POWER SUPPLIES

application data

Issued by: Philips Industrie S.A.
Bd de l'Europe, 131 B-1301 Wavre (Belgium)
Tél. 10/41 65 11

ELECTROMAGNETIC INTERFERENCE AND SWITCHED-MODE

POWER SUPPLIES

PHILIPS Industrial and
Electro-Acoustic Systems

PHILIPS

POWER SUPPLIES

application data

Issued by: Philips Industrie S.A.
Bd de l'Europe, 131 B-1301 Wavre (Belgium)
Tél. 10/41 65 11

ELECTROMAGNETIC INTERFERENCE AND SWITCHED-MODE

PHILIPS Industrial and Electro-Acoustic Systems

PHILIPS

CONTENTS LIST

LIST OF FIGURES

FIG. PAGE

PREFACE

This brochure looks at the causes of EMI (electromagnetic interference) in switched-mode power supplies, outlines the precautions taken by manufacturers, and suggests those that can be taken by users to prevent any spurious signals affecting the functioning of other equipment in a system, however sensitive.

1. EMI REVISITED

While at the beginning of the century men were striving hard to transmit radio waves into free space, the ease with which electrical energy is generated today, often requires careful measures to control it or prevent unwanted transmissions.
Electromagnetic interference – unless deliberately produced for jamming purposes – is by definition unwanted!
Where currents are rapidly switched on and off interference voltages are produced. The faster the switching, the wider will be the interference spectrum, possibly up into the MHz range.
Switched-mode power supplies are inherently fast switching devices and in the past have been unjustly labelled as "EMI generators", not always due to poor designs, but often because of misuse and perhaps a lack of understanding.
Nowadays, with excellent designs conforming to internationally recognised norms, plus a little user education, the proven quality and reliability of switched-mode power supplies means that they can be safely applied even for the most sensitive circuits.
Well-designed, well-constructed and well-installed switched-mode power supply systems already find common use in such critical areas as the medical field, sensitive measuring instruments, computer data-banks, machine control, analytical equipment, etc. without any adverse EMI effects.

2. ELECTROMAGNETIC INTERFERENCE

2.1 Phantom Circuits

It is a well-known fact that radio transmission from a circuit is made possible because the basic electrical elements of resistance, inductance and capacitance are present not only in the wiring, but in the free space surrounding it. Likewise, the unwanted EMI uses these "phantom" component paths in wiring and free space, which do not normally appear on circuit diagrams.
These phantom elements are the major causes of undesired signals in equipment, sometimes through common coupling, for example, via a resistive common earth circuit, or by electromagnetic or electrostatic coupling fields.

In practical terms, EMI generated by an interference source inside the equipment, can be transferred to the outside world in many ways.

a. Interference signals can exist as an output voltage or current on connecting cables, e.g. the mains, or the output terminals. It is then called conducted interference.

b. Electric currents varying within a conductor or circuit component produce varying electro-magnetic fields in the vicinity of the current-carrying conductor. The propagation of those fields is called radiation.

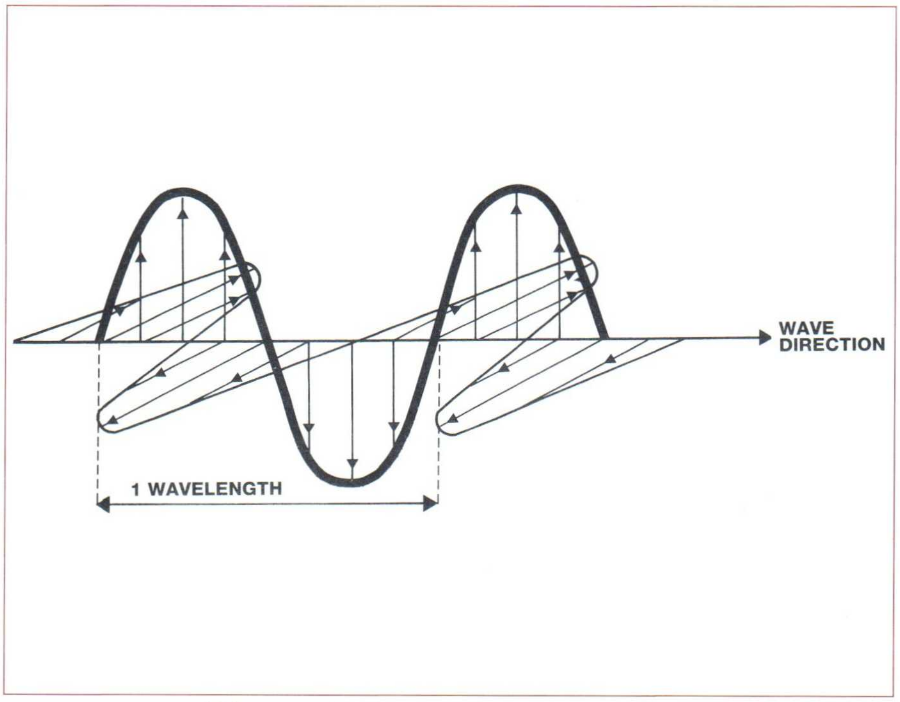


FIG. 1. ELECTROMAGNETIC RADIATED WAVE

2.2. Electromagnetic Radiation

Electromagnetic radiation is composed of two inseparable parts: an electric field (E) and a magnetic field (H) at right-angles to each other. These complementary fields vary in intensity and polarity at the frequency of the electric current flow producing them. (FIG. 1)

Fortunately, when considering EMI, the intensity decreases as the electromagnetic field gets further away from the source. (FIG. 2)

The intensity of the E electric field is measured in volts/metre and is high in proportion to the H magnetic field component for high-impedance fields (open-line circuits, rod aerial, etc.)
The intensity of the H magnetic field is measured in amps/metre and is high in proportion to the E electric field component for low-impedance fields (closed-loop circuits, loop aerial, etc.). (FIG. 3)

As seen, all electric fields gradually lose some of their intensity in generating a complementary magnetic field, and vice versa. Also, as the intensity decreases with distance from the current source, fields have a normal impedance of 377 ohms beyond about one wavelength.
Within a distance of one wavelength, fields are called near fields. Such fields may influence nearby circuits by capacitive or inductive coupling. One has to remember that the expression "near field" is not an absolute term but that it has to be considered as a function of the frequency. (FIG. 4)

Electromagnetic fields beyond about 3 λ are defined as far fields. These are usually referred to as plane waves because the spherical wave-front impinging on a screen at this distance is relatively flat. The far field waves are radiated outwards and not re-absorbed by the source producing them. It will be realised that these distances are important for the interference frequency when designing electromagnetic shields.

