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Improvements in EMI Performance of Inverter-Fed Motor Drives

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Abstract- Measurements of conducted radio-noise emissions from a commercial PWM inverter with an induction motor are presented. It is determined that the common mode emissions predominate the noise level and the spectrum components in this type of system, which result from the derivative of the line to ground voltages at main circuit (dv/dt) and the circuit parameters, consisting of the physical stray inductance of the main circuit conductors and distributed capacitance formed between the circuit conductors and grounded chassis/frame, most of which concentrate in motor windings and power-semiconductor devices in this system. Modeling and simulations of the system for purpose of evaluation of EMI are presented. Several strategies suppressing conducted radio-noise emissions are proposed, which are practically feasible for cost-effective EMC designs. Both the simulation and experimental results demonstrate that high level radio-noise were significantly suppressed and the EMI performance of the system are able to meet the CISPR and FCC limits on conducted emissions for digital devices [1] [2].

1. INTRODUCTION

The inherent switching mode operation of modern static power converters used in industrial and domestic appliances, leads to a myriad of problems caused by unwanted harmonics. The problems involved in harmonic control over the power frequency range up to the 35th order are already well addressed, and an application guide has been provided in IEEE Std. 519-1992 [3]. However, in the case of Radio Frequency Interference (RFI) associated with the use of power electronics, especially for the case of industrial motor drives, there has been no mandatory test requirement governing the unwanted noise produced nor has the problems concerned been well documented. On the other hand, the subject of Electromagnetic Interference (EMI) or RFI for communication and computer applications have been an important aspect of those product's performance because Electromagnetic Compatibility (EMC) regulations or standards have existed in varying degrees of complexity and completeness in most major countries. These restrictions require the electro-magnetic emissions/susceptibilities of all "digital devices" to be below certain limits. Digital devices having clock frequencies that exceed 9 kHz cannot be legally sold in the US unless they have been tested and found not to exceed limits on radiated and conducted emissions set by the Federal Communications Commission (FCC). Also, countries in Europe have imposed similar requirements on digital devices. A committee, which deals with the emerging problem of EMI, well known as International Special Committee on Radio Interference(CISPR), has produced various technical publications, which dealt with measurement techniques as well as recommended emission limits [1]. Several European countries have adopted versions of CISPR's recommended limits. It can now be said that the subject of EMC is of worldwide concern to manufacturers of digital products as it is a critical aspect in the marketability of their products. Thus far, concerns have focussed mostly in low power level applications of digital devices as the FCC has temporarily exempted five subclasses of digital devices from meeting the technical standards of the requirements in 1987 [1]. One of these 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 electronics systems. It is generally recognized that the exempted devices are still subject to the general conditions of operation such that no harmful interference should be generated or that interference must be accepted that may be caused by the operation of an authorized radio frequency device. Although not mandatory, it is strongly recommended that the manufacturer of an exempted device endeavor to have the device meet the specific technical standards in FCC's regulations. Also since the exemptions mentioned are temporary, the rules can be revised forcing major design problems for equipment manufacturers not designing for low EMI.

Although the subject of EMC is well documented on low power digital devices, applications of digital techniques in the higher power ranges concern situations different than with a signal processing system. Some issues particular to high power switching are important in establishing to what degree the power electronics system would produce and interfere with nearby electrical or electronic devices or systems. The following topics involved in this paper address each of the aspects concerned, i.e., the mechanism causing conducted emissions from a typical inverter-motor drive system, its signal strength and spectrum, and cost-effective EMC design methodology for minimization.

2. EXPERIMENTAL SYSTEM

A. Test Equipment and Instrumentation

A commercial inverter and induction motor, forming a basic application configuration in industry, was chosen as the Equipment Under Test (EUT) for the measurements of the conducted emissions from the inverter as shown in Fig. 1. The specifications of EUT are shown in Table 1.

