Improvements in EMC Performance of Inverter-Fed Motor Drives

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***Abstract*— An experimental investigation of conducted radio-noise emission from a conventional pulse width modulated (PWM) inverter of medium power feeding an induction motor is described. It is determined that the inverter system generates considerable impulse currents through the power leads feeding the system resulting in serious conducted electromagnetic interference (EMI) problems and significant voltage waveform distortion in the power system. The dominant emission sources in the system are identified. A proposed model of the drive system for the purpose of evaluation of EMI are developed. Several low-cost strategies for improvement in EMC performance of the PWM inverter are then proposed. Experimental results demonstrate that disturbance from the modified system can be dramatically reduced and that the EMC performance of the system has come very close to meeting the IEC CISPR and FCC limits on conducted emissions for digital devices [1], [2], [7].**

I. Introduction

THE ROLE of static power converters in industrial and domestic applications has grown rapidly due to the ease in which power can be manipulated with high efficiency. As with most technological innovations, however, a complete understanding and solution of its negative side effects have lagged its introduction to the marketplace. For example, as the digital devices entered our world a few decades ago the inherent high switching frequency operation has lead to significant problems, i.e., electromagnetic interference (EMI) with communication and broadcast systems. The electromagnetic interference signals can be transmitted from any source to a susceptible unit by means of conduction, radiation, and common impedance coupling, or by any combination of these means and can result in unacceptable response or malfunction of victim device. To ensure the compatibility of devices operating in a common electromagnetic environment a new engineering discipline, electromagnetic compatibility (EMC), has evolved and EMC regulations set for several classes of products, including digital devices, have appeared in most major countries. For example, digital devices having clock frequencies that exceed 9 kHz cannot be legally sold in the United States unless they have been tested and found not to exceed limits on radiated and conducted emissions set by the Federal Communications Commission (FCC). One of the most important international standards setting organizations for commercial EMC is CISPR, the International Special Committee on Radio Interference in IEC (International Electrotechnical Commission), which develops recommended EMC test limits and test procedures. Most countries use CISPR standards for their own regulations. The European community (EC) approach has been to develop a common set of EMC requirements, which are collectively known as the European norms (EN's) and are largely based on CISPR and IEC standards. Thus far, concerns have focused mostly in low power level applications of digital devices. However, the imposition of standards there for high power equipment is rapidly approaching.

Paper IPCSD 95–52, approved by the Industrial Power Converter Committee of the Industry Applications Society for presentation at the 1994 IEEE Applied Power Electronics Conference and Exposition–APEC '94, Orlando, FL, February 13–17. This paper was supported by the Electric Power Research Institute (EPRI). Manuscript released for publication July 11, 1995.

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IEEE Log Number 9415007.

Disturbance problems involved in harmonic control over the power frequency range up to the 35th order resulting from the use of the static power converter, have been well addressed in numerous publications, and an application guide has been provided in IEEE Standard 519-1992 [3]. This publication, however, is not intended to cover the effects of radio frequency interference (RFI). Electromagnetic disturbance problems associated with the use of static power converters, especially for power drive systems, have not been well addressed nor have mandatory test requirements appeared as the FCC temporarily exempted five subclasses of digital devices from meeting the technical standards of the requirements in 1987 [1]. One of these exempted classes concerns industrial control systems used in an industrial plant, factory, or public utility. However, this exemption does not imply that EMC problems can be neglected in power drive applications because they are still subject to the general condition that no harmful interference be caused. In the industrial and domestic spheres, with its progressively increasing use of electronic control systems, data processing equipment, and other sensitive devices, the heart of matter is to what degree these high power converters will produce unwanted electromagnetic noises and interfere with nearby devices. If the interference is unacceptable, then the regulations concerned with this application will certainly appear and be imposed on those products for governing the EMC performance. Hence, it is of concern to all, that EMI problems be minimized even when standards do not presently exist.

There already exists a small body of literature concerning the EMI problems in static power converters [14]–[17]. In these references the RF noise emissions from power electronic devices were described in some particular applications, for

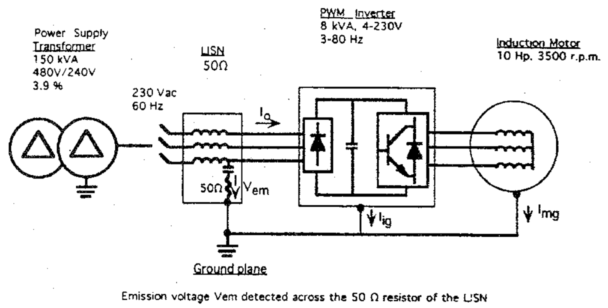


Fig. 1. Measurement of conducted radio noise emissions from inverter-motor drive.

instance the earlier SCR controlled converters [14]. Techniques for diagnosis and reduction of conducted noise emissions from a power supply filter was also proposed [15]. So far, however, the literature regarding EMI effects in high-power high-speed switching converters, especially in high-power motor drive systems is still lacking. For the purpose of this investigation a pulse width modulation (PWM) inverter of 8 kVA feeding an induction motor was chosen as the test equipment and measurements of conducted emissions from the system were conducted with reference to the standard procedures set for measuring EMI from digital devices [4]–[6]. The experimental results demonstrate that the PWM mode drive system clearly generates considerable impulse currents through the power leads resulting in serious EMI problems and significant voltage waveform distortion in the power system. The spectrum of these interference signals cover a wide frequency band, e.g., not only consisting of the components at the device switching frequency and their harmonics but also extending into the radio frequency band. Furthermore, the strength of these emissions far exceeds the standard limits for digital devices.