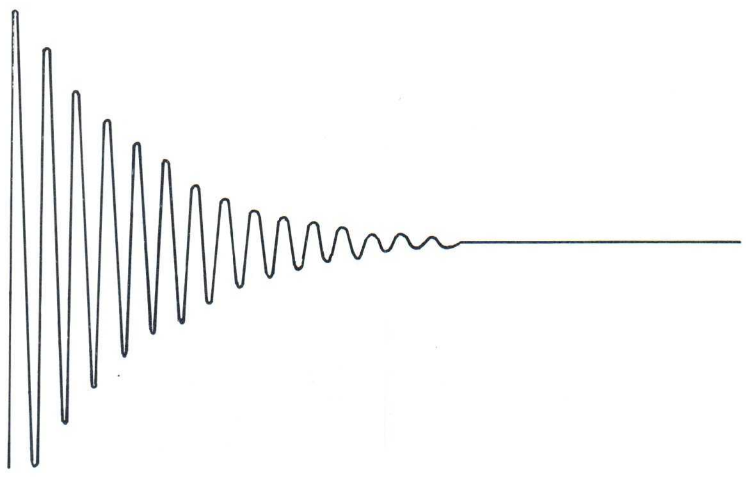


FIG. 2. RADIATION FIELD DECREASING WITH DISTANCE

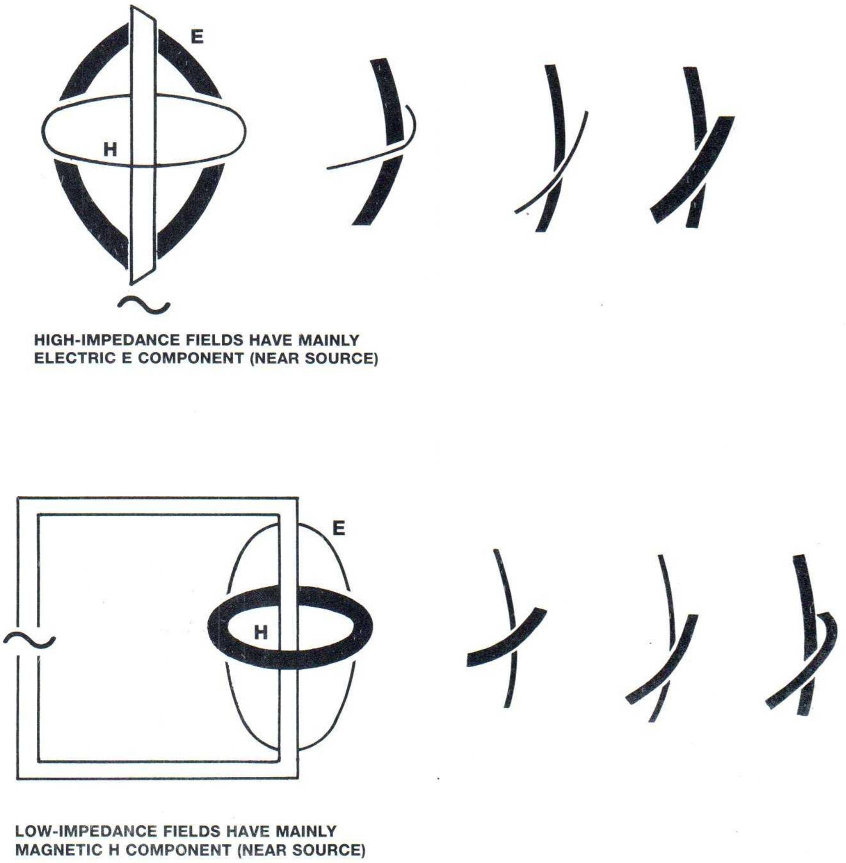


FIG. 3. H-E FIELD RELATIONSHIP VS SOURCE IMPEDANCE

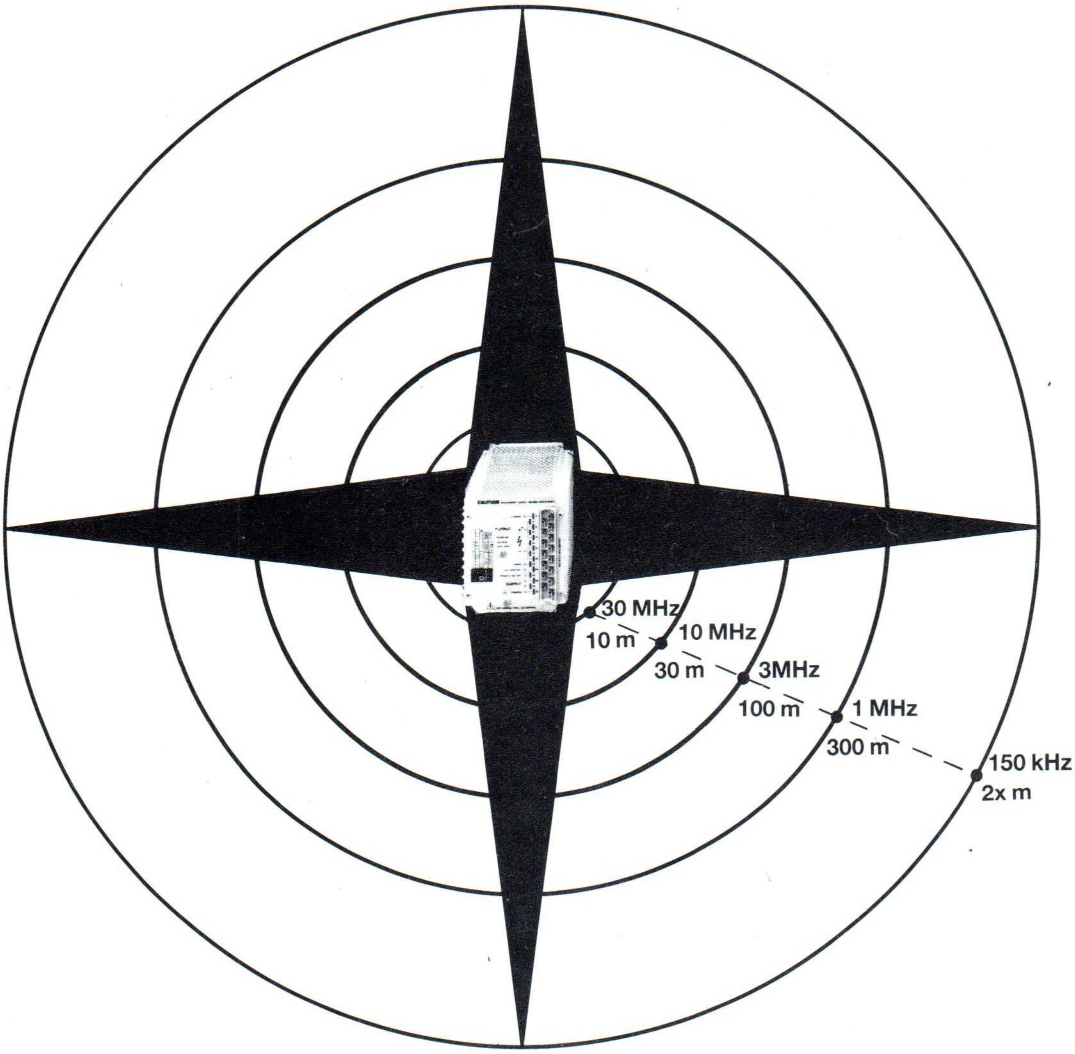


FIG. 4. POLAR DIAGRAM REPRESENTATION OF THE EXTENT OF ONE WAVELENGTH NEAR FIELD OVER 150 kHz TO 30 MHz

3. STANDARDS RELATING TO EMI

3.1 Defining the Norms

The value of EMI that can be tolerated and also the basis for measurements are defined in a number of international standards by IEC/CISPR. National regulations such as VDE (West Germany) and FCC (U.S.A.) have been adopted from these recommendations.
Briefly defined, these standards are:
CISPR 11: describing the limits and methods of measurement of EMI characteristics of industrial, scientific and medical radio frequency equipment.
IEC 478-3: especially dedicated to power supplies; gives also EMI tests for d.c. output.
VDE 0871: radio frequency suppression of r.f. equipment for industrial, scientific, medical and similar purposes. Applicable to all equipment using or producing frequencies above 10 kHz, excluding telecommunication equipment, but including data processing installations, computers and office machines. This standard also applies to SMPSs.
VDE 0875: for equipment producing high frequency created by commutation at a frequency lower than 10 kHz (e.g. thyristor controls). Specifications for radio interference suppression of electrical appliances and systems. More oriented to household appliances and power tools.
CENELEC HD 344: the values are fully covered by VDE standards.
FCC, part 15: two limits for conducted noise, similar to that of the VDE; an A level for industrial equipment and a B level for consumer devices.

The VDE 0871 standard has in fact been adopted by Philips for comparing the level of interference conducted to the mains by their SMPS range, since it has the widest frequency range, includes all other standards and is therefore universally accepted by customers.
The IEC 478-3 has been retained for comparing the output line level.

Frequency range of these standards

Standard	10kHz 150kHz 450kHz 30MHz 300MHz 18GHz	Restriction
CISPR 11	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	mains 100-415 V
IEC 478-3	XXXXXXXXXXXXXXXXXXXXXXXXXX	conducted EMI source 25 A
VDE 0871	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	some surgical instruments
VDE 0875	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	if battery powered, no measurements belowe 30 MHz
FCC part 15	XXXXXXXXXXXXXXXXXXXX	conducted EMI

3.2. Accepted Standards for Conducted EMI

(the dotted lines indicate a part of VDE 0871 that is still under discussion)

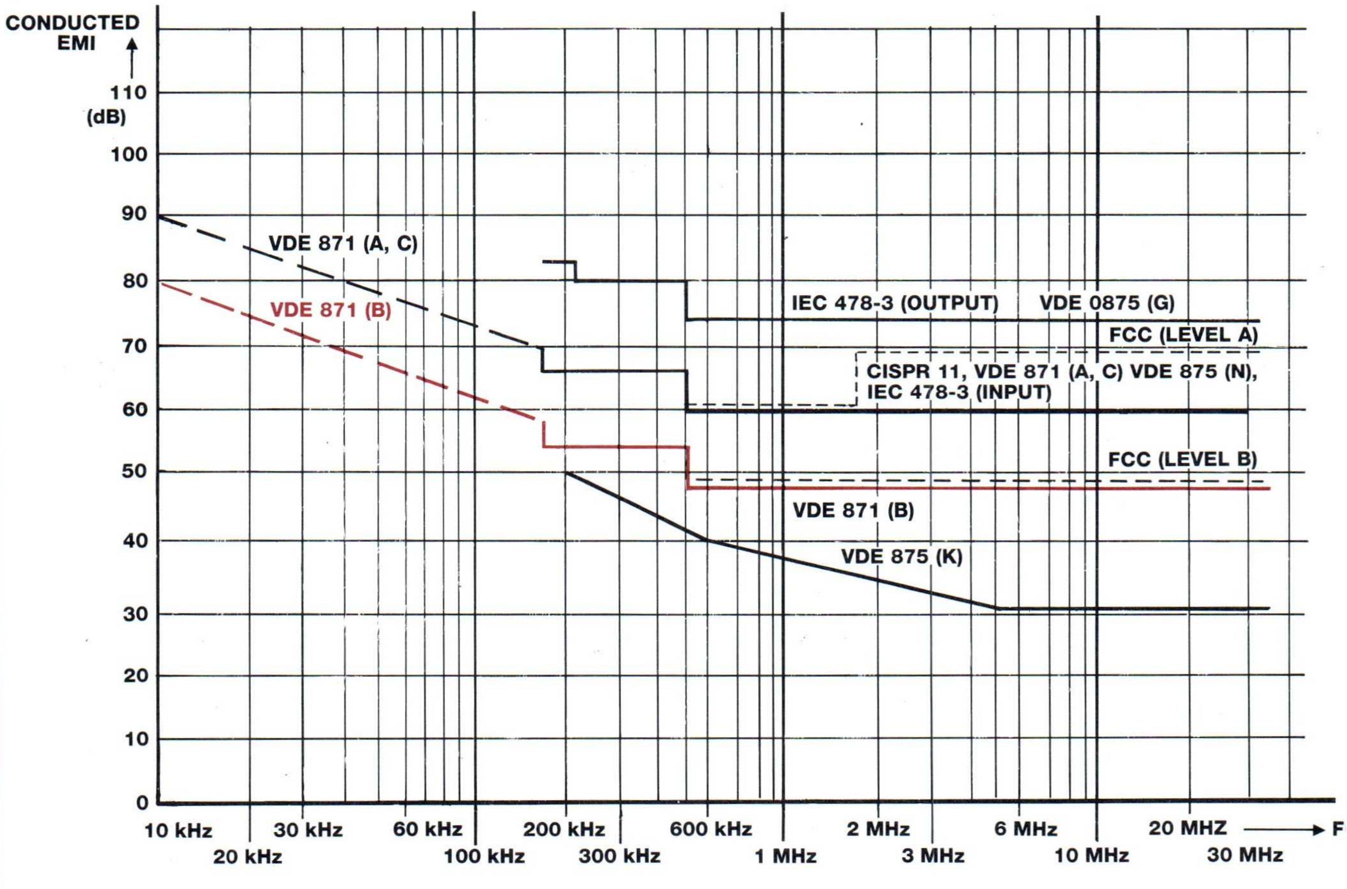


FIG. 5. COMPARISON OF CONDUCTED EMI STANDARDS

3.3. EMI Legislation

In many countries, it is now illegal to sell electronic equipment that has not received approval by a specifically certified laboratory.
Especially, the legislation in West Germany, based on VDE standards, is well documented and very strict.
It is worthwhile to have a closer look at this legislation. For equipment, defined under VDE 0871, the "Deutsche Bundespost" (Post office) delivers two kinds of approvals: a general approval ("Allgemeines Genehmigung") and an individual approval ("Einzelgenehmigung"). To obtain a general approval, the equipment shall meet the VDE 0871 level B. It is necessary to perform a type test, under supervision of the VDE. After approval, the equipment can be used without further problems. It may also bear the VDE 0871 EMI bench-mark (Funkschutzzeichen). Any equipment, not meeting the level B (but still under the A-limit), has to be sent to the VDE office for type-testing. If compliance has been achieved, it is a FTZ number (Fernmelde-Technische Zentralamt), accorded. After installation, the customer needs a licence from the Post office to use the equipment.
This severe legislation justifies the efforts of Philips to meet the VDE 0871 level B.