TABLE 1
SPECIFICATIONS OF THE TESTED SYSTEM

Transistor Inverter	
Control system	Sinusoidal wave PWM control
BJTs modules	500V, 40A
Feed back diodes	500V, 40A
Output voltage	3-Phase, 4V--230V
Output frequency	3 Hz-80 Hz
Induction motor	
Rating	3-phase 60 Hz 10 Hp 3500 r.p.m
Frame	254 U

For the purpose of measurement of the EMI from this system, the standards listed in [4] [5] [6] were chosen as references. A Line Impedance Stabilization Network (LISN), having the required impedance characteristic of 50 Ω over the specified frequency range was constructed and inserted between the power mains and inverter (EUT). The LISN, EUT and all power lines among them were placed on an grounded aluminum plane 2 x 2 meters in size with the required configuration.

Test instrumentation: A spectrum analyzer with an appropriate attenuator was used with a peak detecting function so that the measured results are somewhat greater than quasi-peak detector function required by FCC or CISPR, but they still present an approximate level. Another instrument used for waveform observation is an oscilloscope. Both the analyzer and oscilloscope were supplied through an isolated transformer and were grounded as required.

Power mains in test site are supplied through a 100 ft cables by a 150 KVA transformer as shown in Fig. 1.

B. Testing for Conducted Emission

The conducted EMI of this inverter-motor system is measured by picking up the radio-noise voltage across the 50 Ω resistor of the LISN during certain test conditions.

Test conditions of EUT are as follows:

1. Ambient noise only.
2. Inverter with open output.
3. Inverter with motor running but not loaded.

3. CONDUCTED EMISSIONS FROM EUT WITHOUT COMPENSATION

A. Experimental results

The experimental results obtained from original inverter-motor drive system are shown in Fig. 3 and Table 2. The results are summarized as follows:

a. PWM operation of inverters clearly generate large conducted emissions through the power leads which exceeds FCC limits for conducted emissions by 25 to 30 dBμV in the MHz range. The spectrum of emissions range from tens of kilohertz through more than 20 megahertz, which depends upon the configuration of operation of the system.

b. The large impulse emission currents also cause waveform distortion of the line voltages, especially on the line to ground voltages and appear also in the line currents. The depth of the impulse notches could exceed 20% of the sine wave voltage. A larger impedance in power supply could cause even more distortion in the voltage waveform. The waveform as in Fig. 3 was obtained when the inverter was supplied directly from the mains from a 150 KVA power transformer and through leads having length of about 120 feet.

c. Leakage currents that flow to the ground from motor's frame or inverter's enclosure would produce a zero sequence current at the input power leads of the inverter. These currents have impulses with a peak value from a fraction of an ampere to a few amperes. The leakage currents occur during the switching instants of the devices in inverter and also simultaneously with the emission noise voltage at the power leads, which were observed at the LISN, as shown in Fig. 3. If both the motor and inverter are isolated from ground, the zero sequence current at the power leads disappeared. In addition, the noise voltage was observed to decrease to very small value.

d. The PWM waveform of the inverter output voltage usually has damping oscillation components that always appear in the line to ground voltages. A pure square waveform occurs on the line to line voltage when no load (open circuit) has been connected to the inverter terminals.

e. The amplitude of the inverter output current does not apparently affect the emissions noise level.

B. Some observations of the noise emission mechanism

In view of the experimental results the mechanisms of the emissions from a inverter-motor system are proposed as follows:

Every switching operation of devices in the inverter imposes a high voltage derivative dv/dt, greater than 1000 volt per microsecond, not only on the line to line voltages but also on the line to ground voltages at the output circuit. Furthermore, the switched system is always under an unsymmetrical state with respect to power supply voltage during the switching mode operation.

During each switching event mentioned above, a winding of the motor or length of conductor or a piece of semiconductor in the device, acts as a plate of a capacitor with respect to the grounded metal frame. During the switching transient a charging/discharging current flows through these distributed capacitances to the ground and return to power main along miscellaneous paths. This current may be referred as zero sequence current. Since all the conductors have stray inductance and the losses exist in the current paths, the charging/discharging current during switching transients consist of a damped oscillation with a complex wide bandwidth spectrum. These R.F. currents, flowing through the input and output terminals, may produce harmful electromagnetic interference (EMI). Because the two main source stray capacitance are the motor windings and semiconductor devices, which may range up to a few nanofarads, they dominate the R.F. currents, and so, the common mode emissions.