The essential switching behavior having an effect on radio noise emissions from the system during the switching period has been identified in this investigation. In particular, the combination of the switching action of solid state devices yielding a high rate of the change in voltage (dv/dt) upon the switched circuits and existing parasitic capacitance to ground produces charge/discharge impulse currents flowing through power mains and results in EMI problems. The nonlinear turn-on/off characteristics of the devices which generates higher-order harmonics worsen the situation. For analysis and reduction of conducted emission noise a model of the system and simulations for purpose of evaluation of EMI are developed. Several cost-effective strategies for improvement in EMC performance of the inverters are proposed. Experimental results demonstrate that the disturbance from the modified inverter drive system has been dramatically reduced and that the EMC performance of the system comes close to meeting the IEC CISPR and FCC limits on conducted emissions for digital devices.

II. Experimental Environment

In this study a commercial inverter feeding a induction motor through short feeder (1.5 m) was chosen as the equipment under test (EUT). The measurement configuration, shown in Fig. 1, includes the following components:

- Commercial Grade Transistor Inverter: 8 kVA, input 3-phase, 230 V, 24 A, 60 Hz; output 3-phase, 4-230 V, 22 A, 3-80 Hz; sinusoidal wave pulse width modulation (PWM) control; modular bipolar junction transistors 500 V, 40 A as the switching devices;
- Induction Motor: 10 hp, 3-phase, 60 Hz, 200 V, 3500 r/min, frame 254 U;
- Line Impedance Stabilization Network (LISN): 20 A, 230 V, 50 μH/ 50 Ω, having the required impedance characteristic over the specific frequency range, inserted individually between the power mains and inverter (EUT) in each phase;
- Ground Plane: aluminum sheet of 3 mm, 2×2 m in size.

The power mains in the test site were supplied through 35-m cables by a 150 kVA transformer as shown in Fig. 1. The calculated impedance of the power system at the terminals of test site is about 0.03 Ω for 60 Hz.

For the purpose of measurement of the EMI from this system, the standards listed in [4]–[7] were chosen as references. The LISN, inverter, motor, and all interconnected power lines were placed on the ground plane in the required configuration and equipment cases were directly bolted to ground, respectively.

As test instrumentation a spectrum analyzer with a peak detection function and an appropriate attenuator were used to measure the emission noise levels (in dBμV) so that the measured results are somewhat greater than quasi-peak detector function required by the FCC or CISPR by a few dB. Another instrument used for waveform observation was an oscilloscope with wide frequency bandwidth. Both the analyzer and oscilloscope cases were grounded at the same ground plane as specified. In addition to the voltage V_{em} across the 50 Ω at the LISN, the voltage and current waveforms in the system were also observed under different test conditions, including motor ground current I_g, common mode current of power mains I_0, etc.

Traditionally ac power line filters are utilized to reduce the RF noise emissions from the equipment, so that for comparison, two commercial power line filters were chosen. The circuit for the filters are shown in Fig. 12 and the values of their components are as follows:

- Filter #1: LC filter, 3×20 A, 250 V, $L_1 = 2.8$ mH, C_2 0.015 μF, $C_1 = 1$ μF;
- Filter #2: Feed-through capacitor, 3×30 A, 250 V, $C = 4.4$ μF.

The conducted emission noise from the test inverter-motor system was measured by picking up the radio-noise voltage V_{em} across the 50 Ω resistor of the LISN during appropriate test conditions as follows:

1) ambient noise only obtained by disconnecting the EUT;
2) inverter turned on but no load connected at its output terminals (open circuit);
3) inverter feeding induction motor operating at a certain frequency but with no external mechanical load applied (no load).

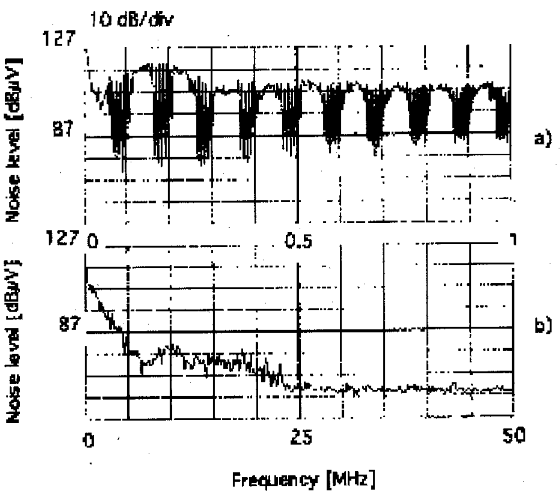


Fig. 2. Experimental conducted noise level from a conventional PWM inverter feeding induction motor. Noise detector: peak value, dBμV. (a) frequency range 0 Hz to 1 MHz. (b) frequency range from 0 Hz to 50 MHz.

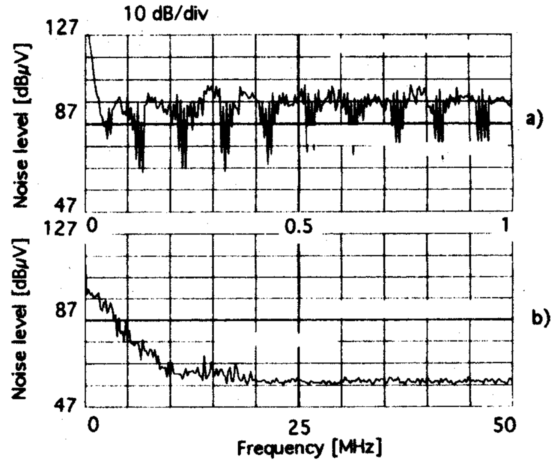


Fig. 3. Experimental conducted noise level from a conventional PWM inverter with no load connected. Noise detector: peak value, dBμV. (a) frequency range from 0 Hz to 1 MHz. (b) frequency range from 0 Hz to 50 MHz.