4. EMI IN SWITCHED-MODE SUPPLIES

4. 1 The Cause

The fundamental cause of EMI in a switched-mode power supply stems from its fast-switching mode of operation as it converts the rectified mains into a rectangular waveform. The switching frequency itself may only be as low as 25 kHz, but the rapid change of voltage and current produces interference over a broad frequency range. The edges generate harmonics, which fall by 20dB per decade, at the lower frequencies. Because switching is not instantaneous however, the slope suddenly becomes 40 dB per decade at a higher frequency.
At shorter switching times, the edges get steeper and this critical frequency point is displaced even higher in the frequency spectrum, thus increasing the EMI amplitude. (FIG. 6)

These fast switching currents generated within the circuit, often at high amplitudes, are potential sources of electromagnetic interference through unwanted coupling.
Moreover, because the power supply is a source of electrical energy, it is inevitably coupled to other equipment. Often, a power supply feeds sensitive data equipment where the effects of EMI could be serious if action is not taken to eliminate it. (FIG. 7)

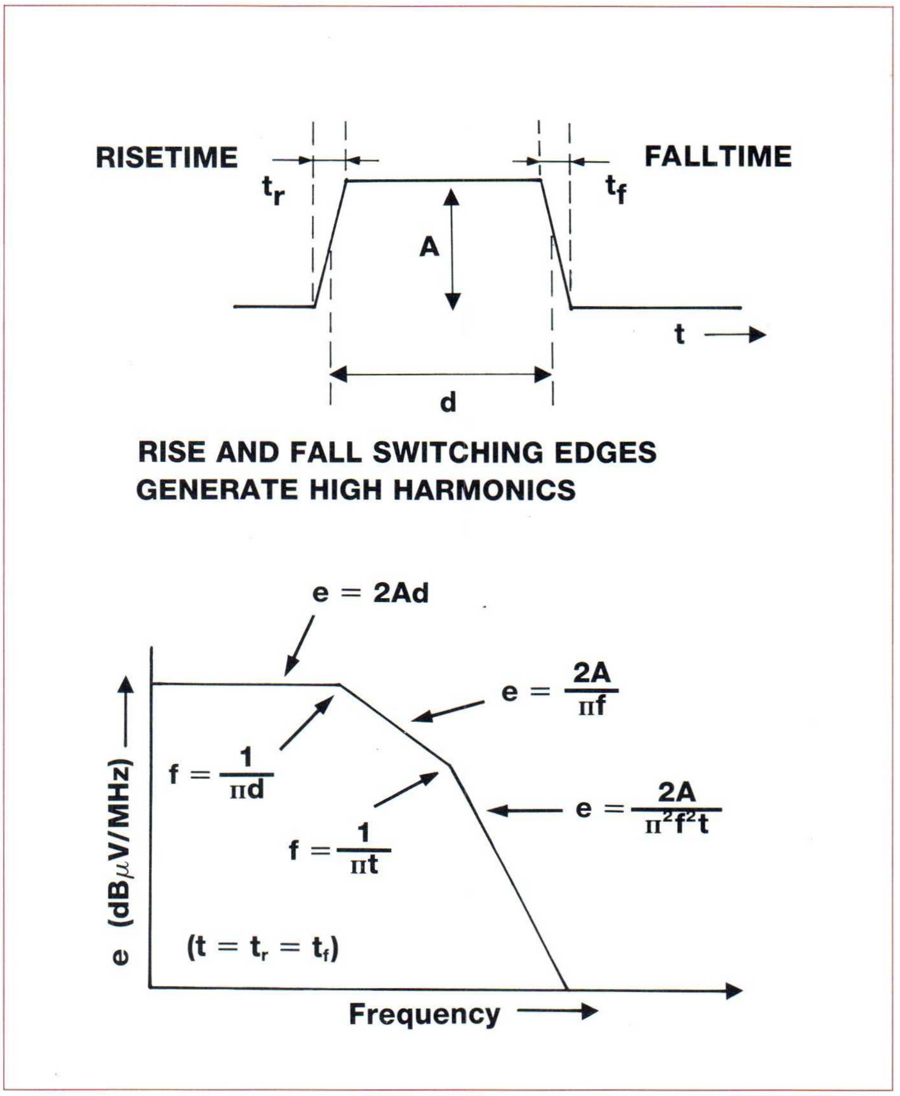


FIG. 6. SPECTRUM OF HARMONIC AMPLITUDES IN SWITCHING WAVEFORM

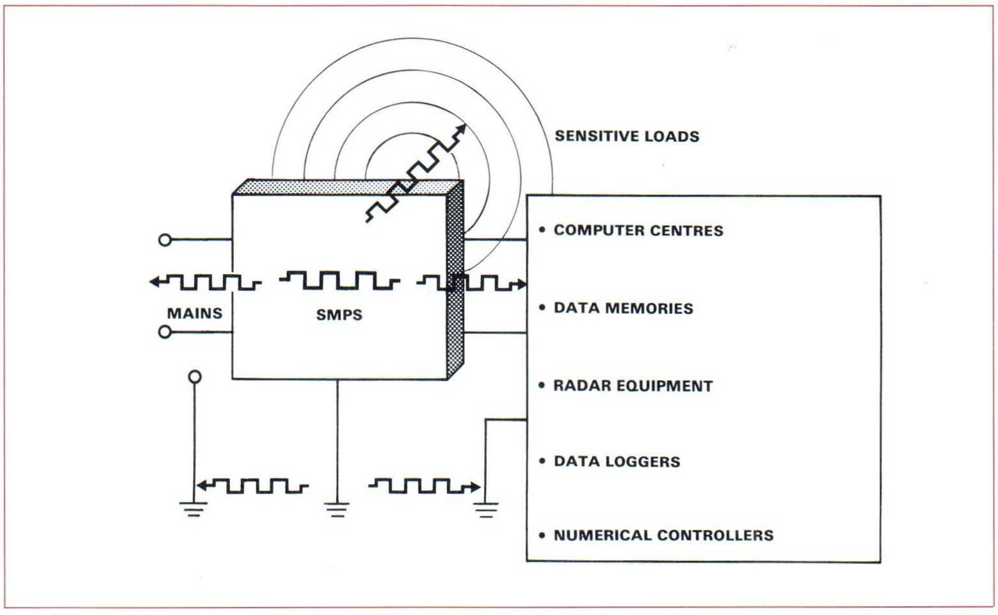


FIG. 7. POTENTIAL SOURCES OF ELECTROMAGNETIC INTERFERENCE

4.2 The Cures

Fortunately, various techniques are available at the design and manufacturing stages to suppress interference in switched-mode power supplies to below internationally recognised limits. Briefly, these can be listed as follows:

* Electromagnetic shielding
* Electrostatic shielding
* Earthing
* Attention to component and wiring layout.

Interference may either be produced by direct radiation or conducted via the input and/or output terminals.

The solutions may be best considered by looking at a typical switched-mode power supply circuit to evaluate the possible interference paths it contains. (FIG. 8)

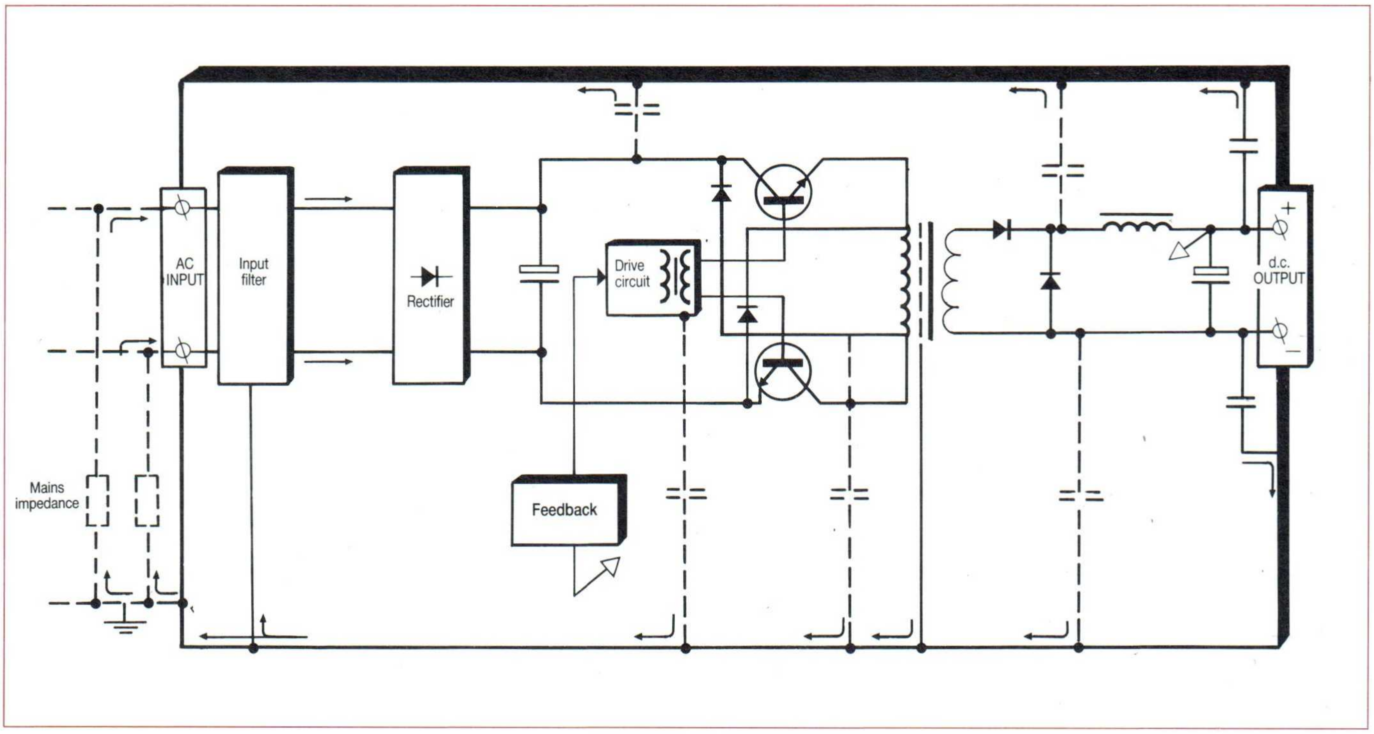


FIG. 8. TYPICAL SMPS CIRCUIT SHOWING INTERFERENCE PATHS

4.2.1. *Direct radiation*

Although this is more difficult to detect than conducted interference, it is easier to cure by adequate screening. The power supply can be enclosed in a metal box. Ideally, this should be solid and continuous, but for practical purposes, because a power supply must have an input and output and be sufficiently ventilated, openings must be present.
Adequate shielding (80 dB) is provided by copper, aluminium and steel 3 mm thick shields for frequencies from 10 kHz.
Above 1 MHz, most leakage can be attributed to openings in the shields. For EMI above 100 MHz, discontinuities of a few centimetres will make a shield ineffective. The change in field strength obtained with the best shielding designs can be in excess of 120 dB, measured only with specifically designed instruments.
Shield openings that are longer than 0.01 wavelength provide a radiation path for EMI. As shown, in practical cases this situation occurs at frequencies from about 100 MHz. (FIG. 9)

a) Reflection and absorption

Energy passing from one medium to another is invariably partly reflected and partly absorbed by the new medium. Familiar examples are light passing from air to water, and sound hitting a wall. Similarly, when EMI strikes a shield some energy is reflected, some is absorbed due to power losses from induced currents and some passes on through the shield after attenuation.

In order to contain or attenuate the EMI, the shielding properties of a material must be as effective as possible. This asks for a material that is a good reflector and yet has good absorbing characteristics for the portion of the energy that passes into it. Fortunately, the total shielding for plane-wave and electric fields can be better than 120 dB for copper, aluminium and steel.

However, it is useful to compare their shielding properties separately in terms of absorption and reflection.

Shield absorption: depends on its conductivity, permeability and thickness.