On the other hand the capacitance, formed by two windings in different phase of the motor or the p-n junction in semiconductor devices or by two wires in different phase, also produce another type of R.F. current, flowing among the power leads during each switching transient. This type of R.F. currents may be referred as differential mode emissions. Because they are somewhat less than common mode emissions in this system and, furthermore, already exist a surge absorbing capacitor (0.15 μF) across the DC link of the inverter, which function as a low pass filters, then only small differential mode emissions were observed on the LISN in this case. Should this capacitor be removed, large emissions were observed at LISN

C. Modeling and simulation for EMI

The traditional modeling of an induction motor for torque or harmonics in the power frequency band clearly can not faithfully describe the switching transients mentioned above, because the distributed capacitance is no longer negligible in the radio frequency range [7]. A suitable model of an induction motor for calculating leakage current in a PWM inverter-motor system was described in [8]. Although this model was adequate in calculating average leakage current it is apparently unable to accurately describe the form of the impulse transient during each switching. A new model of an induction motor for R.F. is proposed in this paper and is shown in Fig. 4 where the parameters R_W, L_W, are the primary resistance and leakage inductance of the motor respectively, and C_c is the capacitance formed by the windings and iron core, and C_W is the capacitance formed between the coils in different phases of the motor. Both C_c and C_W can be obtained by a bridge type meter. The core loss resistance R_c and the coefficients no,n1,n2- - -n9, which represents the unevenly distributed portions of the lumped parameters of the motor due to high frequency effects during the transient condition, are estimated by trial and error.

The switching device, a modular type bipolar junction transistor, is modeled as a switch in series with a resistance and two capacitors, i.e. the junction capacitance C_j involved in reverse recovery current and the capacitance C_k, with respect to the heat-sink, as shown in Fig. 5.

The simulation results for EMI in the selected inverter-motor system for the leakage ground current and for the EMI at the LISN are similar to the experimental results as can be shown by comparing the results in Fig. 6 and Fig. 7.

4. Strategies for EMI suppression

Traditionally, AC power line filters are the normal means to suppress conducted EMI emissions. Two types of commercially available RFI filters were used to estimate their EMI suppression performance. The experimental results, shown in Fig. 8 and Fig. 9, demonstrate that the EMI emissions have been suppressed by as much as 28 dBμV and would meet both the CISPR's or FCC's conducted emissions requirements when such large filters are used. These filters also are shown in Table 2. However, both filters are bulky and several kilograms in weight.

As a design consideration for improved EMI performance of an inverter-motor drive several new strategies are proposed in this paper as follows:

a. Grounding capacitance can be connected from both sides of DC link to heat sink close to switching devices, providing a physically shortest path and thus low impedance for R.F. ground current flowing from switching device and motor load. However, the total capacitance must be restricted to meet the AC leakage-current requirements for power units, i.e., 5 milliamperes, [9]. In this experiment two 0.022 μF capacitors were employed.

b. Line capacitance, normally used for R.F. applications, can be connected across the DC link as physically close to switching devices as possible. This capacitance provides a low impedance for the differential mode R.F. current flowing from switching devices such as reverse recovery current of diodes as well as from the cable-motor load.. The capacitance may be up to few microfarads as desired. Usually as a surge absorber the capacitor at the circuit has played an important role in suppression of differential mode emissions. However, as so far employed, its use is not EMI oriented.

c. Zero sequence inductance can be inserted in each phase of the AC input main circuits of the inverter, providing a high impedance for the R.F. currents to the power mains. In this experiment a 3-phase zero sequence inductance of a few hundred micro henries associated with the extra coupling circuitry was employed that improved the high frequency performance of the inductors, as shown in Fig. 2.

d. A zero sequence inductance, inserted in each phase of the AC output main circuit of the inverter, is able to decrease the derivative of output zero sequence voltages imposed on the motor and suppress the R.F. leakage current of the motor but not affect line to line voltages. An extra coupling circuitry also applied to the inductor as shown in Fig. 2. A grounding connection should be properly made to provide the grounding current paths desired, which include number of design engineering considerations.

