltage-source inverter, two or three of the input phases are always connected together, resulting in large amplitude of switching frequency component at the input terminals. In order to reduce its influence on the power system, large smoothing inductors along with some passive components are needed. In the case of matrix converter, a given input phase is either connected to the motor or is left floating (turned off). The switching frequency component amplitude that needs to be attenuated is, thus, much smaller and results in a much smaller input filter.
4) Control scheme of a matrix converter is complex because of the absence of the dc bus capacitor, which is instrumental in separating the front-end PWM rectifier from the motor-side inverter in the case of a voltage-source inverter. However, recent progress in control concepts has reduced the severity of this drawback significantly.

III. FILTER CIRCUIT CONFIGURATION AND DESIGN

Various additional filters, which are required to achieve a low-noise motor drive system, can be easily integrated with the matrix converter. In this section, normal-mode noise and common-mode noise reduction techniques applied at the output side of a matrix converter employed for controlling a motor are discussed.

Fig. 2 shows the main power circuit of the matrix converter along with the proposed input and output filter configurations. In addition to the standard input low-pass LC filter, a small-sized input EMI filter is added to provide filtering for conducted EMI.

As mentioned in the preceding section, the input LC filter (shown as $L_{\rm in}$ and $C_{\rm O}$ in Fig. 2) is employed to filter the PWM switching frequency so that the switching frequency components do not influence the power system. Although the design and performance specifications for the input LC filter is not part of the topic under consideration here, to satisfy the curiosity of the reader, the resonant frequency of the input LC filter is selected to be much higher than the input supply frequency and significantly lower than the PWM switching frequency. Typically, the resonant frequency is 20 times the supply frequency and about one-third the PWM switching frequency.

The output section consists of a normal-mode filter (NMF) to provide sinusoidal output voltage waveform at the motor terminals. A CMF is also employed at the output in order to attenuate the common-mode voltage and, hence, the common-mode current. Shaft voltage, which mimics the common-mode voltage, also reduces, and this helps reduce the bearing current. Design issues for these filters are discussed next.

A. NMF

The NMF is used to filter the output PWM waveform so that the line-to-line voltage at the motor terminals is sinusoidal. This also helps in alleviating the problems associated with high dv/dt of the output voltage that causes high surge voltages at the motor terminals.

The resonance frequency f_r of NMF is chosen to be in between the output fundamental frequency $f_{\rm out}$ and the carrier frequency f_c. However, while selecting the resonant frequency, the influence of the leakage inductance of the motor should also be considered. Since the induction motor can be modeled with a back electromotive force and a leakage inductance $L_{\rm lkg}$, the effective inductance of the filter is the parallel combination of the filter inductor L_n and the leakage inductance $L_{\rm lkg}$ of the motor. Consequently, the resonance frequency equation uses the effective value of the inductance $L_{\rm eff}$ and the filter capacitance C_n, i.e.,

$$f_r = \frac{1}{2\pi\sqrt{L_{\rm eff}C_n}} \tag{1}$$

$$L_{\rm eff} = \frac{L_n L_{\rm lkg}}{L_n + L_{\rm lkg}}. \tag{2}$$

In order to limit the carrier-frequency current into the filter capacitor, the value of the filter inductor L_n should be large. However, excessively large values for the filter inductance L_n should be avoided to limit the fundamental frequency voltage drop across it under loaded conditions.

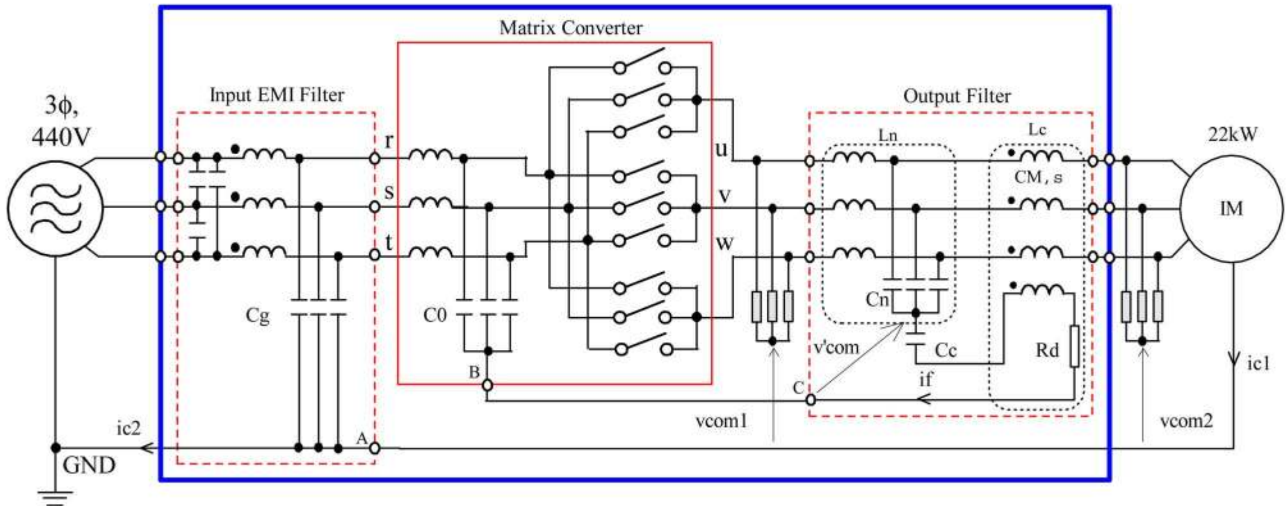


Fig. 2. Configuration of the proposed circuit.

As mentioned earlier, the resonance frequency f_r should be in between the fundamental output frequency f_{out} and the carrier frequency f_c, i.e., $f_{\text{out}} \ll f_r \ll f_c$. Once the resonance frequency f_r and the filter inductance L_n are selected, the filter capacitor C_n is obtained from (1) with a knowledge of L_{lkg}.