Absorption $= 131.5e\sqrt{fG\mu}$ (dB)
where e = thickness in mm
f = frequency in MHz
G = conductivity relative to copper
μ = relative magnetic permeability

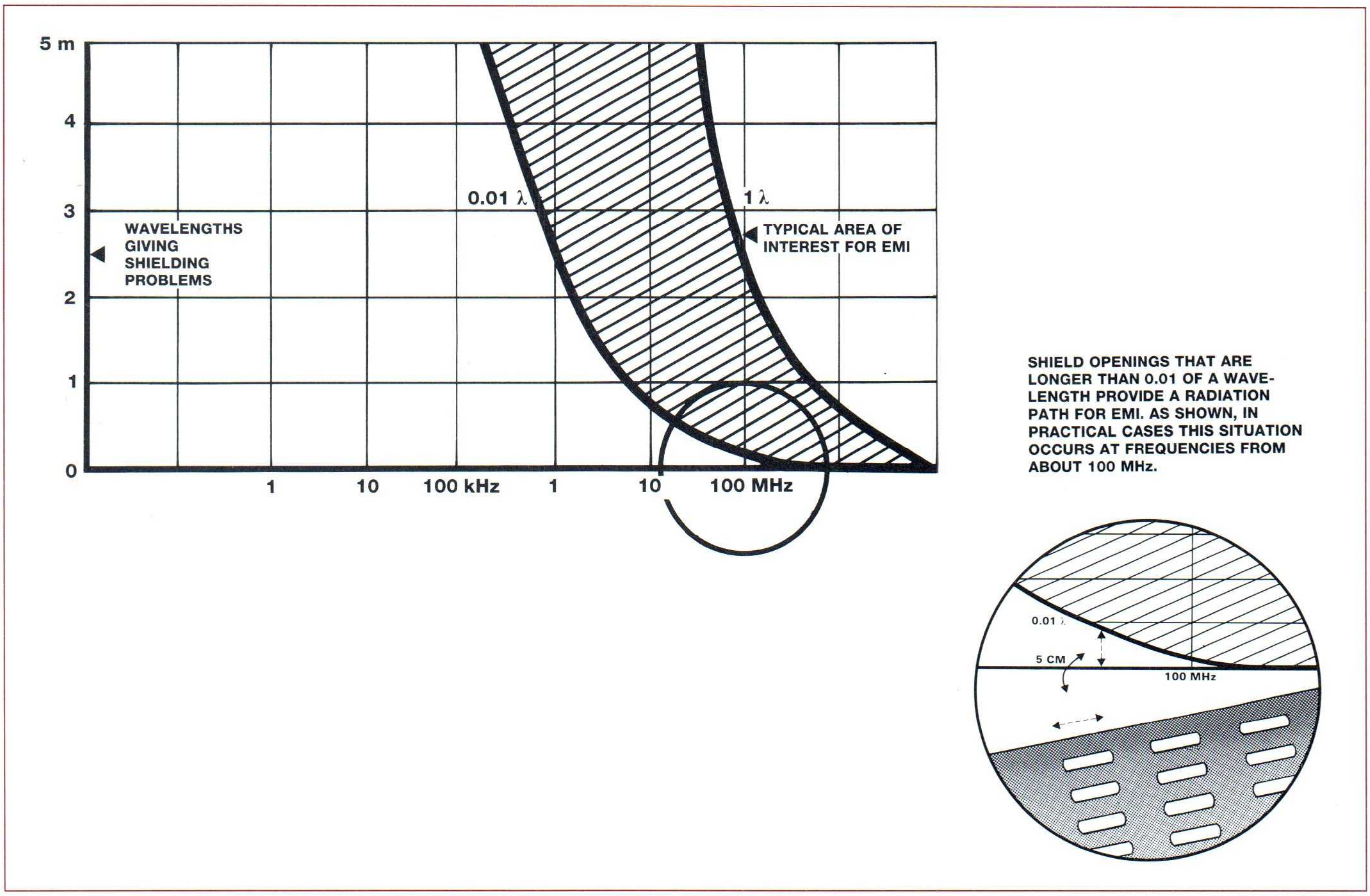


FIG. 9. SHIELD OPENINGS BELOW 0.01 WAVELENGTH REDUCE RADIATION

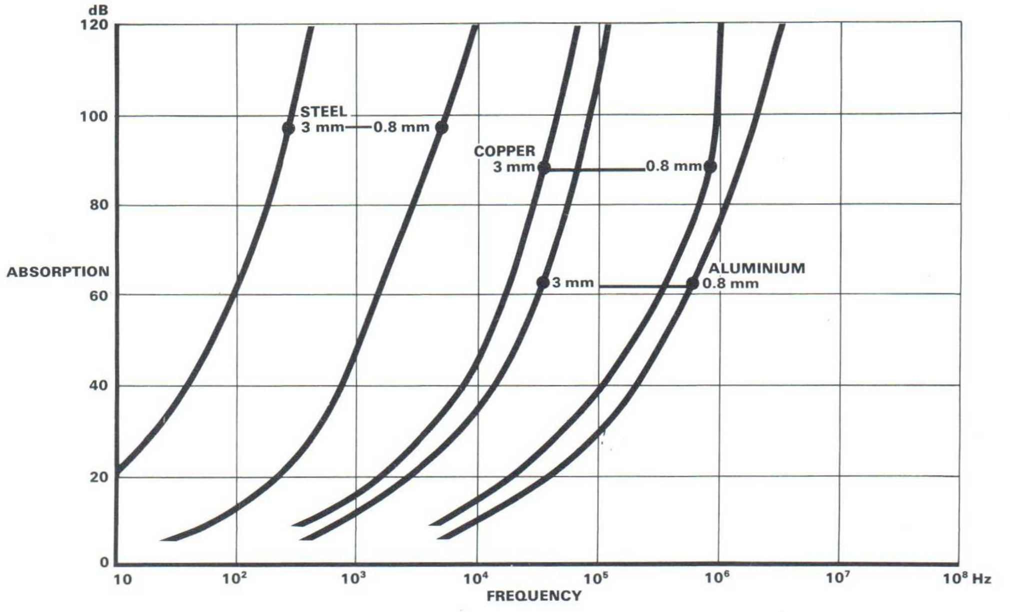


FIG. 10. RELATIVE ABSORPTION PROPERTIES OF SHIELD MATERIALS

Experience has shown that shield thickness is usually chosen between 0.8 mm and 3 mm for mechanical reasons and the absorption effect of such shields in steel, copper and aluminium are shown in Fig. 10. Up to a few kHz, steel is ideal. Above a few MHz, any mechanically suitable metal is a good EMI absorber.

Shield reflection: depends on the impedance of the field.

$$\text{Reflection} = 20 \log \frac{Zw}{Zs} \text{ (dB)} \quad (Zw > Zs)$$

where Zw = impedance of wave at shield

Zs = impedance of shield (generally much smaller than Zw)

In the practical shields considered, thickness does not affect reflection and for practical purposes a plane-wave is assumed. As shown in Fig. 11, high impedance fields are reflected better than low impedance fields, and low-frequency E fields better than H fields.

Copper and aluminium prove better reflectors than steel for the problematic H fields.

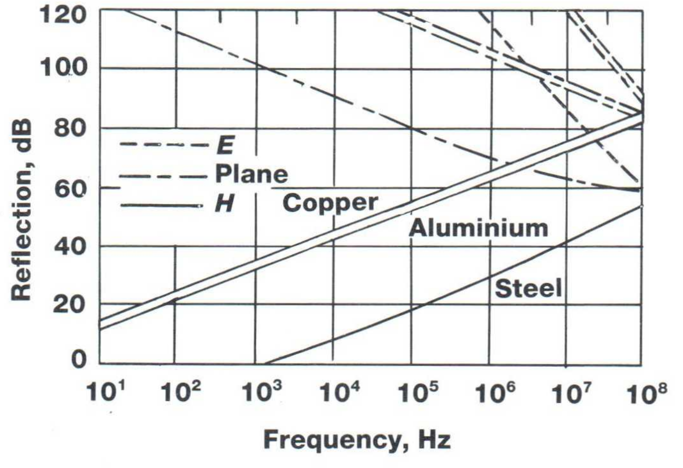


FIG. 11. RELATIVE REFLECTION PROPERTIES OF SHIELD MATERIALS

4.2.2. *Conducted Interference*

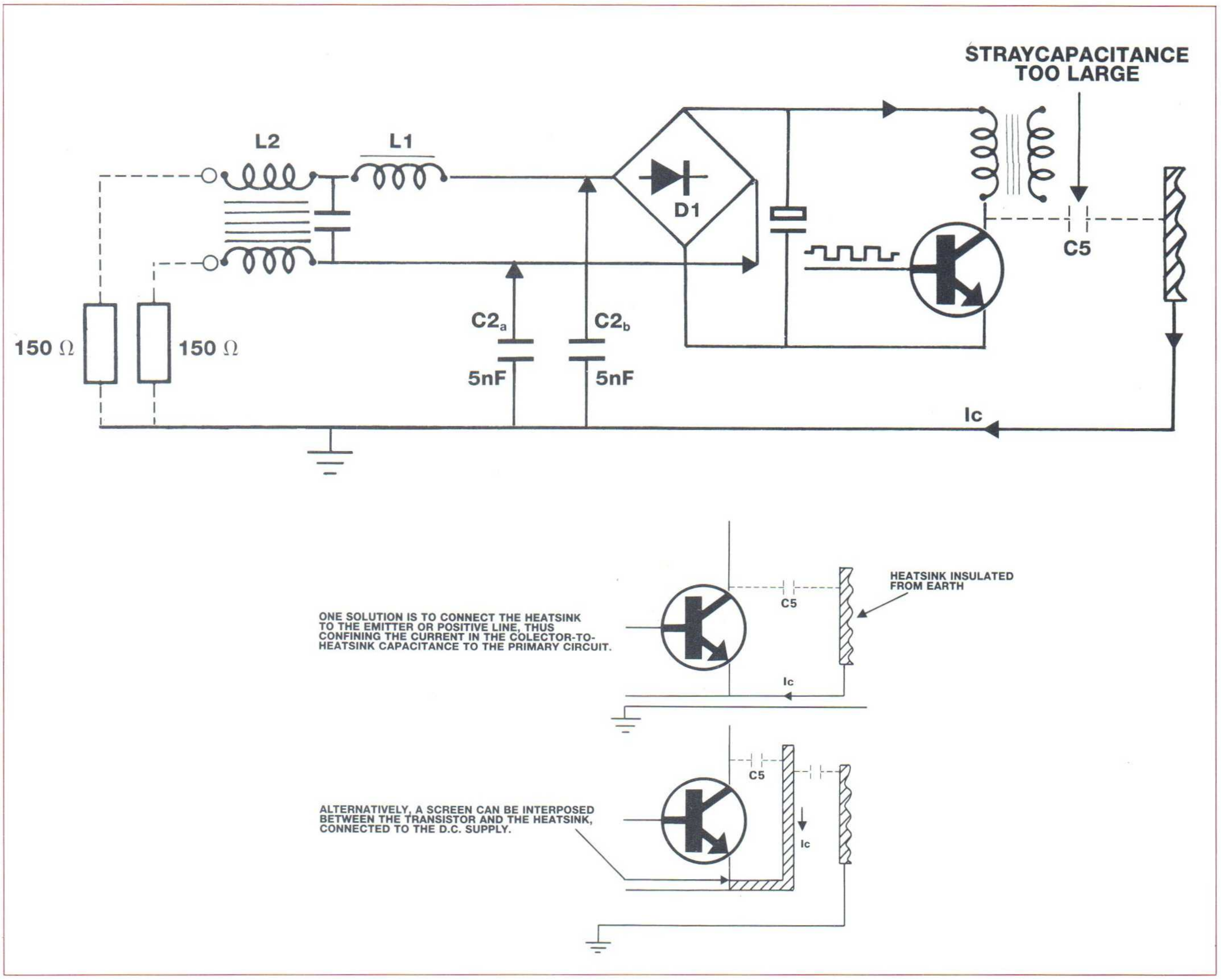


FIG. 12. REDUCING HEATSINK CAPACITIVE COUPLING PATHS FOR EMI

Conduction via input and output terminals is easier to detect, but more difficult to suppress. All aspects of EMI must be taken into account at every stage of design and construction; otherwise, unwanted signals can easily find their way by devious paths to the input and output lines via stray capacitances or inductive and resistive couplings. These paths can be defined by considering the essential elements of the switched-mode power supply shown in Fig. 8:

- switching transistors
- mains filter
- output transformer
- output filter

Each of these stages, together with the wiring layout can contribute to EMI unless carefully designed.

a) Switching transistors

With switching waveforms of about 500 V on the transistor collector, it requires an attenuation of at least one million to ensure that any EMI reaching the mains is within national specifications.