By the use of these measures on the inverter, experimental measurements demonstrate that the R.F. emissions can be decreased by 25 to 30 dBμV and come close to meeting the CISPR and FCC limits on conducted emissions as shown in Fig. 10 and Table 2. Furthermore, the waveform distortion ovserved in the line voltages and line current waveform has generally disappeared. The EMI simulation results carried out for this modified system is basically conformed by the experiment.

TABLE 2
Comparison of EMI Suppression

Test conditions Inverter-motor with....	Emissions dBμV
Original configuration	102.65
Filter #1 3x20A 250V L_d = 2.7 mH C_g = 0.015μF C_l = 1μF	73.04
Filter #2 3x30A 250V C_g = 4.4μF feed through	78.51
Proposed circuit L_0 = 0.2mH C_g = 0.022μF C_l = 4.4μF	71.57

C_l line capacitance
C_g line to ground capacitance
L_d line inductance
L_0 zero sequence inductance

5. Conclusion

a. Switching mode operation of a PWM inverter-motor drive system are associated with the problems of EMI and waveform distortions. They cause critical situations for the electromagnetic environment.

b. The main emission sources of this system are the combination of switching action of devices (dv/dt) and the switched circuit parameters L,C,R. The derivative of line to ground voltage and the capacitance formed by circuit conductors and grounded frame of the power units which produce R.F ground currents flowing into mains equivalent to an R.F. current source .

c. The differential mode emissions from this system are similar to the common mode but the distributed capacitance is between the conductors in different phases. Most DM emissions have already been absorbed by capacitors normally built into the power units.

In addition to using separate power line filters, by properly placing filtering elements C, L in the inverter itself associated with the power unit, one is able to establish a overall cost-effective EMC design. A proposed filtering circuit has been demonstrated in this paper to perform satisfactorily. in suppression of EMI in an inverter-motor drive system at far more less cost when compared with a conventional separate power line filter.

6. Acknowledgment

The work reported in this paper was made possible by support from the Electric Power Research Institute (EPRI) to whom the authors are greatly indebted.

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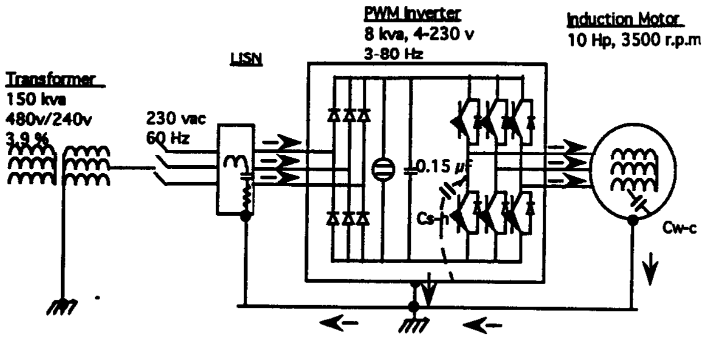
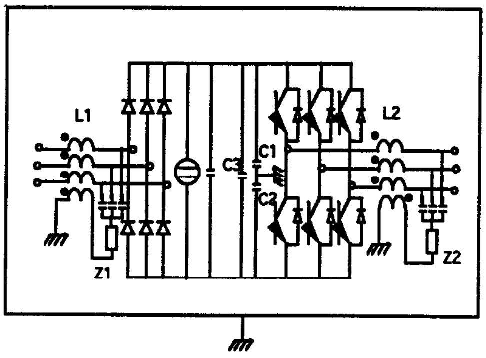