III. Conducted Emissions from EUT Without Compensation

A. Experimental Results

Conducted emission levels from the inverter-motor drive without compensation under prescribed test conditions are shown as Figs. 2 and 3. The voltage and current waveforms are shown in Fig. 4 and Fig. 5. The results are summarized as follows:

a) PWM operation of the inverter-motor system generates large impulse currents of a few amperes through the power mains which clearly result in electromagnetic interference (EMI) and voltage waveform distortion problems.

b) The emission levels depend on system configuration. The more sections in the system energized, the higher the emission level. Maximum emissions occur while the inverter feeds a motor load, resuling in 120 dBμV at the frequency range of 200 kHz, exceeding the CISPR standard limits by 40 dB. The spectrum of emissions features a broadband range from tens of kHz through 25 MHz which is clearly far away from the PWM switching frequency of 4 kHz and its harmonics. Therefore the operation of this inverter in a sensitive environment would surely result in a serious EMI problem.

c) The effects of waveform distortion in the power system appears especially in the line to ground voltage and line voltage as well as in the line current. The depth of the impulse notches of the line voltage exceeds 50 V, i.e., over 20% of the rated voltage. The greater the impedance of the power system the deeper will occur the notch in the voltage waveform. The waveform as shown in Fig. 4 was obtained when the inverter was supplied directly from the mains through a 150 kVA power transformer and through feeders having a length of about 35 m.

d) The observed impulse ground currents flowing from the motor frame or inverter enclosure will produce a common mode current of a few amperes in the leads of the mains. These impulse currents and the emission voltage measured at the LISN occur simultaneously during the switching instants of the devices, Fig. 5. If both the motor and inverter are isolated from ground, the common mode current and the noise voltage was observed to decrease to a very small value.

e) The voltage waveform of motor contains a ringing lasting a few micro seconds instead of a ideal square pulse from the PWM inverter, especially in the line-to-ground voltage of the motor. The current waveform of the motor also has an impulse component of a few amperes.

f) The fundamental current and voltage of the inverter output seem to apparently not affect the emission levels from the inverter-motor system (less than a few dB). Therefore, the inverter operating with a motor at 30 Hz was determined as the test condition in which the system generates maximum emission.

B. Explanations of the Noise Emission Mechanism

In view of these experimental results, some explanations of the mechanisms of the emission from the PWM inverter-motor system can be proposed as follows:

Every switching operation of the devices in the inverter imposes an impulse voltage with the derivative dv/dt (about 3 kV/μS in this case) with a period of hundreds of nanoseconds, not only on the line-to-line voltages but also on the line-to-ground voltage of the output circuits. Furthermore, the switched system, for instance the motor windings are always in an unsymmetrical state with respect to the power supply (dc) voltage during each switching mode operation. In addition, physically, each portion of the motor winding, the output feeder cables to the motor or portion of semiconductor in the device itself, acts as a plate of a capacitor with respect to the grounded metal frame. During the switching transient

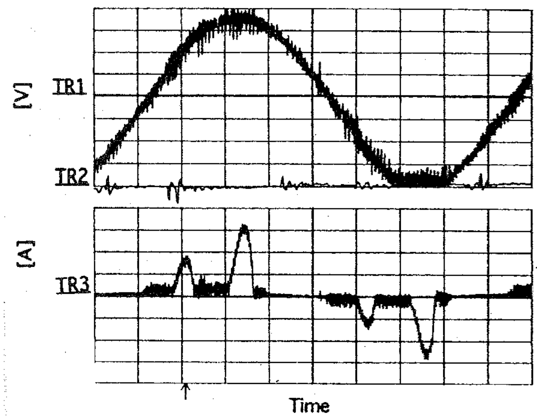


Fig. 4. Mains line to ground voltage and the line current of the conventional inverter-motor, directly supplied from mains. TR1: line to ground voltage 100 V/div., Time 2 mS/div.; TR2: expansion of TR1 100 V/div., Time 20 μS/div.; TR3: line current 2 A/div., Time 2 mS/div.

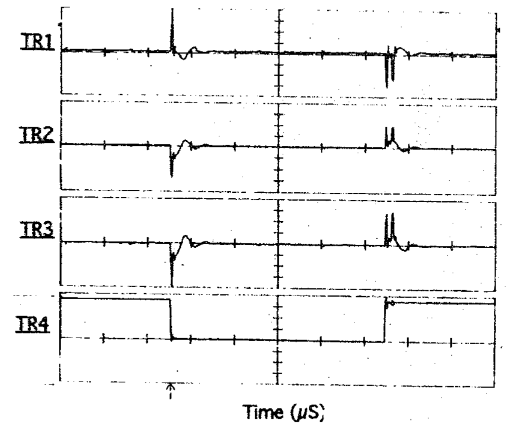


Fig. 5. Experimental voltage and current waveform in the system, a conventional inverter feeding induction motor. Time: 10 μS/div. TR1: noise voltage 10 V/div.; TR2: motor ground current 0.5 A/div.; TR3: common mode current of mains 0.5 A/div.; TR4: motor voltage 100 V/div.

an impulse charging/discharging current flows through these distributed capacitances to ground and returns to the power mains along numerous paths. These currents are referred to as the *common mode current* and are distinctly different from the normal load current. Moreover, since all the conductors have stray inductance and since losses exist in the current paths, these impulse charging/discharging currents serves to explain the high frequency ringing and the complex wide bandwidth spectrum of the conducted EMI. Because two major components, the motor and the switching devices dominate the value of parasitic capacitance and range to several nanofarads in this test system they also tend to dominate the common mode emissions of the tested system.