Using a practical mains filter giving a mains-to-earth attenuation of 100 and considering the first relevant harmonic to be 10 per cent of the peak-to-peak collector voltage, the attenuation required between collector and heatsink must be about 1000 times. This means that the maximum capacitance (C5) from collector to earth must be one-thousandth that of 10 nF, the total of C2 and C3; i.e. it must not exceed 10 pF.

When a mica washer is used between a TO-3 encapsulated transistor and heatsink, the capacitance is typically 100 pF, which would result in ten times the permitted interference.

One solution is to connect the heatsink to the emitter or positive line, thus confining the current in the collector-to-heatsink capacitance to the primary circuit.

Alternatively, a screen can be interposed between the transistor and the heatsink, connected to the d.c. supply. (FIG. 12)

b) Mains Filter

An iron-cored choke L1 may be used in series with the mains input with a parallel capacitor C1 to attenuate line-to-line interference (Isymm), which is usually a maximum at the lower frequencies.
The VDE 0871 extends the frequency range for EMI down to 10 kHz instead of 150 kHz as in VDE 0875. Therefore, the filtering should be especially effective for the switching frequencies 25, 33 or 50 kHz.

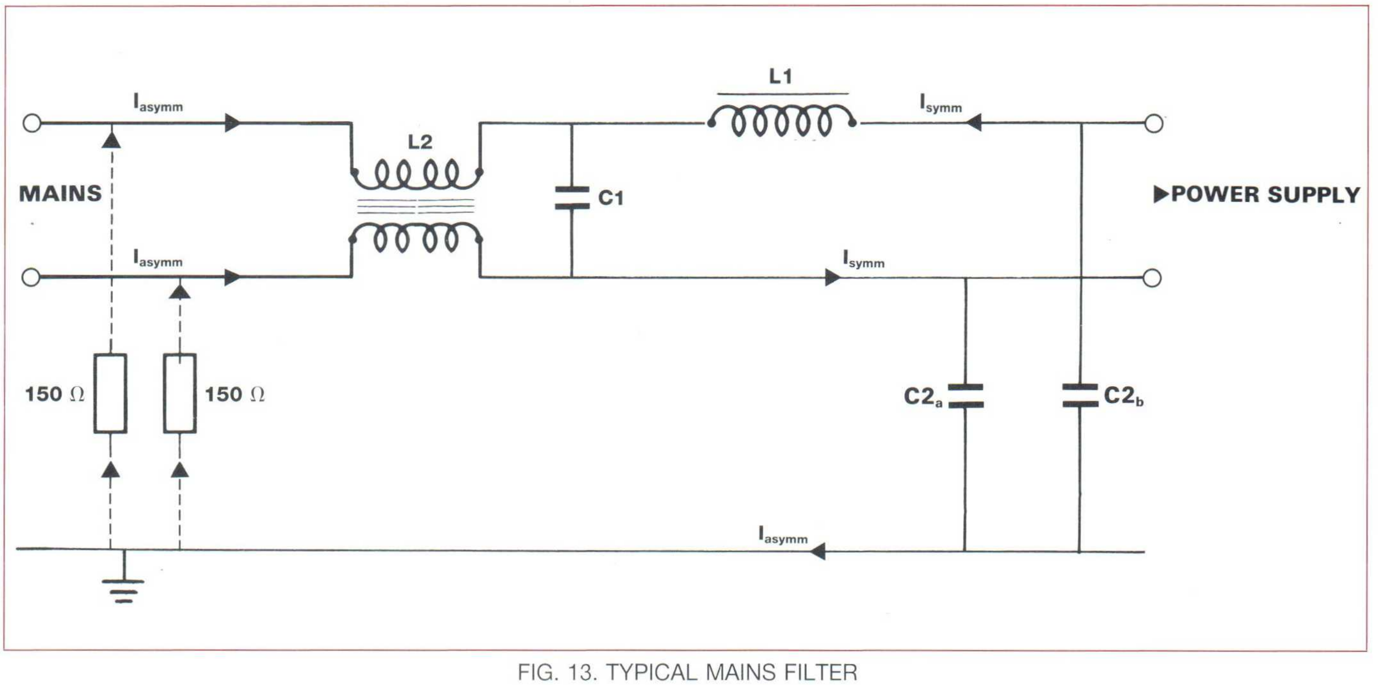


FIG. 13. TYPICAL MAINS FILTER

In the example, the high inductance of the bifilar-wound choke L2 and the two shunt capacitors C2a and C2b limit mains-to-earth interference currents (Iasymm) generated in the switching transistor collector-to-heatsink capacitance. (FIG. 13)

The filter network prevents EMI currents flowing into the 150 ohm artificial mains impedances. The 50 Hz currents in the bifilar winding of L2 cancel out and prevent saturation of the core.

c) Common-mode output currents

The same theory for common-mode input currents can be applied for the output of the power supply to explain the common-mode currents that exist between one of the output leads and earth.

d) Output transformer

The inter-wiring capacitance is also a source of earth coupling for the harmonics of the switching waveform. A solution is provided by an electrostatic screen of non-ferrous metal, such as a copper sheet between primary and secondary, which returns the capacitive current to the supply line. Care must be taken to ensure this does not form a short-circuited turn; a suitable gap must be left.
EMI currents can also be produced in the Ferrox-cube transformer core by capacitance between the primary and the core if the latter is simply clamped to an earthed mounting bracket.

If the primary is wound adjacent to the core and capacitance between a high-voltage secondary and core can be ignored, then connecting the core to the positive supply line will reduce EMI. (FIG. 14)

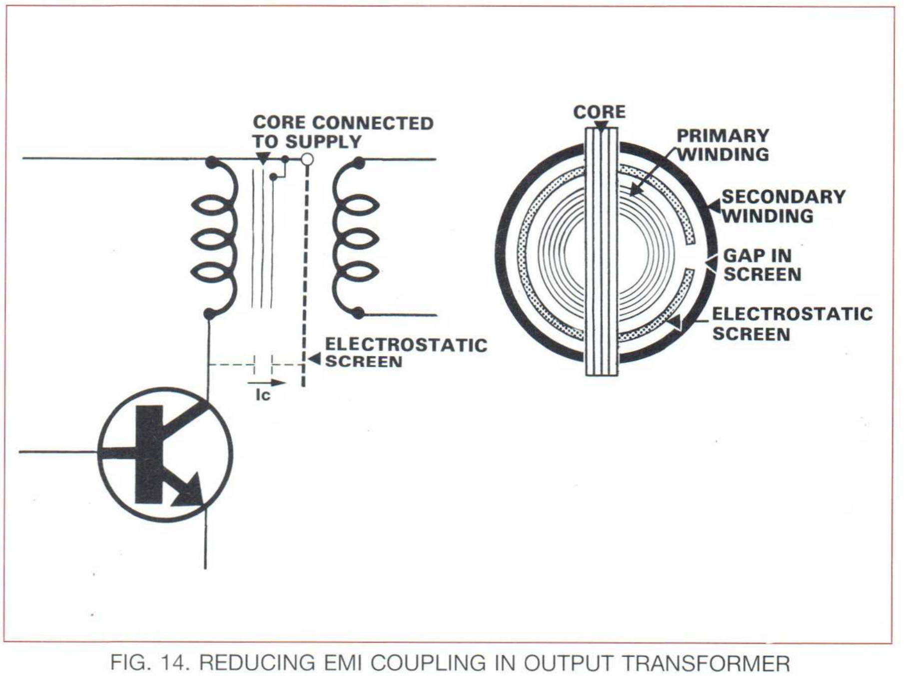


FIG. 14. REDUCING EMI COUPLING IN OUTPUT TRANSFORMER

e) Wiring Layout

Every part of a circuit carrying switching currents must be carefully designed to avoid unwanted coupling by inductive wiring loops and stray capacitances. At the printed circuit board stage this means paying special attention to component layout and printed wiring paths to reduce these effects.
The use of twisted pairs for go and return paths, particularly in the primary switching circuit assists in cancelling out magnetic fields.
A good example of the printed wiring and component layout of a modern switched-mode power supply is shown in figures 15 and 16.