Original Inverter

Common mode R.F current path →

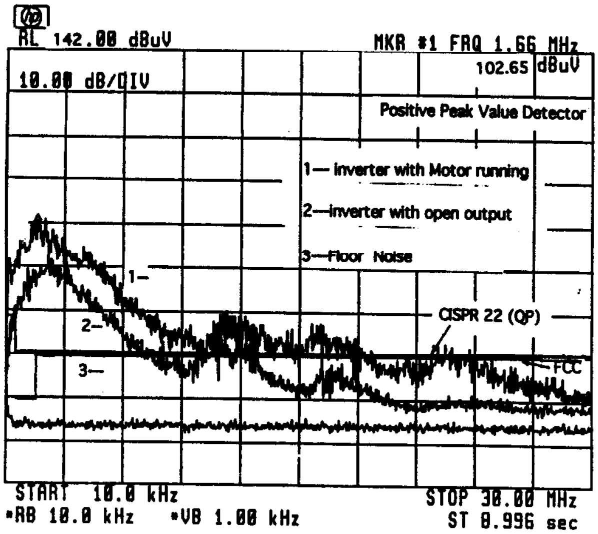
Cw-c , Cs-h Stray capacitance

Fig. 1 a) Measurement of Conducted Radio Noise Emissions from Inverter-Motor Drive

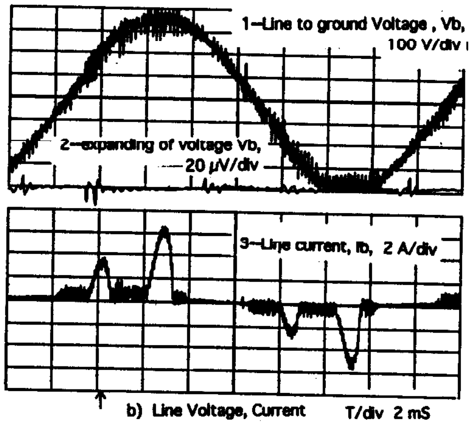


L1, L2	100 μH–200μH
C1,C2	0.02 μF, the sum of grounded capacitance less than 0.055 μF
C3	2.2 μF

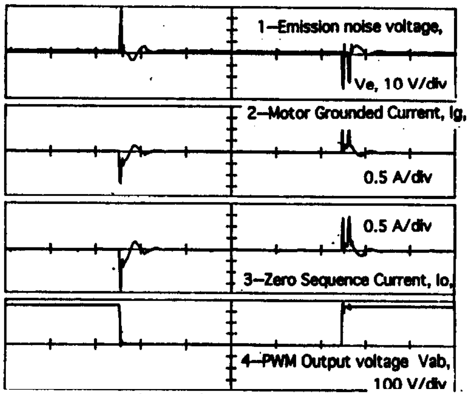
Fig. 2 Schematic Diagram of Modified Inverter



a) conducted emissions with original inverter



b) Line Voltage, Current T/div 2 mS
with original Inverter directly Connected to Mains



with original inverter
c) Emission noise voltages and Grounded Currents
T/div 10 μs