Based on the aforementioned design guidelines, an NMF was designed for a matrix converter rated at 22 kW, 460 V, with an output current rating of 50 A, and operating at a carrier frequency of 8 kHz. The value of the NMF filter inductance L_n is selected to be 0.98 mH to limit the voltage drop across it at 60 Hz and 50 A to an acceptable level. Typical leakage inductance of a motor for this application was found to be 4.2 mH. Based on this information, the effective inductance was calculated to be 0.8 mH. The resonant frequency f_r is selected to be around 3 kHz, which is higher than 60 Hz and lower than the carrier frequency of 8 kHz. For this resonant frequency, the filter capacitor C_n is computed to be 3.3 μF. Fig. 3 shows the measured impedance and phase characteristics of the NMF with the induction motor connected to the output of the NMF. The sweep frequency for the measurement ranged from 100 Hz to 10 MHz. Fig. 3 also shows multiple resonance points beyond the first marked resonant point. The higher order resonance points are due to the parasitic capacitance across the filter inductance. It shows that the parasitic effects dominate at higher frequency. It adversely affects the filter performance and hence should be given due consideration, especially while designing filters for filtering conducted noise spectrum.

B. CMF

The CMF is used for attenuating the common-mode voltage and, hence, the common-mode leakage current through the motor and cable. Common-mode voltage causes shaft voltage that is responsible for bearing current. Thus, the CMF also helps in attenuating the shaft voltage and, hence, the bearing current in the motor.

The common-mode voltage is defined as the voltage between the electrical neutral of the inverter output and a reference point. The reference point is usually the ground potential of the system. From a high-frequency point of view, the dc bus midpoint (in voltage-source inverters) can be considered to be at the ground potential and, thus, can be viewed as the reference point. In a matrix converter, there is no dc bus. However, the input section consists of a low-pass LC filter that has a floating neutral formed by the filter capacitors, as shown in Fig. 2. This floating neutral can be considered to be a reference point from common-mode voltage point of view.

The principle behind canceling the common-mode voltage using a four-winding common-mode choke is described in [9]. To obtain the common-mode voltage, the authors in [9] employed a three-phase common-mode voltage-sensing transformer that shows high normal-mode impedance but low common-mode impedance. In this application, since the neutral of the NMF is available, there is no need to use a common-mode voltage-sensing transformer. The design philosophy of the four-winding common-mode inductor is briefly described next.

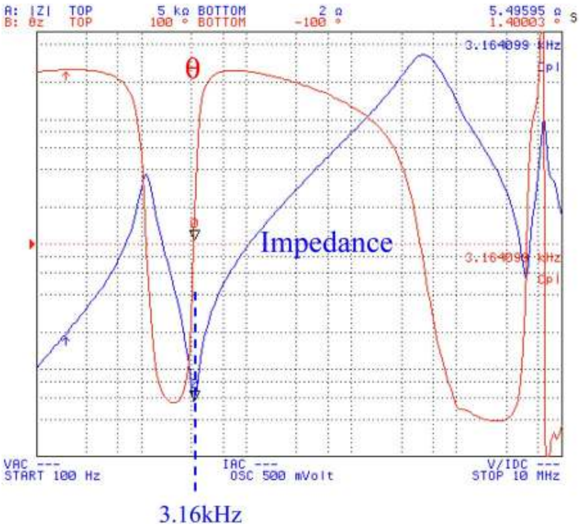


Fig. 3. Impedance and phase angle versus frequency characteristics of NMF (including motor impedance).

There are two important criteria that have to be satisfied while designing the four-winding common-mode choke.

1) The voltage across the fourth winding of the common-mode choke should not cause it to saturate.
2) The current through the fourth winding should be limited to a safe value to protect the insulated gate bipolar transistors (IGBTs).

The inductance of the fourth winding is selected so as to limit the current through it to a safe and low value well below the rating of the matrix converter. A suitable core is selected that can accommodate all the four windings, keeping in mind that three of the four windings need to carry rated current of the matrix converter. Based on the desired inductance value and a suitable core, the number of turns needed is calculated from the core manufacturer's data sheet. This procedure entails some amount of trial and error because achieving any desired inductance is a compromise between core area and number of turns.

Once a core area and number of turns are selected, (3) is used to estimate the flux density to ensure that the core will not saturate when rated voltage is impressed across the fourth winding. In (3), N is the number of turns, $V_{\mathrm{cc(rms)}}$ is the root-mean-square (rms) value of the common-mode voltage, B_m is the peak flux density, A_e is the core cross-sectional area for the flux path, and f_c is the carrier frequency, i.e.,

$$B_m = \frac{V_{\mathrm{cc(rms)}}}{4.44 \cdot f_c \cdot N \cdot A_e}. \tag{3}$$

If the estimated flux density is higher than that suggested by the core manufacturer, the number of turns or the core area or both are adjusted to fall within compliance.

As mentioned earlier, because of the proposed integration scheme, there is no need to employ a common-mode voltage-sensing transformer. Instead, the neutral of the NMF is used as the common-mode voltage sense point. The value of the capacitors used in the NMF is dictated by the design of the NMF and, hence, cannot be altered. In order to effectively impress the common-mode voltage across the fourth winding, the inductance of the fourth winding L_c in combination with the common-mode capacitance formed by three parallel capacitors C_n should form a resonant circuit such that the resonant frequency is much higher than the fundamental output frequency and much lower than the carrier frequency of the common-mode voltage, which is very similar to the criterion outlined while determining the resonant frequency of the NMF. Since neither C_n nor L_c can be altered significantly, a series capacitor C_c, the value of which can be altered, is added to tune this circuit to meet the frequency criterion, i.e., $f_{\mathrm{out}} \ll f_{\mathrm{rcom}} \ll f_c$. f_{rcom} is the resonant frequency of the common-mode circuit. Correct choice of C_c ensures full common-mode voltage to appear across L_c, thereby effectively canceling it and preventing it from appearing at the motor terminals. A damping resistor R_d is used for dampening the oscillations in the fourth winding circuit.