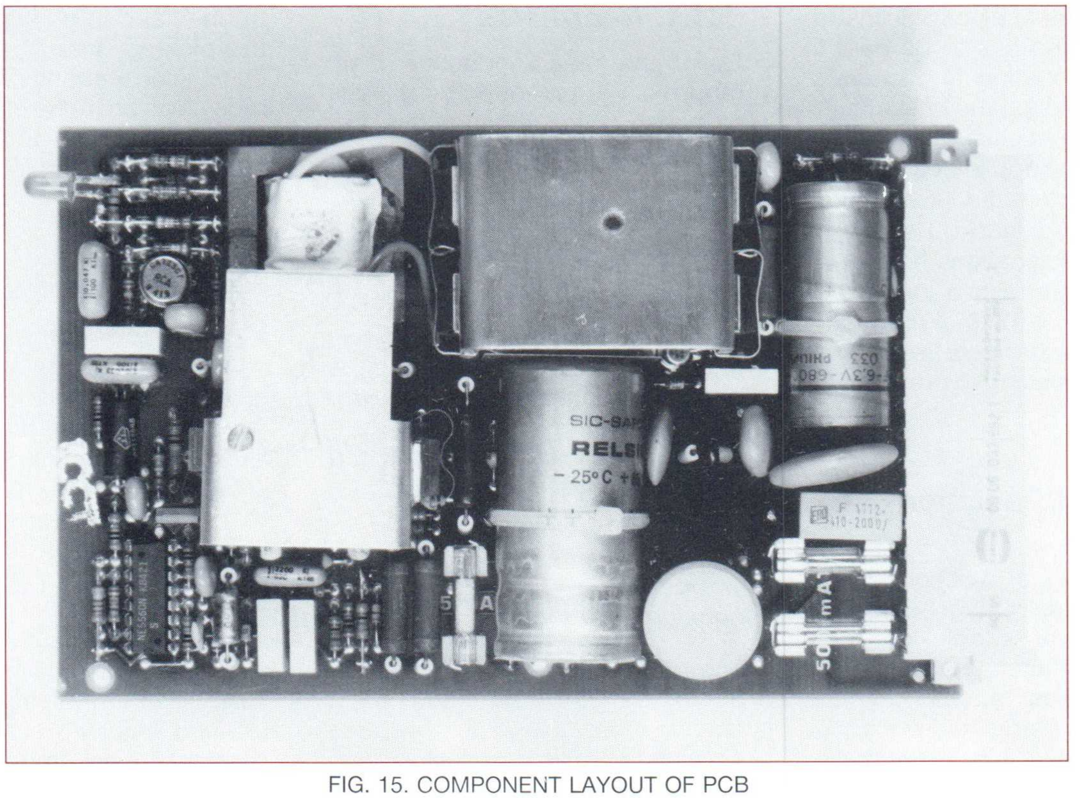


FIG. 15. COMPONENT LAYOUT OF PCB

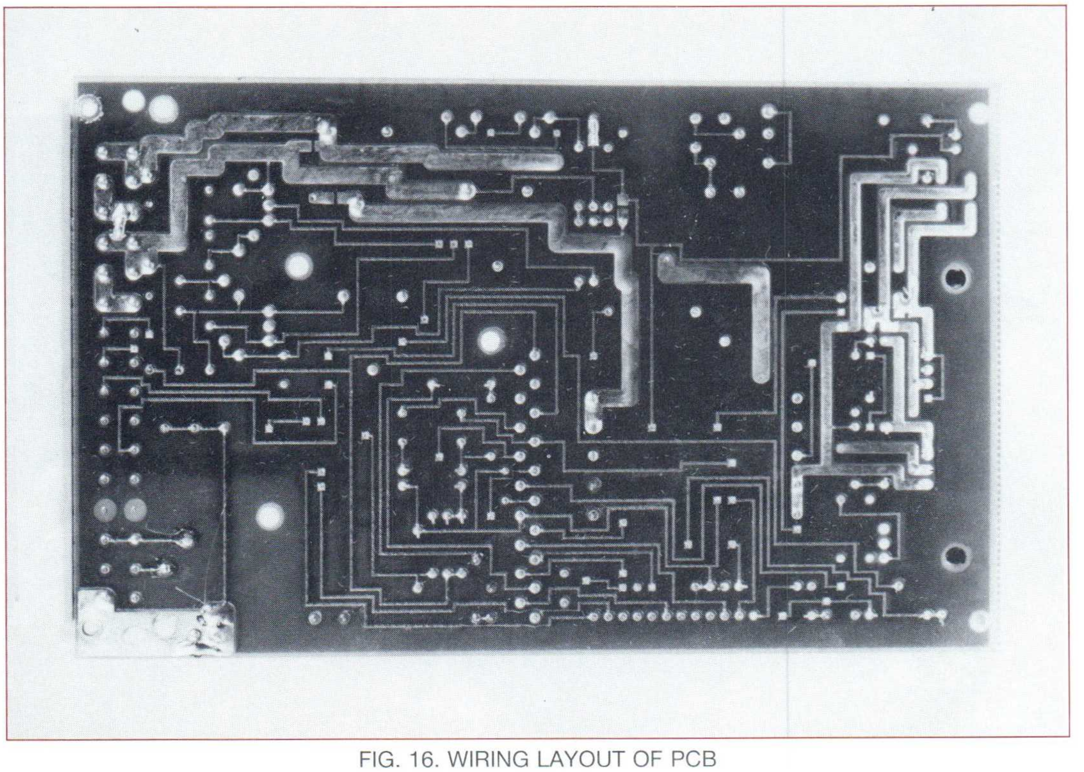


FIG. 16. WIRING LAYOUT OF PCB

5. PRACTICAL CONSIDERATIONS

Although good product designs go a long way towards eliminating radiated and conducted EMI in the power supply, problems can occur in practical situations where the SMPS is only a part of the whole system.
As with any other electronic instrument, attention has to be paid to equipment location and connection in order to get the best results. High-quality enclosed switched-mode power supplies easily meet the highest international standards regarding radiation. The same exacting specifications hold good for the cost-effective open versions intended for rack-mounting when reasonable care is taken in the system building to prevent EMI leaks.

5.1 Direct Radiation

As discussed in Section 2, the radiated electromagnetic field from a power supply not only decreases in intensity as the distance increases, but also changes in character, from a highly magnetic field in the vicinity of the power supply to a plane electro-magnetic wave at further distance. It is therefore useful to consider the radiation problems in relation to these distances.

5.1.1. *Near fields*

Even the near induction field (approx. 1 λ) can often be difficult to measure, and although this presented some problems when evaluating power supplies, the weak field strengths present are in fact a back-handed compliment to the quality of the design.
If EMI was emitted at the frequency of light, one would merely have to install the system in a darkened room to detect it! However, Philips Wavre has devised a handy probe in order to detect and plot EMI fields in the vicinity of power supplies.

Looking for trouble!

The probe consists of a wire loop 5 cm x 6 cm connected via a coaxial cable to the Y input of a sensitive measuring oscilloscope, or to a spectrum analyser if desired.
Measurements were made with the probe connected by a 75-ohm coaxial cable of 95 cm to a Philips PM 3240 oscilloscope (rise-time 7 ns, impedance 1 M-ohm, 15 pF).
It must be emphasised that the large loop is in fact looking for trouble, and in no way represents the pick-up area of practical circuits. Consequently, the measured values are only relative in practice, stray pick-up being very much smaller than indicated.

Field strength evaluation

A large number of measurements have been made on various types of both open and closed power supplies using the pick-up probe. Illustrated examples are given of several of these measurements both in and around the mounting racks, showing the points of maximum interest.

Although the results are shown graphically in two-dimensional form for convenience, it will be realised that the radiation field is omnidirectional, modified by the presence of nearby metal conducting or reflecting surfaces.