Fig. 3 Conducted Emissions from Inverter-Motor drive, with original inverter

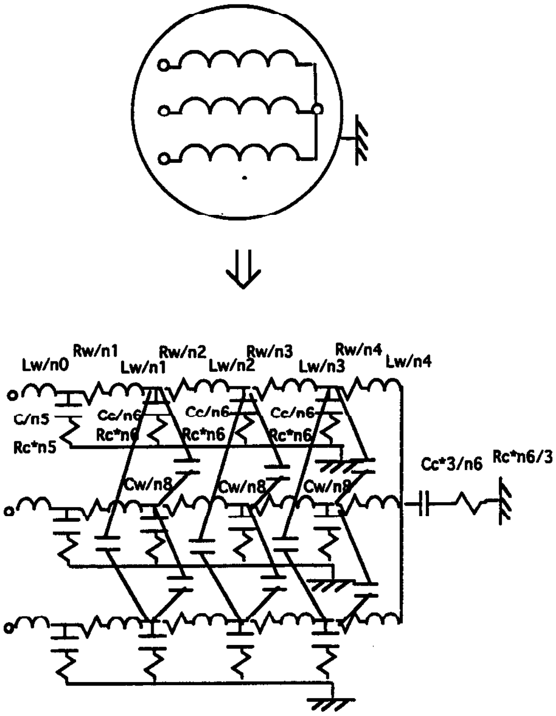


Fig. 4 Model of Induction Motor for Radio Frequency

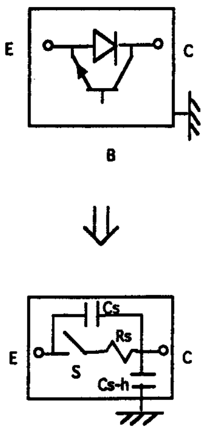
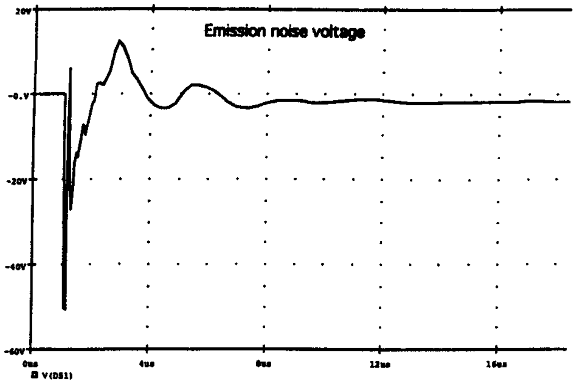
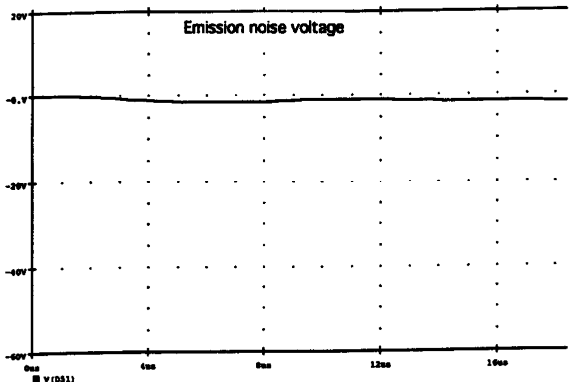