Similarly, the capacitance formed by two windings in different phases of the motor or by the p-n junction in the semiconductor devices or by two portions of conductor in different phases also produce another type of RF current, flowing around the power leads during each switching transient. This type of RF current is commonly referred to as the *differential mode emissions*. They are somewhat less than the common mode emissions in this system since there already has been installed a surge absorbing capacitor (0.15 μF in this case) across the dc link of the inverter, which function as a low pass filter. Smaller differential mode emissions were observed at the LISN in this case. When the surge absorbing capacitance was removed, much greater emissions could be observed at the LISN. The diodes used both in the inverter switching modules and the rectifier bridge are also one of the EMI sources due to their reverse recovery current switching transient. These emissions may also be referred to as the differential mode.

C. Modeling and Simulation for EMI

The traditional modeling of an induction motor for prediction in the power frequency band clearly cannot faithfully describe the switching transients of the type discussed in this paper because the distributed capacitances of the motor are no longer negligible in the RF range [8]. A model that accounts the effects of capacitance of winding-to-frame as a lumped capacitance in an induction motor was proposed in [9] for the purpose of calculating the average leakage current in a PWM inverter-motor system. This model, however, can not be easily applied to the analysis of RF phenomena because the effects of distributed parameters of motor windings must be considered. The influence of winding capacitance on high-frequency time harmonic losses and the motor model including distributed parameters was described in [10] complete with simulation and experimental results. Resonant behavior of the motor input impedance was indicated in the frequency range from tens of kHz to hundreds of kHz for different motors whereupon the impedance became capacitive in the higher frequency ranges.

As the switching operation of a PWM inverter generates an excitation voltage with frequencies covering the RF range from tens of kHz through tens of MHz, the behavior of system, especially its response with a motor load should clearly be studied as so to understand the effects associated with the use of static converters. An experimental frequency response of the input impedance of a three-phase induction motor, 10 hp in this test case, for different connections of the motor terminals was obtained by using a high quality LCR meter with frequency scanning. One of these results for the connection usually used for inverter-fed applications is shown as Fig. 6. These experimental results confirm that the motor is basically a reactive load in the high frequency band with an apparent resonance. Beyond its resonant frequency, say 38 kHz in the test motor, the motor eventually becomes a capacitive reactance with a rapidly decreasing impedance magnitude to a few tens of ohms. It may then be presumed that in addition to the inductance of windings, capacitance in the motor and iron losses in the iron core dominate the impedance characteristics in the RF range. Since the literature concerning the behavior of motor and drive systems in the RF range is still lacking and many problems, for instance EMI problems, are certainly associated with the system's characteristics in RF range this issue is of considerable importance. A model of induction model for RF is thus proposed to approach the RF behavior of motor under fast switching operation of power supplies, shown in Fig. 7, as follows:

a) A phase-belt winding of the motor is represented as a basic element of the model consisting of $L_{\text{we}}, R_{\text{we}}, C_{\text{we}}, C_{\text{ce}}$, and R_{ce}, in which L_{we} is the leakage inductance considering the mutual coupling among the phase-belt windings in a phase winding, C_{we} the interturn capacitance of coils, R_{we} the losses through the winding including the copper losses and the induced iron loss, C_{ce} the capacitance formed by winding with respect to the iron core, and R_{ce} the losses in the paths of capacitance current flowing along the iron core. Grouping the coils in a phase-belt winding is suggested as a reasonable approach to consider the effects both of the mutual magnetic coupling and the interturn capacitive coupling among the coils in a phase winding.
b) The entire motor windings are modeled, therefore, by replicating the physical connection in the motor. The capacitance between the phase-belt winding in different phases is represented by C_{pe}, in which the connection for C_{pe} repeats the wiring of the phase winding. The total value of L_w, C_c, C_p of a phase winding can be obtained by the LC meter. The values of $L_{\text{we}}, C_{\text{ce}}, C_{\text{pe}}$, the elemental values of phase-belt winding, are then an appropriate fraction of L_w, C_c, respectively, in which the values of C_c, C_p are in the range of nanofarads. The value of the inductance L_w is determined by whether the leakage flux or the total magnetizing flux will be subject to the connections of the terminals which determine whether zero sequence or normal phase current flows.
c) The interturn capacitance C_{we} can only be measured by separating the coils from the motor, for instance, before being inserted into slots, in which the values of C_{we} range to tens of picofarads. This quantiy has simply been estimated in this study.
d) As both R_{we} and R_{ce} are frequency varying parameters due to the skin effects and they would vary by orders of magnitude within the RF range. As this quantity has influence primarily on the damping of the transient they may be estimated by referring to the measurement with an LCR meter for the frequency range of interest .

Based on the model developed, simulation results of the ac response of the input impedances of the induction motor, Fig. 8, basically agrees with the experimental results in a comparable frequency range. It may then be said that for sufficiently high frequencies, far beyond its resonant frequency, the motor is basically a capacitance network consisting of two types of capacitance, one formed by the winding to iron core capacitance C_c, the other the interturn capacitance C_p.

The switching device, a modular-type bipolar junction transistor, was modeled in this study as a switch in series with a resistance and two capacitors, Fig. 9, i.e., the junction capacitance C_j involved in the reverse recovery current and the capacitance C_k, with respect to the heat-sink. Both C_j and C_k can be obtained by measuring or referring to device data books. The turn on/off times of the switch as a parameter in PSpice simulation were chosen in accordance with the characteristics of the switch device used in the actual inverter.