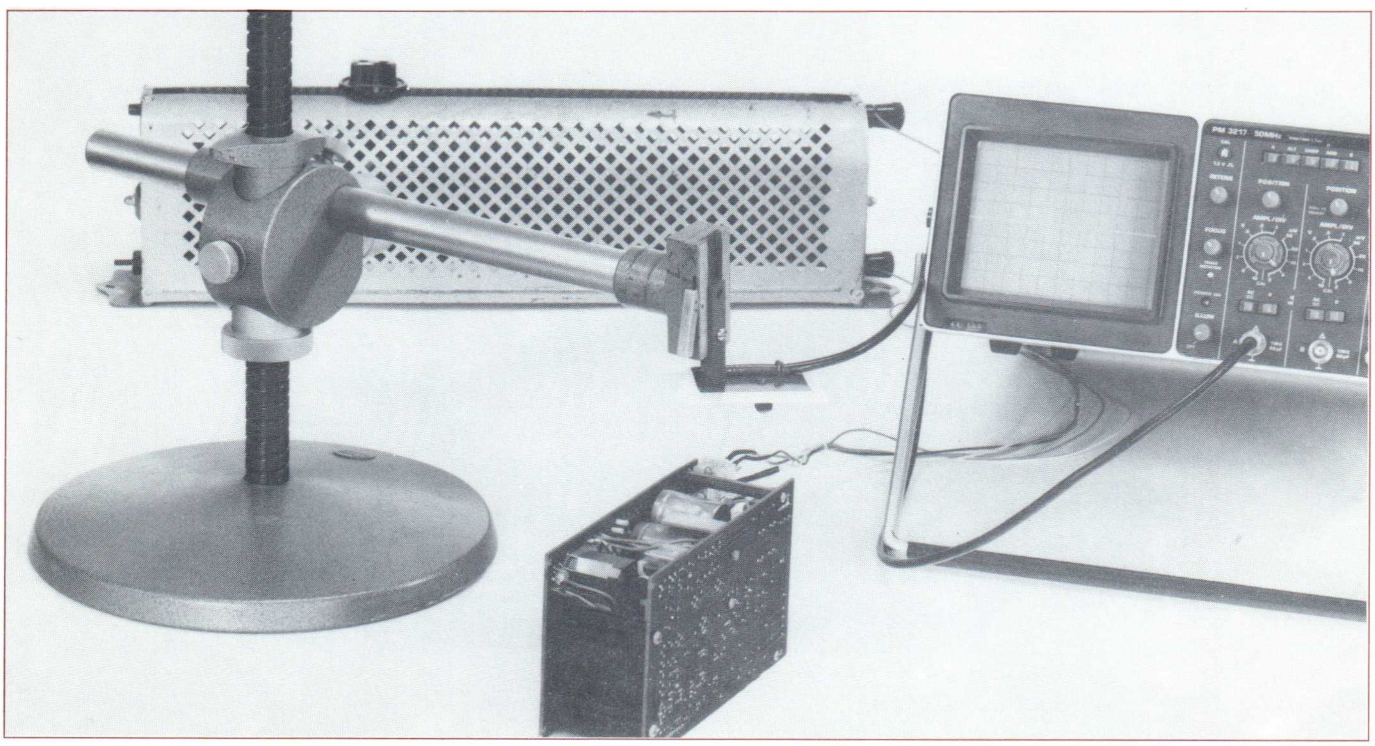


FIG. 17. LOOP PROBE CONNECTED TO A SENSITIVE OSCILLOSCOPE

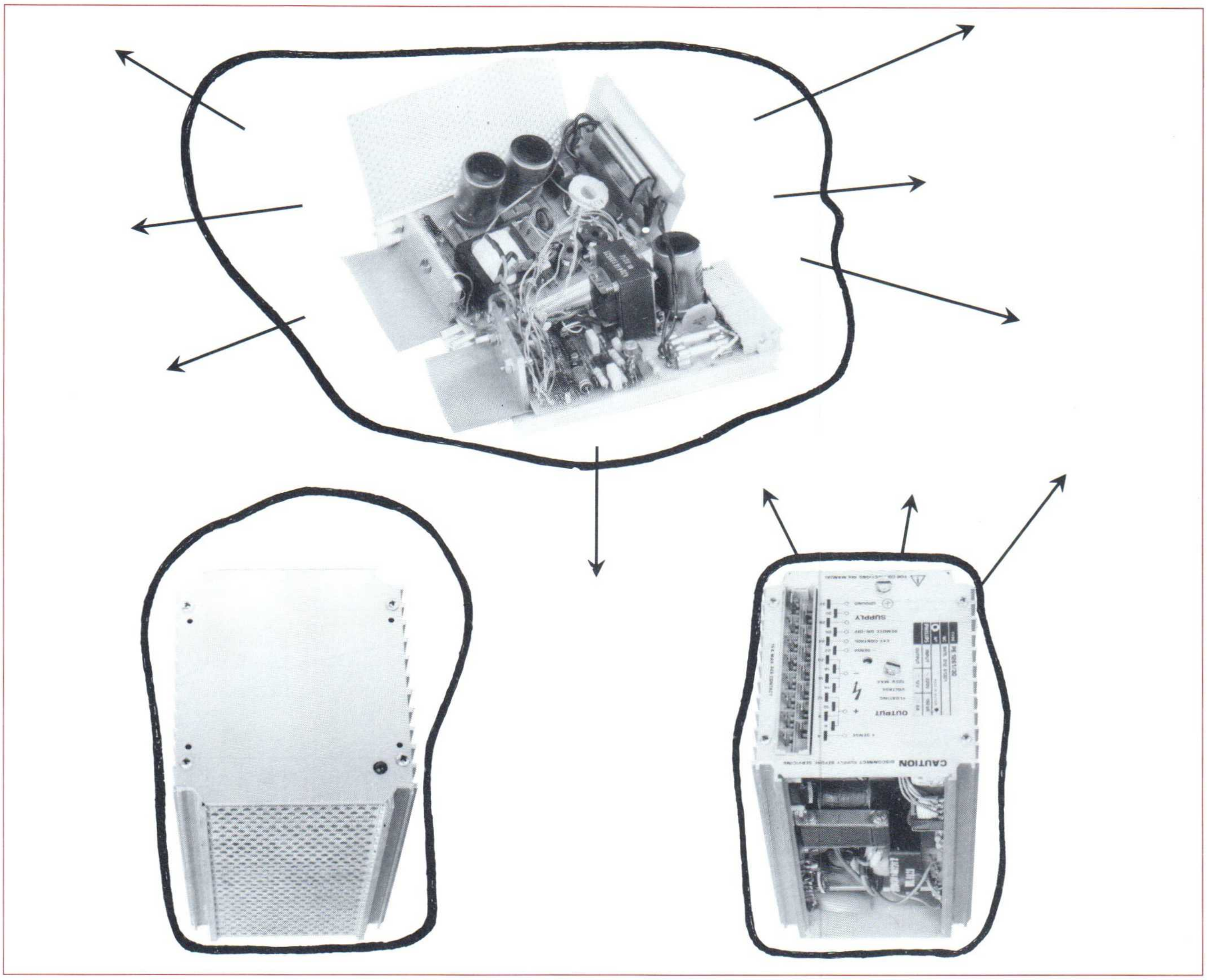


FIG. 18. INFLUENCES OF METAL SURFACES ON RADIATION

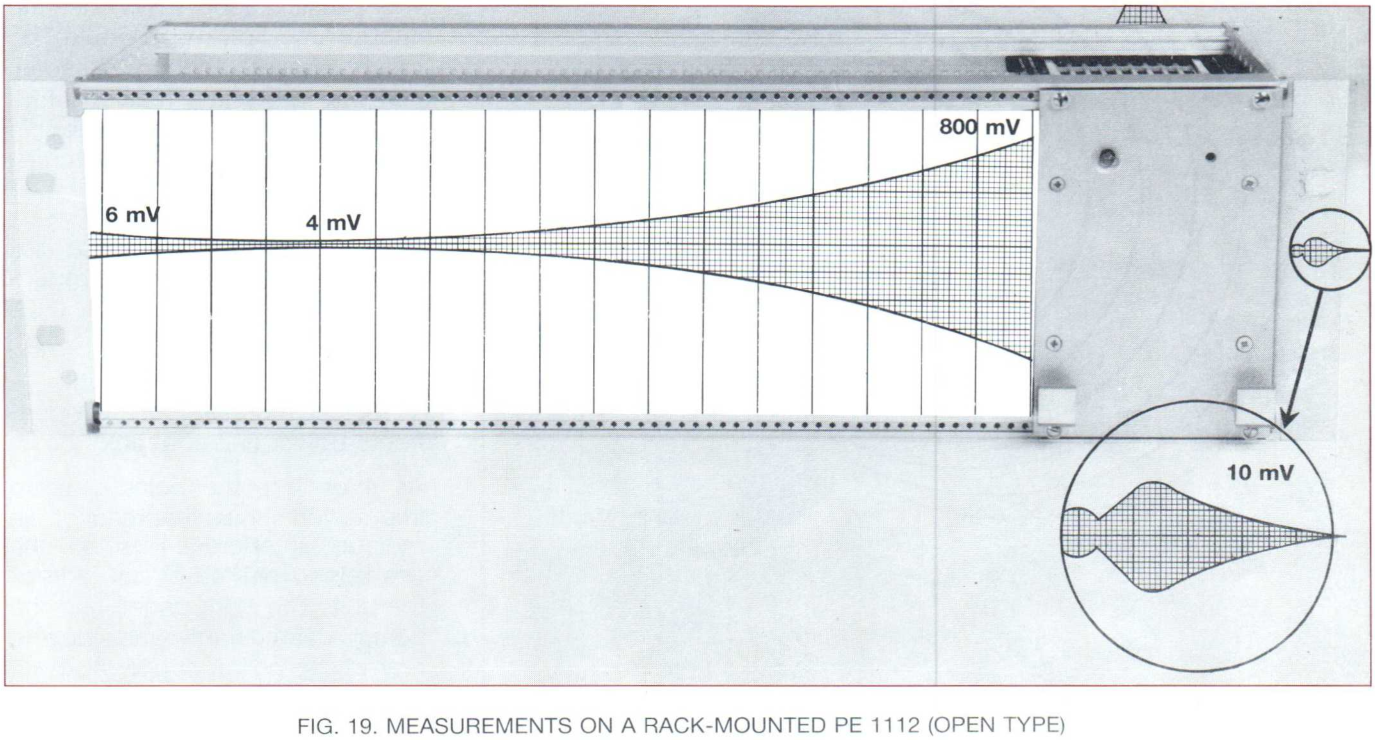


FIG. 19. MEASUREMENTS ON A RACK-MOUNTED PE 1112 (OPEN TYPE)

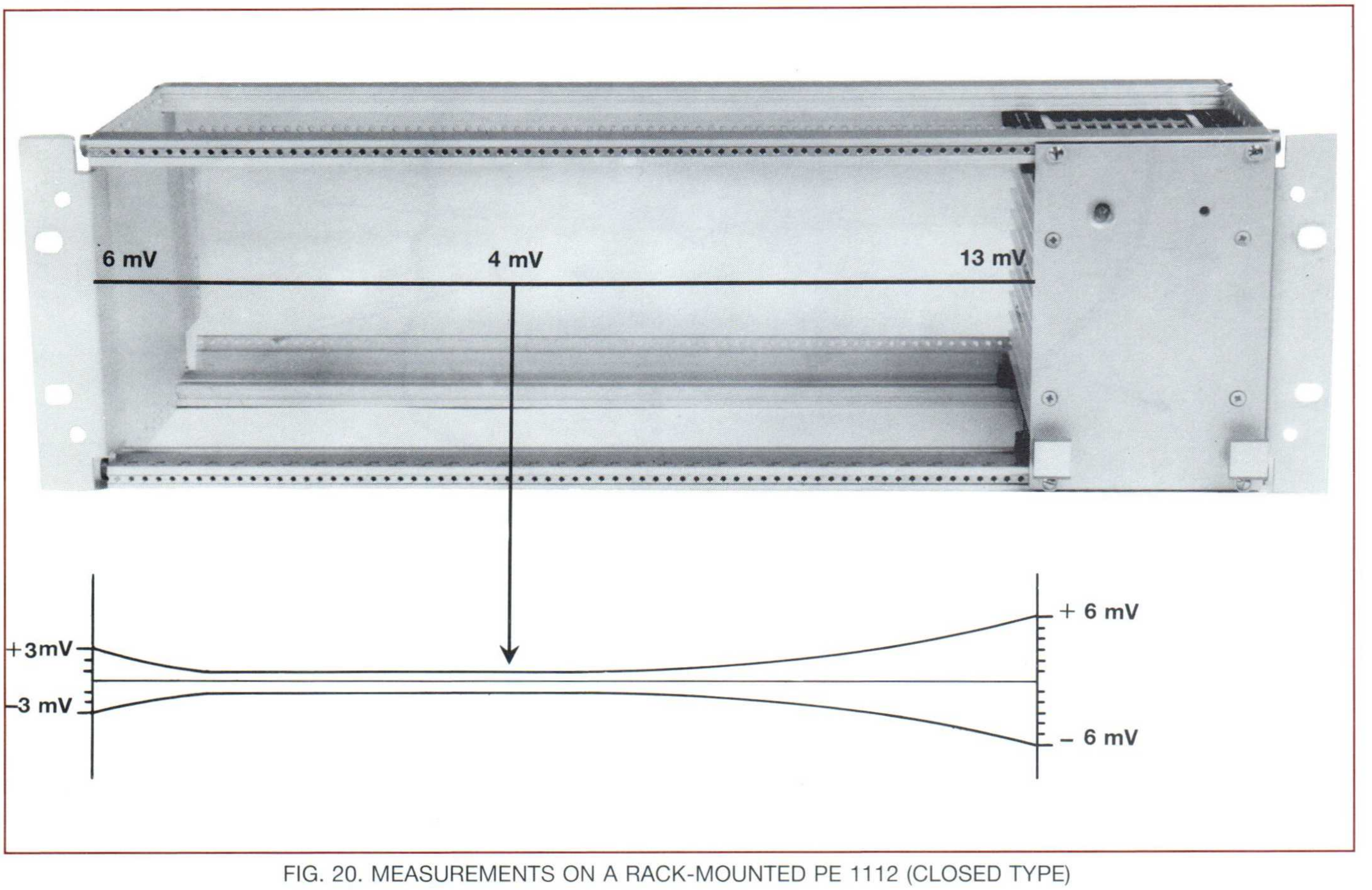


FIG. 20. MEASUREMENTS ON A RACK-MOUNTED PE 1112 (CLOSED TYPE)

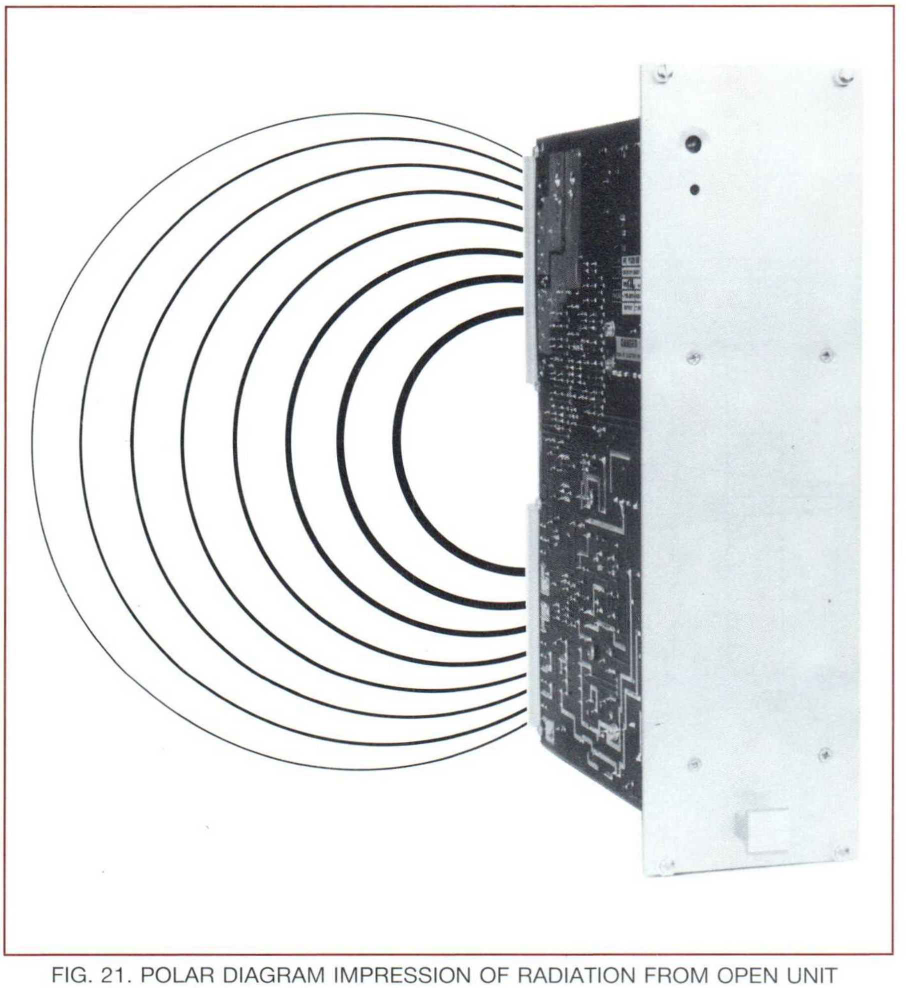


FIG. 21. POLAR DIAGRAM IMPRESSION OF RADIATION FROM OPEN UNIT

The test methods are shown together with details of the main results inside and outside the rack for the more cost-effective open-version.