Unlike the strategy proposed in [15], the filtering technique advocated here cancels the common-mode voltage such that there is no common-mode voltage at the motor terminals and, hence, no shaft voltage.

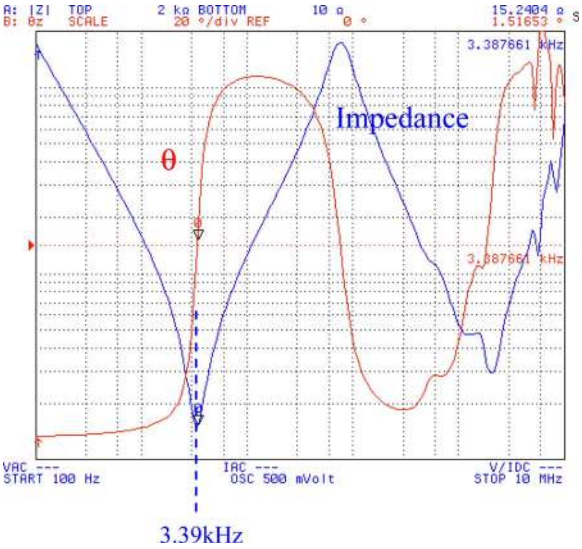


Fig. 4. Impedance and phase angle versus frequency characteristics of CMF.

Based on the aforementioned guidelines, a CMF was designed for the same matrix converter specified earlier. The inductance of the CMF was designed to be 3.85 mH. This value of inductance was large enough to limit the flow of common-mode current through the fourth winding. C_c was calculated to be about 1 μF such that the resulting resonant frequency is around 2.6 kHz, which is higher than the maximum fundamental frequency and much lower than the 8-kHz carrier frequency of the matrix converter.

Fig. 4 shows the measured impedance and phase characteristics of the CMF. The sweep frequency for the measurement ranged from 100 Hz to 10 MHz. The measured value of the CMF inductance was only 2.3 mH, resulting in the actual resonant frequency of the common-mode circuit to be around 3.5 kHz, as shown in Fig. 4. This value still meets the frequency criterion discussed earlier. Similar to the parasitic effect observed in Fig. 3 with regard to the NMF, parasitic effects are observed in Fig. 4 as well. In this case, as will be explained later, the effects are quite serious and detrimental to the proper operation of the CMF. Care should be taken to reduce the winding parasitic capacitance to improve the conducted EMI performance. This topic will be further discussed in Section V.

Fig. 5 shows the effect of the proposed integrated filter on performance issues that include input current harmonic distortion, normal-mode voltage, common-mode voltage and current, shaft voltage v_{shaft}, and bearing current i_b [16]. In order to provide a fair comparison, Fig. 5 also includes results obtained from a conventional two-level inverter and matrix converter without additional filters. Carrier frequency of the two-level inverter as well as the matrix converter is set at 8 kHz. The definition of the labels in Fig. 5 is given in Fig. 2.

Fig. 6 shows the actual unit of an environmentally harmonious power converter—a complete system that consists of the integrated filter and a matrix converter. The dimensions of the matrix converter integrated with the filters, as shown in Fig. 6,