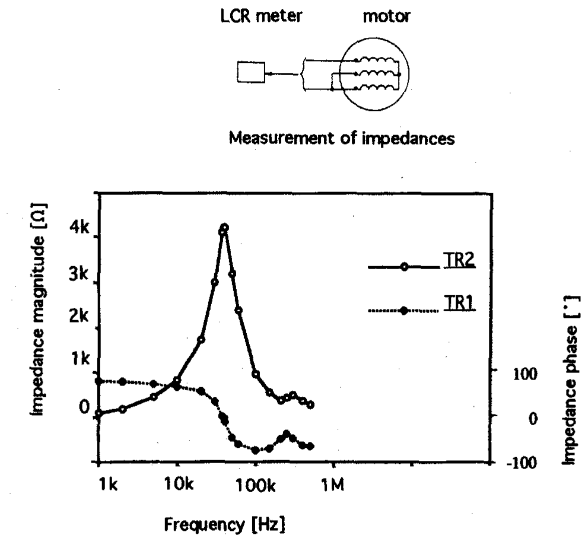


Fig. 6. Experimental input impedances of motor in frequency range from 1 kHz to 500 kHz. TR1: impedance phase degree [°], TR2: impedance magnitude [Ω].

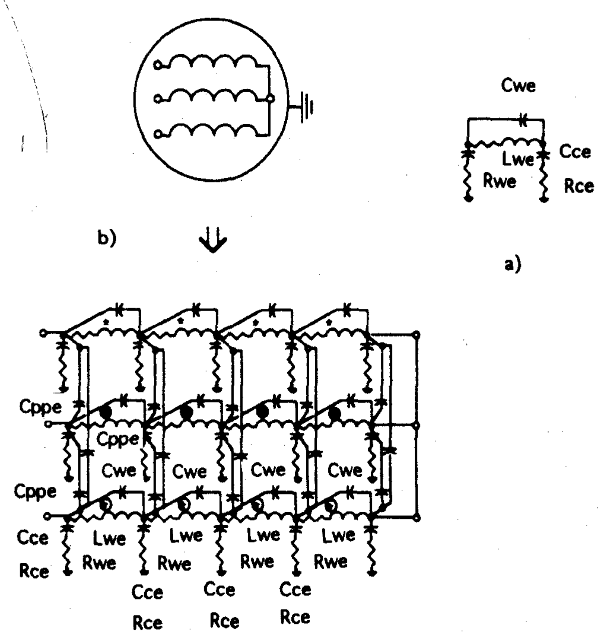


Fig. 7. Model of the induction motor for radio frequency. (a) For one phase-belt winding. (b) For 3 phase-motor winding.

The remaining elements in the main circuit of the system, e.g., the LISN and feeders can be modeled as RCL circuit elements. The model of the entire test drive system for EMI estimation then may be realized and the simulation results of the leakage ground current of motor and the emission noise voltage at the LISN for conventional inverter are shown in Figs. 10 and 11, respectively. The waveforms are clearly similar to the experimental results shown in Fig. 5.

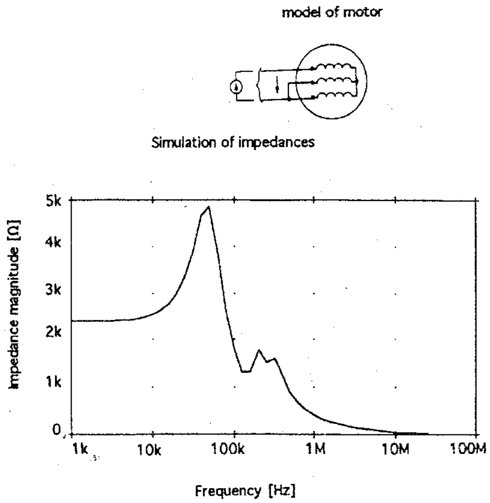


Fig. 8. Simulation results of input impedances of motor.

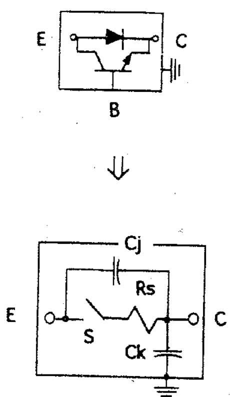


Fig. 9. Model of switching device for radio frequency.

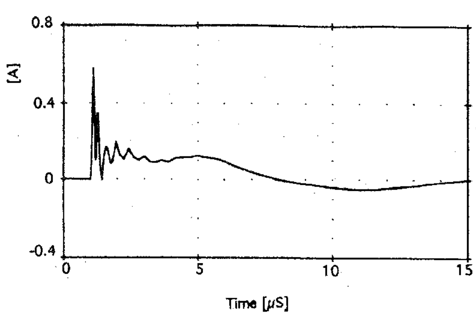


Fig. 10. Simulation results of motor ground current fed by a conventional inverter.

D. Strategies for EMI Suppression

Traditionally, ac power line filters have been the normal means to suppress conducted EMI emission. Two types of commercially available RFI filters were selected to estimate their EMI suppression performance. The schematic circuit of each of the filters and the experimental emissions from the system with the use of filters are shown in Figs. 12 and 13. In these tests the filter was placed as closely as possible

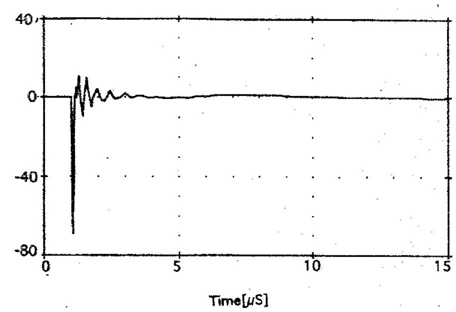


Fig. 11. Simulation results of conducted noise voltage from a conventional inverter feeding induction motor.