Fig. 5 Model of Switching Device for Radio Frequency

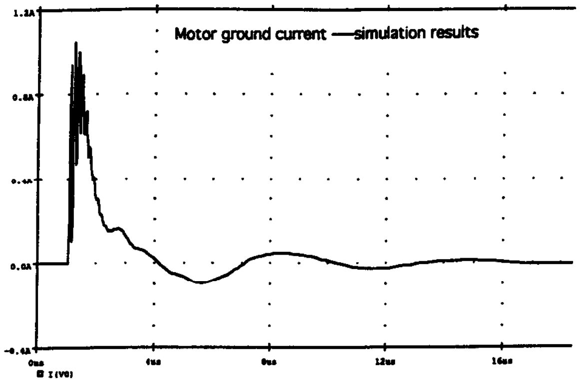


a) with original inverter

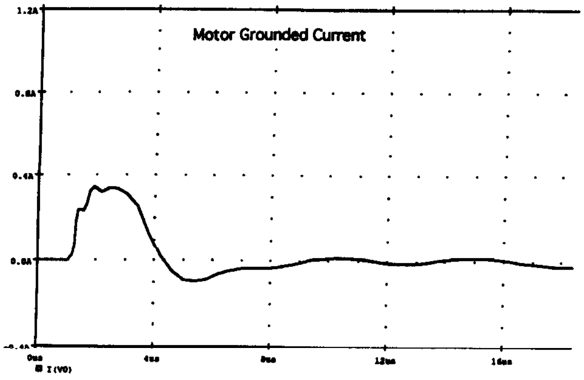


b) with modified inverter

Fig. 6 Conducted Emissions from Inverter-Motor drive —simulation results



a) with original inverter



b) with modified inverter

Fig. 7 Motor ground current —simulation results

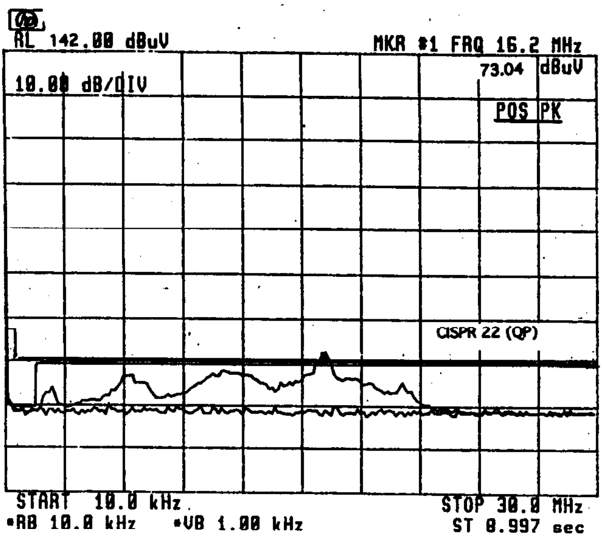


Fig. 8 Conducted Emissions from Inverter-Motor drive, with power line filter No.1

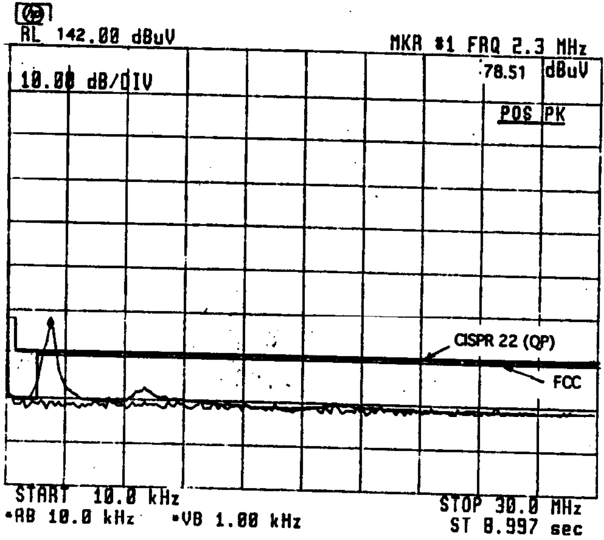
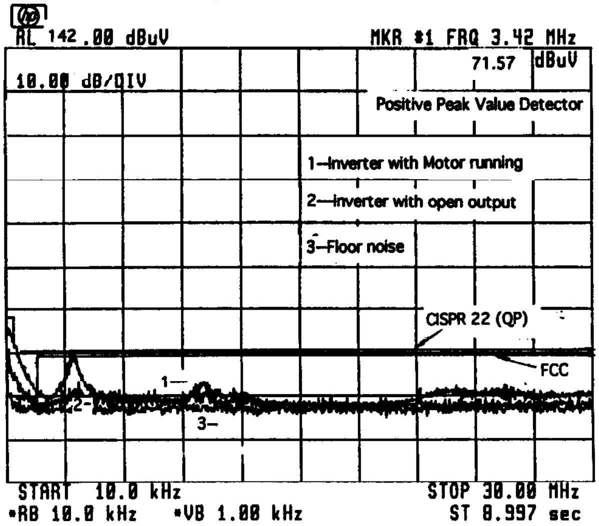
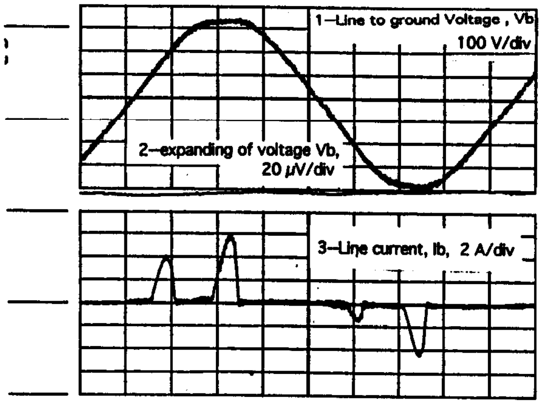


Fig. 9 Conducted Emissions from Inverter-Motor drive, with power line filter No. 2



a) Conducted emissions



b) Line Voltage, Current T/div 2 mS
with modified Inverter directly Connected to Mains

Fig. 10 Conducted Emissions from Inverter-Motor drive,
with modified inverter