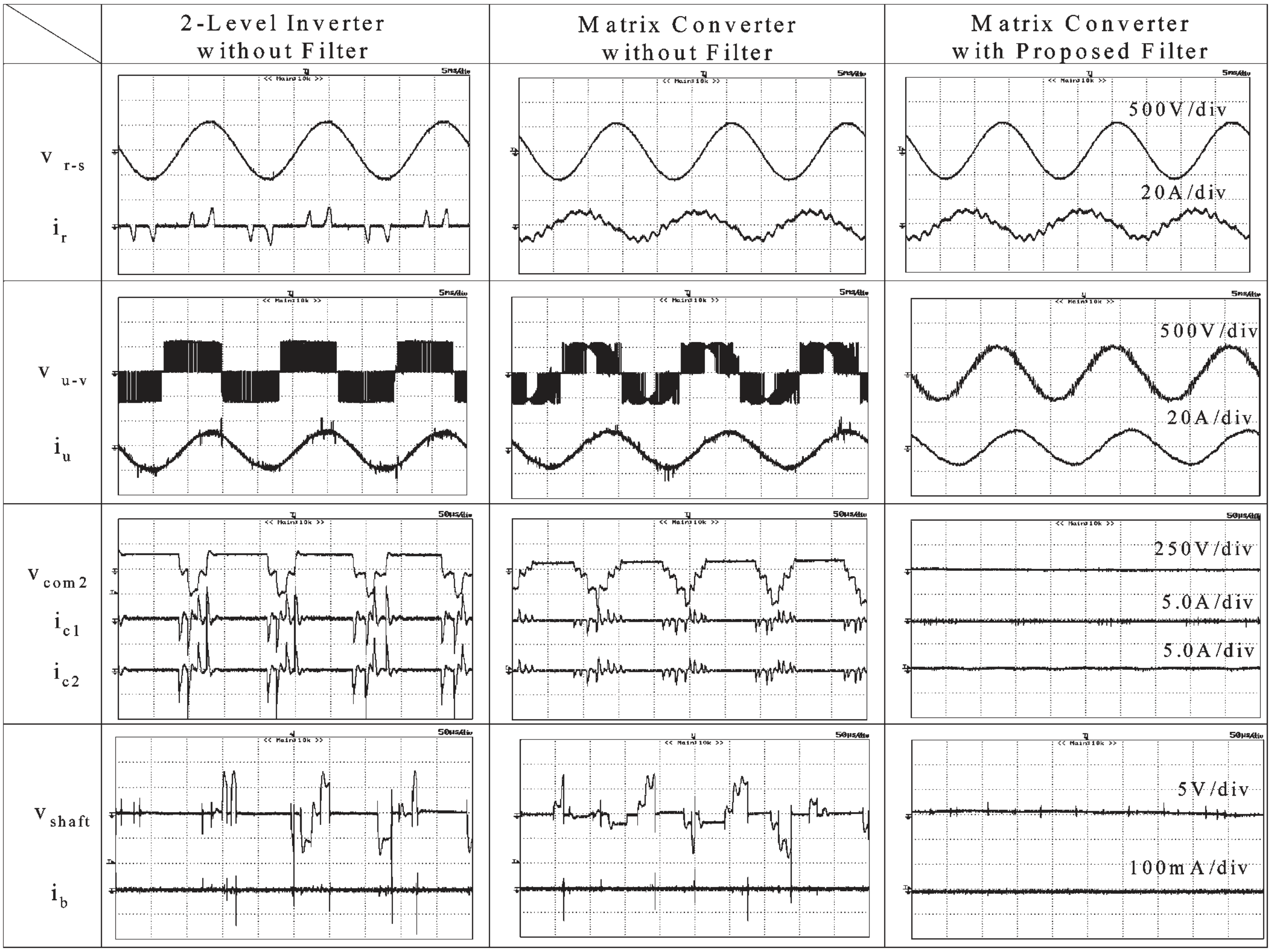


Fig. 5. Comparison of experimental results.

Fig. 6. A 400-V 22-kW environmentally harmonious matrix converter.

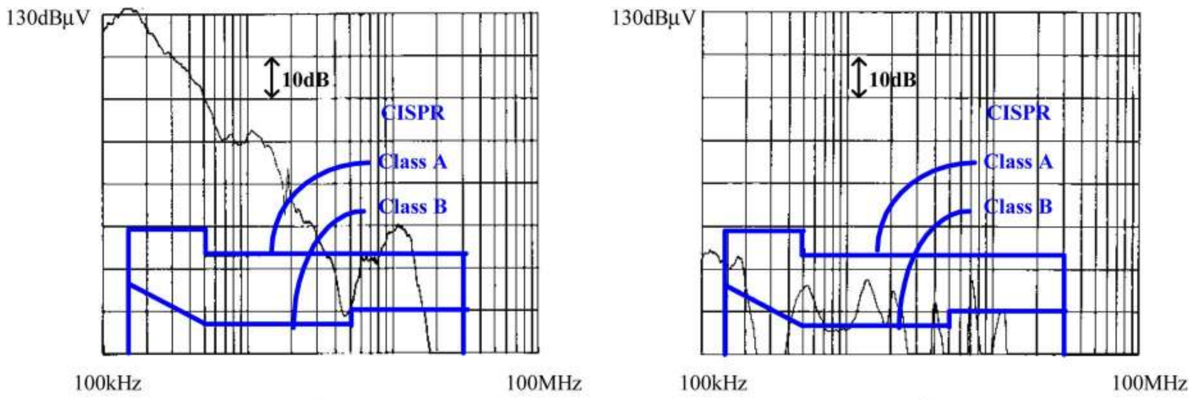
are as follows: width, 530 mm; height, 700 mm; and depth, 290 mm. An equivalent back-to-back voltage-source inverter with similar integrated filter would have occupied 37% more volume than the matrix converter of Fig. 6.

C. Influence of Integrated Filter on Efficiency and Performance

Adding filtering components to a power converter is generally associated with losses and hence can be said to reduce the overall efficiency. Tests were conducted with and without the integrated filters to quantify the reduction in efficiency when the filters were employed. In the case of the filter designed here, tests showed that the efficiency of the matrix converter with integrated filter reduced by 1.5%.

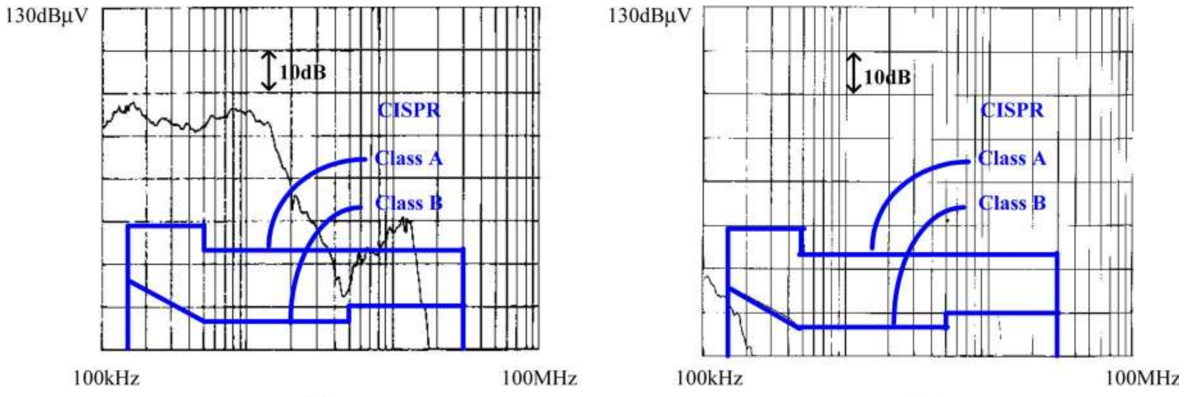
However, there are technical publications [17], [18] that show the significant improvement in motor efficiency when a motor is supplied with sinusoidal waveform compared to PWM waveform. Although such estimation is left for future work here, the authors expect that the improvement in motor efficiency masks the increased losses due to filtering, thereby keeping the system losses at the same level.

Influence of introducing output filters on the dynamic performance of the matrix converter should also be considered. Since the matrix converter is intended for use in an industrial setting, the dynamic response in such applications is typically limited to 200 Hz. The NMF designed here has a resonant frequency of 3 kHz and is seen not to affect the dynamic performance of the drive system.