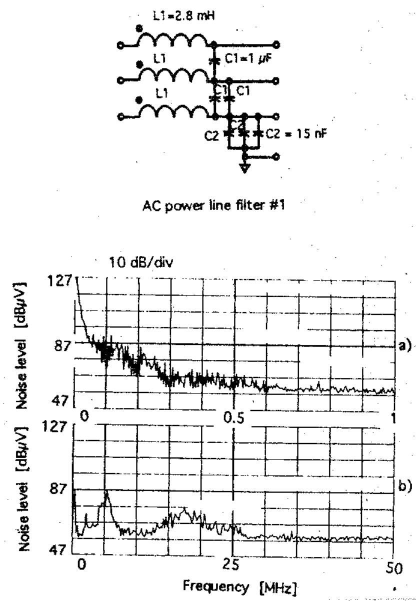
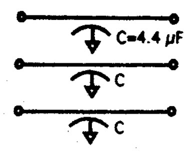


Fig. 12. Experimental conducted noise level from a conventional inverter with ac filter #1, feeding induction motor. Noise detector: peak value, dBμV. (a) frequency range from 0 Hz to 1 MHz. (b) frequency range from 0 Hz to 50 MHz.

to inverter and grounded through a braided wire of 30 cm in length. It was confirmed that the emission levels were suppressed by 20 to 45 dBμV but this result still exceeds the CISPR limits by 10 to 15 dB at some frequencies. Should the grounding provisions of the filter make direct low-resistance contact with the ground plane, the emission levels from the filter-inverter would probably come to meet the limits. However, it would be difficult to shorten the ground wire provisions as required to accomplish this result. In addition, both filters are bulky and several pounds in weight and would be a substantial extra cost for most applications.

As a low-cost alternative for improvement in EMC performance of an inverter-motor drive, several strategies for inverter EMI alleviation are proposed in this paper as follows, see Fig. 14.

a) The grounding capacitance can be connected from both sides of the dc link to the heat sink close to the switching devices providing a physically short path and thus low impedance for RF ground current flowing from the



AC power line filter #2

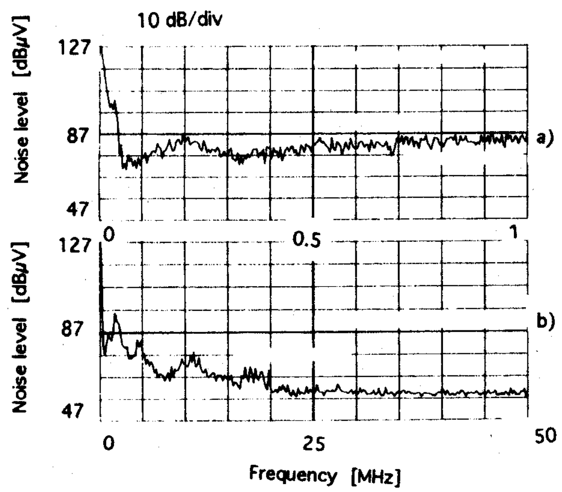


Fig. 13. Experimental conducted noise level from a conventional inverter with ac filter #2, feeding induction motor. Noise detector: peak value, dBμV. (a) frequency range from 0 Hz to 1 MHz. (b) frequency range from 0 Hz to 50 MHz.

switching device and motor load. However, the total capacitance should be restricted such that the ac leakage-current requirements for safety apply to this kind of equipment. In this experiment two 0.022 μF capacitors were employed to meet the 5 mA leakage current limits for power units set by UL [13].

b) The line capacitance with as low an ESR and internal inductance as possible can be connected across the dc link as physically close to the switching devices as possible. This capacitance provides a low impedance for the differential mode RF current flowing from switching devices such as the reverse recovery current of the diodes as well as from the cable-motor load. This capacitance may take on a value up to a few microfarads as desired. It should be mentioned that the capacitance banks of thousands of μF existing across the dc link are not effective for filtering RF current due to their high ESR and internal inductance resulting in low-resonance frequency of about 10 kHz. In some cases, the capacitor in this circuit, e.g., acting as a surge absorber, plays an important role in suppression of differential mode emissions. However, as so far employed, its use has not been EMI oriented.
c) Line capacitance can be connected across the ac power input terminals as close to the diode rectifier as possible. These three capacitances serve as another shunt circuit in combination with the capacitance at dc line for differential mode noise compensation, particularly for the noise caused by the diodes of rectifier. The value of these capacitances can be a fraction of a μF, chosen by experimentation.

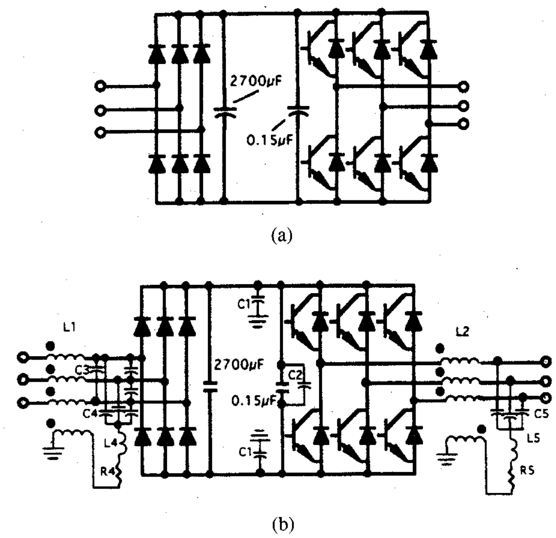


Fig. 14. Main circuit of inverter. (a) Conventional inverter. (b) Modified inverter with EMI suppression components.

d) A common mode inductance can be inserted in each phase of the ac input main circuits of the inverter as used in conventional ac filters, providing a high impedance for the RF currents to the power mains. In this experiment a 3-phase common mode inductance of only several hundred μH with an additional coupling circuitry was employed. The use of the extra coupling circuitry increases the insertion loss by a few dB compared to that without the coupling circuit.
e) A common mode inductance of a several hundred μH, inserted in each phase of the ac output main circuit of the inverter, it is able to reduce the dv/dt, the time derivative of output common mode voltages imposed on the motor but not affect the line to line voltages. Extra coupling circuitry can also be applied to the inductor that further improves the performance of the common mode voltage. The circuit can also reduce the RF leakage ground current of the motor so that this approach can also be used to improve the EMC performance on the output side of inverter. However, experimental results appear to show that a common mode inductance placed on the output side of inverter is not as effective as that placed on the input side to suppress conducted EMI appearing in the mains.

A grounding connection inside the inverter should be properly made to provide for the desirable RF current paths, and include a number of design engineering considerations. By the use of these EMI suppression components incorporated within the inverter itself, both the simulation and the experimental results of the emission noise levels and the voltage and current waveform obtained in the test drive system are shown as Figs. 15 to 20, and summarized as Table I which compares

TABLE I
CONDUCTED EMISSION FROM INVERTER-MOTOR SYSTEMS WITH DIFFERENT FILTERING TECHNIQUES

	Conducted emissions, Peak detector	dBμV
Frequency range (MHz])	0.15–0.5	0.5–30
CISPR limits (quasi-peak detector)	79	73
Inverter without EMI compensation	120	107
Inverter plus ac filter #1	85	85
Inverter plus ac filter #2	85	95
Inverter with EMI suppression components	87	71

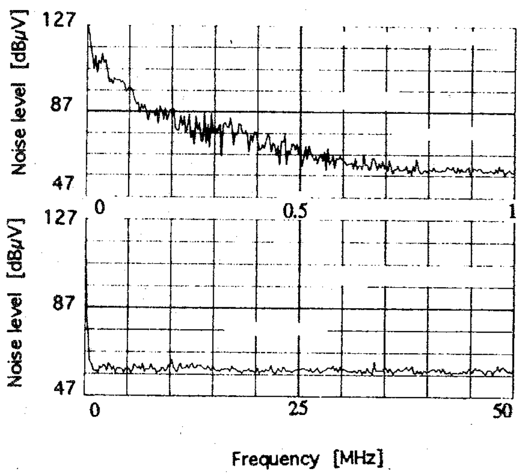


Fig. 15. Experimental conducted noise level from the inverter with EMI suppression components feeding induction motor. Noise detector: peak value, dBμV. (a) Frequency range from 0 Hz to 1 MHz. (b) Frequency range from 0 Hz to 50 MHz.

results with and without EMI suppression components and with conventional ac power line filters.

These experimental results demonstrate that the conducted emission noise from the modified inverter feeding a induction motor can be dramatically reduced. These results are summarized as follows:

a) Emission noise levels havebeen reduced by 35 to 40 dB, especially effective for frequencies over 400 kHz, but still in excess by 5 to 8 dB in the low-frequency range from 150 to 400 kHz. The improvements in emission performance can also be confirmed by comparison of the voltage and current waveforms in which the amplitude of the emission voltage has been reduced from 50 V peak with conventional inverter to 3.5 V peak with the modified inverter, Figs. 15, 16, and 17. Varying the amplitude of the motor fundamental current would probably have not much influence on the emission levels from the system.

b) The impulse common mode current of over 2 A peak with the conventional inverter has been shaped to form a smooth current of about 0.4 A with low-frequency content. The motor ground leakage current has been reduced to about one-fourth the value of the former value as well. Therefore, waveform distortion in power system caused by the impulse current due to the operation of PWM inverter has been greatly reduced in the line voltage, line-to-ground voltage, and line current, Figs. 17 and 18.

c) The ringing in inverter output voltage has also improved, again see Fig. 17.

d) The simulation results of the waveforms of both the motor leakage current and emission noise voltage carried out for the modified inverter system, as shown in Figs. 19 and 20, basically compares well with the experimental results.

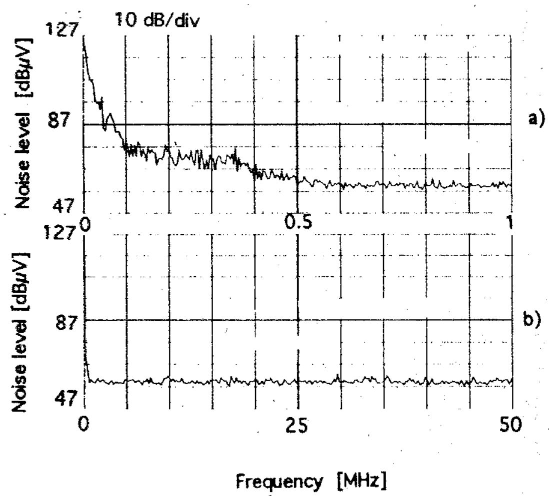


Fig. 16. Experimental conducted noise level from the inverter with EMI suppression components, but no load connected. Noise detector: peak value, dBμV. (a) Frequency range from 0 Hz to 1 MHz. (b) Frequency range from 0 Hz to 50 MHz.