(a) (b)

Fig. 7. Effect of EMI filter on the conducted EMI without CMF. (a) Without EMI filter. (b) With EMI filter ($C_g = 1\ \mu$F).



(a) (b)

Fig. 8. Effect of EMI filter on the conducted EMI with CMF. (a) Without EMI filter. (b) With EMI filter having reduced capacitance ($C_g = 0.1\ \mu$F).

D. Effect of Input EMI Filter on the Power System

Fig. 7(a) shows the conducted EMI in a matrix converter without any filter, whereas Fig. 7(b) shows the same for a matrix converter with an input EMI filter. From Fig. 7(a), it is clear that the matrix converter cannot meet the strict CISPR-11 standards on its own. Even after employing a standard input EMI filter, from Fig. 7(b), it is seen that the resulting system meets class A, but not class B, of the CISPR-11 standards. It should be pointed out here that the results shown in Fig. 7 were obtained with no CMF at the output of the matrix converter.

The low-frequency ground leakage current can become high due to large values of the line-to-ground capacitors used in the input EMI filter. Large ground leakage currents can inadvertently trip the ground fault interrupter (GFI) relay, thereby shutting the electrical system down. Furthermore, large values of ground currents can corrode underground metallic pipes used in many industries and power generation plants. Ground currents have also been linked to lower milk production in dairy farms.

The value of the EMI filter capacitor can be minimized by taking advantage of the output CMF, which helps reduce the common-mode current. This is important since it would reduce the leakage current into the system ground and improve safety levels while using EMI filters. Results of such an investigation are presented next.

IV. OPTIMIZING THE INPUT EMI FILTER

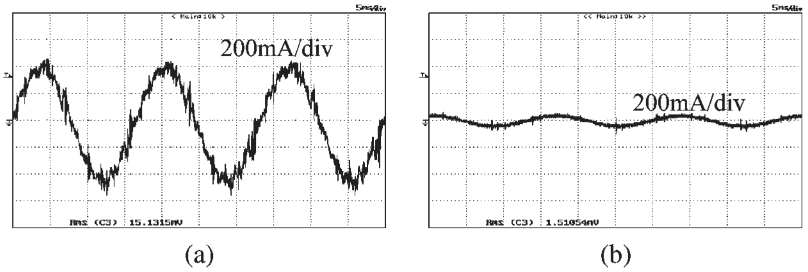
From Fig. 7(b), it is seen that in order to meet CISPR-11 class B level, the value of the line-to-ground capacitor needs to be greater than 1 μF. A larger value of line-to-ground capacitance could lead to safety problems for humans and animals alike. The supply frequency ground leakage current for a grounded delta system is given by

$$I_{\text{leak}} = \sqrt{3} \cdot V_{\text{l-l}} \cdot \omega \cdot C_g. \tag{4}$$

In (4), $V_{\text{l-l}}$ is the rms value of the line-to-line voltage. On the assumption that the power source is a grounded delta system with a line-to-line voltage of 440 V, the leakage current is computed to be 287 mA for a supply frequency of 60 Hz and C_g of 1.0 μF.

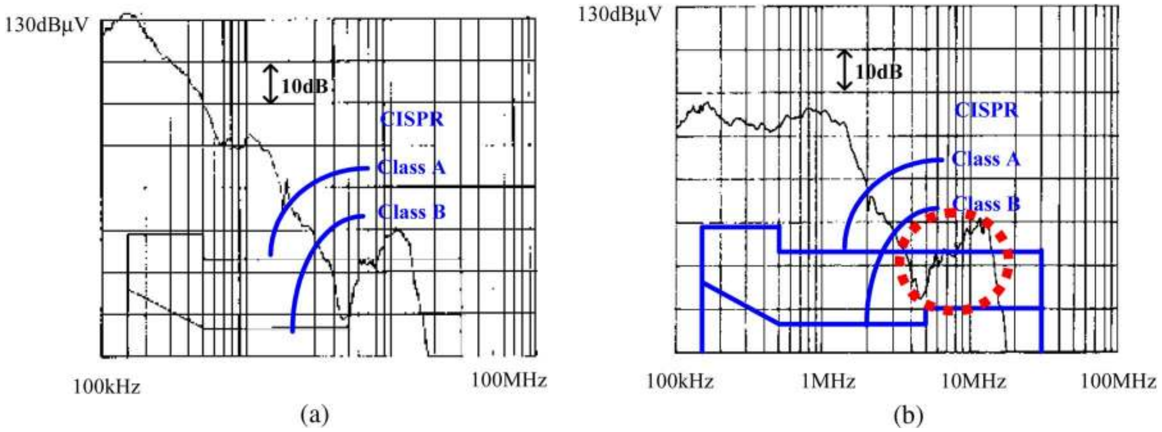
Fig. 8 shows the conducted EMI test result of a matrix converter with an output CMF. Comparing Figs. 7(a) and 8(a), the conducted EMI at 150-kHz is seen to have decreased by 20 dB or more. This means that line-to-ground capacitance can be reduced to one-tenth of its old value. Therefore, supply frequency ground leakage current can be reduced to one-tenth of its original value.

Fig. 8(b) shows the results with the reduced value of input EMI filter capacitors. It is clear that the performance has not



(a) (b)

Fig. 9. Ground leakage current measurement results. (a) $C_g = 1.0\ \mu$F. (b) $C_g = 0.1\ \mu$F.



(a) (b)

Fig. 10. Comparison of conducted EMI with and without CMF. Circled area shows ineffectiveness of CMF in the megahertz range due to parasitic capacitance. (a) Without CMF. (b) With CMF.

deteriorated and the resulting worst case ground current is theoretically estimated to have reduced.

Fig. 9(a) shows the leakage current measurement result when the line-to-ground capacitance in the input EMI filter is 1.0 μF. Fig. 9(b) shows the same after the line-to-ground capacitance is reduced to 0.1 μF. A 440-V delta system with one of the phase grounded was used as the power source for this measurement. From these results, it is clear that the leakage current has significantly reduced, and integrating the input EMI filter with CMF, as shown here, is expected to alleviate problems caused by large leakage currents.

V. PARASITIC EFFECTS IN CMF

Fig. 4 also shows multiple resonance points beyond the first marked resonant point. The parasitic capacitance across the start and end of a phase winding is thought to be the major contributor to the high-frequency multiple resonant points. It shows that the parasitic effects dominate at higher frequency, setting up multiple resonance points. The effect of parasitic capacitance can be observed on comparing Fig. 10(a) and (b). From Fig. 10, it can be concluded that due to the parasitic capacitance, the attenuation of conducted noise in the megahertz range is poor. In order to confirm the observed results of Fig. 10, the gain versus frequency of the CMF by itself was measured using an impedance analyzer. The plot is shown in Fig. 11. It can be seen that the parasitic capacitance causes the gain to reverse its trend at the resonant points. The ideal gain plot is shown as a dashed line.

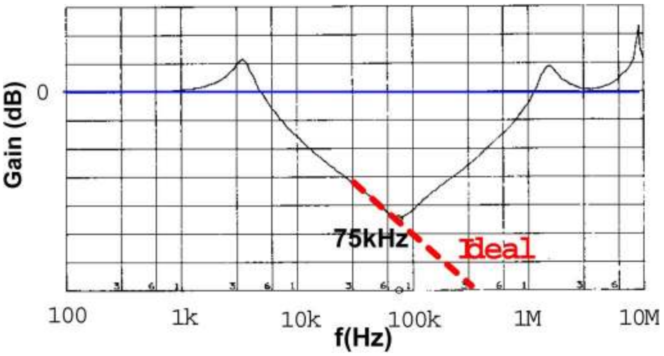


Fig. 11. Plot of gain (in decibels) versus frequency (in hertz) for the CMF used. Due to parasitic capacitance, the gain plot shows increase in gain above the parasitic resonance point of around 75 kHz. Ideal plot is shown by dashed line.

A model was developed based on measurements from an impedance analyzer. This model is shown in Fig. 12(a). Theoretical impedance versus frequency plot was also developed for the model of Fig. 12(a), which is shown in Fig. 12(c). From Fig. 12(c), it is clear that the proposed model mimics the high-frequency effect to a good degree. It is thus clear that by reducing the parasitic capacitance, the performance of the CMF in the megahertz range can be significantly improved.

VI. SUMMARY OF TEST RESULT

Table II compares the results observed thus far. When employing the proposed integrated filter with a matrix converter,

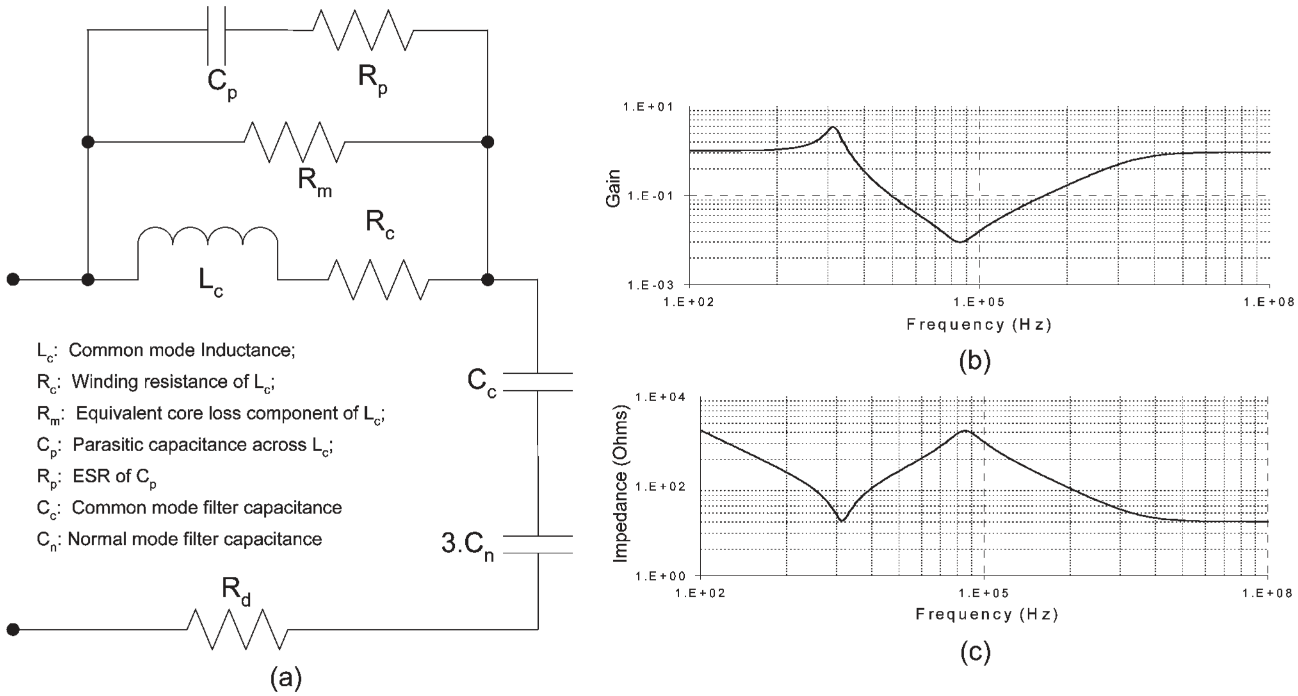


Fig. 12. Study of parasitic effects in CMF. (a) Theoretical model. (b) Gain versus frequency plot for the model. (c) Impedance versus frequency plot for the model.