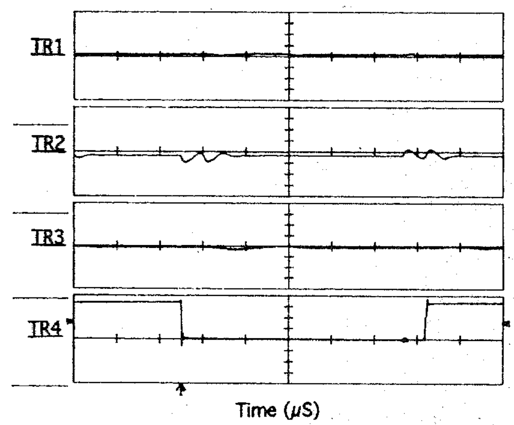


Fig. 17. Experimental voltage and current waveform in the system, the inverter with EMI suppression components feeding induction motor. Time: 10 μS/div., TR1: noise voltage 10 V/div.; TR2: motor ground current 0.5 A/div.; TR3: common mode current of mains 0.5 A/div.; TR4: motor voltage 100 V/div..

It is very significant to note that the cost and the weight of the EMI suppression components employed in the modified inverter, Fig. 14, are five to ten times less than that of conventional ac power line filters.

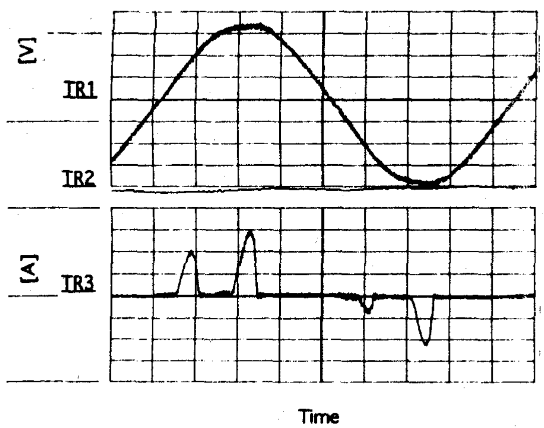


Fig. 18. Mains line to ground voltage and the line current of the inverter-motor with EMI suppression components, directly supplied from mains. TR1: line to ground voltage 100 V/div., Time 2 mS/div.; TR2: expansion of TR1 100 V/div., Time 20 μS/div.; TR3: line current 2 A/div., Time 2 mS/div.

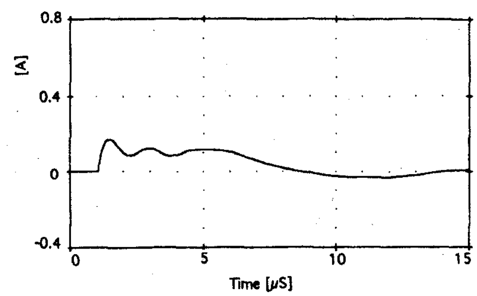


Fig. 19. Simulation results of motor ground current fed by a inverter with EMI suppression components.

IV. Conclusion

In the paper it has been shown that switching mode operation of a PWM inverter used in power drive system clearly generates large impulse currents through the power leads which are associated with problems with EMI and voltage waveform distortion in the power system. The emission levels from the static power converters may be expected to be more serious than that produced by low power information technology equipment due to the higher dv/dt and greater distributed capacitance in the high power applications.

The major emission sources of this system are the combination of switching action of devices (dv/dt) and the switched circuit parameters. Therefore, motor, power switch devices, and a long feeder under switching conditions may become the principal noise sources due to their large distributed capacitance, in which the charge/discharge currents are produced and flow into the mains, and act as equivalent RF current sources. Nonlinear devices existing in the main circuit, such as diodes, are also noise sources since the reverse recovery effect produces higher order harmonic components covering the RF ranges.

AC power line filters, the traditional means of suppression of EMI exhibit inherent disadvantages, such as extra volume and cost for installation; a strict grounding connection; need

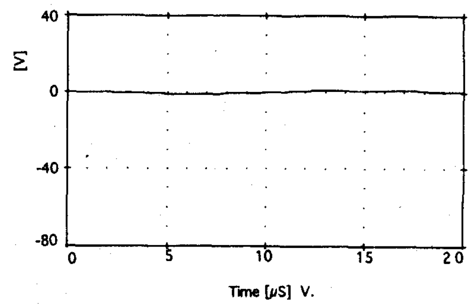


Fig. 20. Simulation results of conducted noise voltage from a inverter with EMI suppression components.

for proper choice of insertion loss for common mode and differential mode with a specific application. Otherwise, the filtering effects can be degraded.

Based on the understanding of the sources generating EMI, by properly placing filtering elements L, C in the converter itself associated with the power unit, one is able to establish an overall cost-effective EMC design. A proposed filtering circuit has been demonstrated in this paper to perform satisfactorily with excellent effectiveness in suppression of EMI from the inverter drive so much so that it comes close to meeting the CISPR or FCC limits for digital devices. Furthermore, the cost and weight of the elements used are 5 to 10 times less than that of conventional ac power line filters for implementation of the same filtering level. Therefore, the possibility of producing "clean" inverters with a cost-effective EMC solution becomes feasible.

Acknowledgment

The authors are greatly indebted to the Electric Power Research Institute (EPRI) for its support.

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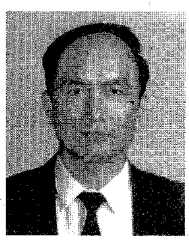

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