TABLE II
COMPARISON OF PERFORMANCE

Performance Parameter	Two-level inverter without filter	Matrix converter without filter	Matrix Converter with proposed filter
EMI Noise level at 150kHz	> 130(dBμV) (fails CISPR 11, Class A and Class B requirements)	125(dBμV) (fails CISPR 11, Class A and Class B requirements)	< 66(dBμV) (passes CISPR 11, Class B requirements)
Common mode voltage step	200V	100V to 187V	Zero (non-existent)
Common mode current	6.5A(max)	3A(max)	0.25A (max)
Shaft voltage	7.5V(max)	7.5V(max)	2V(max)
Ground Leakage current	-	300mA(rms) *1	30mA(rms)*1
Bearing current	0.4A(max)	0.3A(max)	Zero (non-existent)
THD of input current	> 75% (no-load operation)	< 10% (no-load operation)	< 10% (no-load operation)

*1 When employing a 440V delta power supply with a grounded phase as the power source.

an ideal type of power converter may be promoted as an environmentally harmonious drive system.

- The proposed circuit can pass the strict CISPR-11 class B standard. It means that this system is suitable for hospital and household applications.
- Common-mode voltage at motor side is cancelled and is almost zero. Therefore, common-mode current, shaft voltage, and bearing current are suppressed effectively. Common-mode current is seen to have become less than one-tenth of its original value, shaft voltage is seen to have reduced to less than one-third of its original value, and bearing current is seen to have become almost zero. Lower common-mode components prevent motor bearing damage and provide for a long-life motor drive system.
- Ground leakage current is also reduced even on employing input EMI filter to meet the CISPR-11 class B standard. Since the grounding capacitors of input EMI filter can be minimized due to the effect of integrating it with the CMF, the ground leakage current is shown via simulation to have reduced to one-tenth of its original value.
- Input current harmonics is also reduced because of the basic nature of a matrix converter. Input current total harmonic distortion is seen to be less than 10% even under no-load condition.

VII. CONCLUSION

A matrix converter with integrated filter is proposed to achieve an environmentally harmonious system with low input current distortion, low output voltage distortion, low EMI, and with no common-mode voltage. Salient features of the proposed integrated filtering system are as follows.

1) The matrix converter with the proposed integrated filter is seen to have sinusoidal normal-mode voltage across the motor terminals.
2) Tests conducted on the output filter show that the matrix converter efficiency reduces by only 1.5% for the size discussed in this paper.

3) Common-mode voltage, shaft voltage, common-mode current, and bearing current are seen to have been eliminated on using the proposed integrated filter system.
4) Conducted EMI has been significantly reduced in the proposed integrated filter system, and the system can now be said to comply with CISPR-11 class B levels.
5) The value of the line-to-ground capacitance in the input EMI filter has been reduced from 1.0 to 0.1 μF, resulting in a significant reduction in the ground leakage current, thereby alleviating problems arising due to nuisance ground fault currents.
6) The size of the matrix converter with the integrated filter is observed to be 27% smaller in volume compared to a comparable back-to-back voltage-source inverter.

REFERENCES

[1] G. L. Skibinski, R. J. Kerkman, and D. Schlegel, "EMI emissions of modern PWM ac drives," *IEEE Ind. Appl. Mag.*, vol. 5, no. 6, pp. 47–80, Nov./Dec. 1999.

[2] D. Paice, *Power Electronic Converter Harmonics*. Piscataway, NJ: IEEE Press, 1995.

[3] *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, IEEE Std. 519-1992.

[4] M. M. Swamy and S. Rossiter, "Case studies on mitigating harmonics in ASD systems to meet IEEE 519-1992 standards," in *Proc. IEEE IAS Annu. Meeting*, 1994, pp. 685–692.

[5] Y. Murai, T. Kubota, and Y. Kawase, "Leakage current reduction for a high-frequency carrier inverter feeding an induction motor," *IEEE Trans. Ind. Appl.*, vol. 28, no. 4, pp. 858–863, Jul./Aug. 1992.

[6] S. Ogaswara and H. Akagi, "Modeling and damping of high frequency leakage currents in PWM inverter-fed ac motor drive systems," in *Proc. IEEE IAS Annu. Meeting*, 1995, pp. 29–36.

[7] S. Ogaswara, H. Ayano, and H. Akagi, "Measurement and reduction of EMI radiated by a PWM inverter-fed ac motor drive system," in *Proc. IEEE IAS Annu. Meeting*, 1996, pp. 1072–1079.

[8] A. von Jouanne, D. Rendusara, and P. Enjeti, "Filtering techniques to minimize the effect of long motor leads on PWM inverter-fed ac motor drive systems," *IEEE Trans. Ind. Appl.*, vol. 32, no. 4, pp. 919–926, Jul./Aug. 1996.

[9] M. M. Swamy, K. Yamada, and T. Kume, "Common mode current attenuation techniques for use with PWM drives," *IEEE Trans. Power Electron.*, vol. 16, no. 2, pp. 248–255, Sep. 2001.

[10] H. Akagi and T. Doumoto, "An approach to eliminating high frequency shaft voltage and leakage current from an inverter driven motor," in *Proc. IEEE IAS Annu. Meeting*, 2003, pp. 452–458.

[11] S. Ogaswara, H. Ayano, and H. Akagi, "An active circuit for cancellation of common-mode voltage generated by a PWM inverter," in *Proc. IEEE PESC*, 1997, pp. 1547–1553.

[12] I. Takahashi, A. Ogata, H. Kanajawa, and A. Hiruma, "Active EMI filter for switching noise of high frequency inverters," in *Proc. IEEE PESC*, 1997, pp. 331–334.

[13] H. P. Krug, T. Kume, and M. Swamy, "Neutral point clamped three-level general purpose inverter—Features, benefits, and applications," in *Proc. IEEE PESC*, 2004, pp. 323–328. CD-ROM.

[14] J. K. Kang, H. Hara, E. Yamamoto, E. Watanabe, A. M. Hava, and T. J. Kume, "The matrix converter drive performance under abnormal input voltage conditions," *IEEE Trans. Power Electron.*, vol. 17, no. 5, pp. 721–730, Sep. 2002.

[15] H. J. Cha and P. Enjeti, "An approach to reduce common-mode voltage in matrix converter," *IEEE Trans. Ind. Appl.*, vol. 39, no. 4, pp. 1151–1159, Jul./Aug. 2003.

[16] K. Yamada *et al.*, "Filtering techniques for matrix converter to achieve environmentally harmonious drives," in *Proc. EPE*, 2005.

[17] A. Boglietti, P. Ferraris, M. Lazzari, and M. Pastorelli, "Influence of inverter characteristics on the iron losses in PWM inverter-fed induction motors," *IEEE Trans. Ind. Appl.*, vol. 32, no. 5, pp. 1190–1194, Sep./Oct. 1996.

[18] J. Huppunen and J. Pyrhonen, "Filtered PWM-inverter drive for high-speed sold-rotor induction motors," in *Proc. IEEE Ind. Appl. Annu. Meeting*, 2000, pp. 1942–1949.

Tsuneo (Joe) Kume (S'69–M'70–LM'03–LS'04–LF'05) received the B.S. degree in electrical engineering from Waseda University, Tokyo, Japan, in 1960, and the M.S. and Ph.D. degrees in electrical engineering from the University of Missouri, Columbia, in 1968 and 1970, respectively.

In 1960, he joined Yaskawa Electric Corporation, Kitakyushu, Japan. In 1966, he was on a leave of absence to study at the University of Missouri. After returning to Yaskawa Electric Corporation, he developed the first commercially produced general-purpose transistor PWM inverter. He also played key roles in developing the vector-controlled transistor inverter in 1979, which was successfully applied to drive systems in various fields such as machine tools and the iron and steel industry. He moved to the U.S. in 1996 to join Yaskawa Electric America, Inc., Waukegan, IL, as the Director of R&D, where he continued his activities in the field of power electronics and motor drives. Currently, he is a Technical Advisor with Yaskawa Electric Corporation, Kitakyushu, Japan.

Dr. Kume is a member of the Institute of Electrical Engineers of Japan.

Kenji Yamada received the B.E. degree from the Science University of Tokyo, Chiba, Japan, in 1991.

In 1991, he joined the Research Laboratory, Yaskawa Electric Corporation, Kitakyushu, Japan. In 1997, he moved to the Development Center, Yaskawa Electric Corporation, and in 1999, to the Design Section of the Inverter Plant in the same company at Yukuhashi, Japan. In 2000, he developed the first commercially produced 400-V class general-purpose three-level NPC inverter in the world. Since 2002, he has been with the Corporate R&D Center, Yaskawa Electric Corporation, as a Manager. His research interests include motor drives and various power conversion techniques and topologies.

Mr. Yamada is a member of the IEEE Power Engineering Society and the IEEE Electromagnetic Compatibility Society. He is also a member of the Institute of Electrical Engineers of Japan.

Tsuyoshi Higuchi received the B.S. and M.S. degrees in electrical and electronics engineering from Kagoshima University, Kagoshima, Japan, in 2000 and 2002, respectively.

He joined the Corporate R&D Center, Yaskawa Electric Corporation, Kitakyushu, Japan, in 2002. His research interests are in ac motor drives and mitigation techniques for EMI produced by power converters.

Mr. Higuchi is a member of the Institute of Electrical Engineers of Japan.

Eiji Yamamoto received the B.S. degree in mechanical engineering from Kyushu University, Fukuoka, Japan, in 1991.

He joined the Research Center, Yaskawa Electric Corporation, Kitakyushu, Japan, in 1991. He was with the Development Center from 1997 to 2002 and moved to the Electrical Design Section, Inverter Technology Department, Drives Division, Yaskawa Electric Corporation, Yukuhashi, Japan, in 2002. His interests include ac motor drives and various power topologies for inverter applications.

Mr. Yamamoto is a member of the Institute of Electrical Engineers of Japan.

Hidenori Hara received the B.S. and M.S. degrees in electrical engineering from Nagasaki University, Nagasaki, Japan, in 1995 and 1997, respectively.

He joined the Development Center, Yaskawa Electric Corporation, Kitakyushu, Japan, in 1997. In 2002, he moved to the Electrical Design Section, Inverter Technology Department, Drives Division, Yaskawa Electric Corporation, Yukuhashi, Japan. His interests include ac motor drives and matrix converter topologies.

Mr. Hara is a member of the Institute of Electrical Engineers of Japan.

Toshihiro Sawa received the M.S. degree in electrical and electronics engineering from Sophia University, Tokyo, Japan, in 1975.

In 1975, he joined Yaskawa Electric Corporation, Kitakyushu, Japan, where he was involved in the development and design of adjustable-speed ac motor drives. He is currently the Director and General Manager of the Motion Control Division.

Mr. Sawa is a member of the Institute of Electrical Engineers of Japan.

Mahesh M. Swamy (S'88–M'91) received the B.Eng. degree from Madan Mohan Malaviya Engineering College, Gorakhpur, India, in 1983, the M.S. (Eng.) degree from the Indian Institute of Science, Bangalore, India, in 1986, and the Ph.D. degree from the University of Victoria, Victoria, BC, Canada, in 1991.

In 1992, he joined Energy Management Corporation, Salt Lake City, UT, as a Senior Research Engineer, where he worked on industrial ac motor drives. In 1996, he joined MTE Corporation as the Director of Engineering. Since 1997, he has been with the R&D Group, Yaskawa Electric America, Inc., Waukegan, IL. His interests are in inverter drives and power electronics.

Dr. Swamy is a member of the IEEE Industry Applications Society and the IEEE Power Electronics Society.