Remember that the 800 mV adjacent to the open supply is the pick-up voltage induced in the very sensitive loop. In practice the interference pick-up would be much smaller. As can be seen, half-way along the rack the EMI would be practically negligible even for most sensitive circuits. (FIG. 19)

Pick-up measurements on a closed type show a sixty-fold reduction over the open-version. (FIG. 20)

a) logical mounting of an open-frame power unit in a rack

As expected, the polar diagram impression shows that most of the radiated interference is on the unshielded printed-circuit side of the unit. The front panel, and the heatsink at the right-hand side and rear of the power supply also act as efficient screens for any interference fields.

The logical place in the rack for a PE 1126 supply is therefore at the left-hand side where the heatsink protects other sensitive units in the rack, and the left wall of the rack protects equipment in adjacent racks. (FIG. 22)

b) Illogical mounting position

Taking the extreme case, it is illogical to position the PE 1126 at the right-hand side of the rack unless the other circuits in the rack are insensitive to radiation. However, in system building it sometimes happens that such a position is the only one available, or is dictated by other circuit conditions. Such a position can give rise to probe pick-up of 550 mV approx. (FIG. 23)

FIG. 22. MEASUREMENTS ON A RACK-MOUNTED PE 1126 (OPEN TYPE)

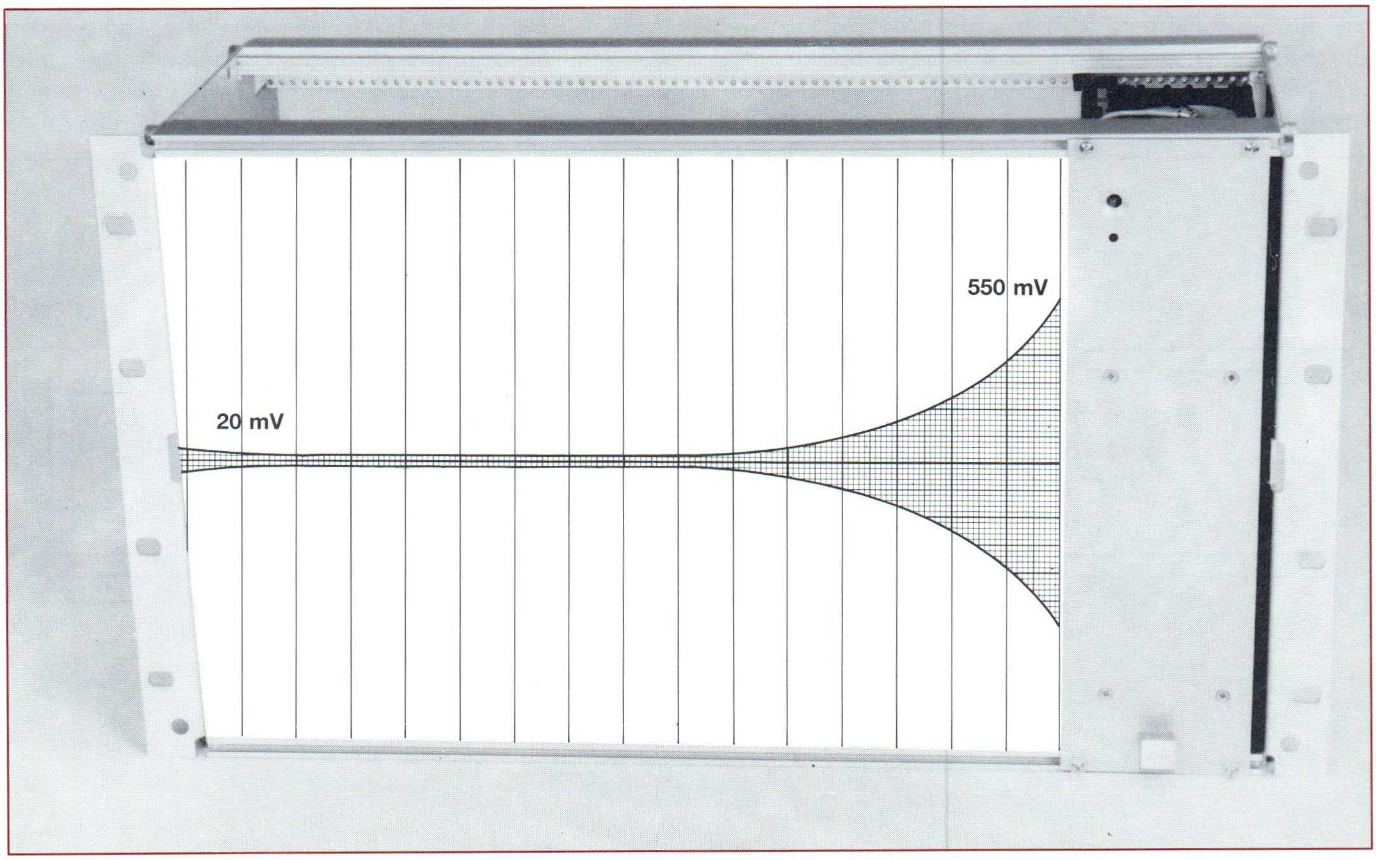


FIG. 23. ILLOGICAL RACK-MOUNTING OF OPEN-FRAME POWER UNIT

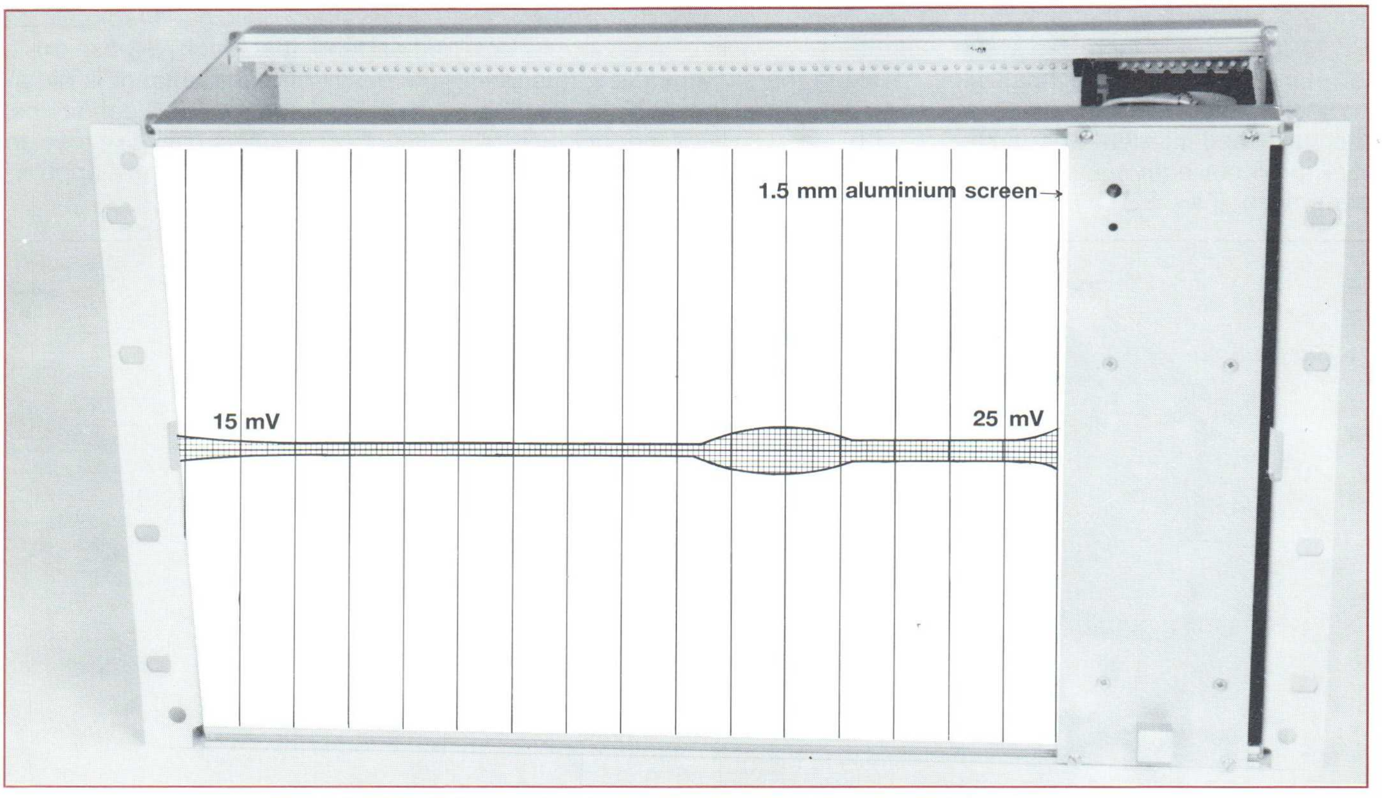


FIG. 24. EFFECT OF ADDING A SCREEN TO OPEN-FRAME VERSION

c) The remedy (FIG. 24)

When circuits of high gain and bandwidth are used in the same rack, shielding for the open-side of the PE 1126 can be effected by a 1.5 mm aluminium plate slotted in the rack adjacent to the power unit. The level then drops to 25 mV, an attenuation of 26 dB.

The screen is connected to the earth for safety reasons rather than for screening efficiency.

Mounting Power Supply outside the rack

If the radiated noise level inside the rack is too high, the SMPS can be installed in another rack, or free-standing. For extremely sensitive circuits, the power supply is best located in another rack at some distance from the rack containing the circuit modules. The common earth connection should be made at a single-point. Pick-up figures below 1 mV can be achieved, satisfying most customer requirements. (FIG. 25)

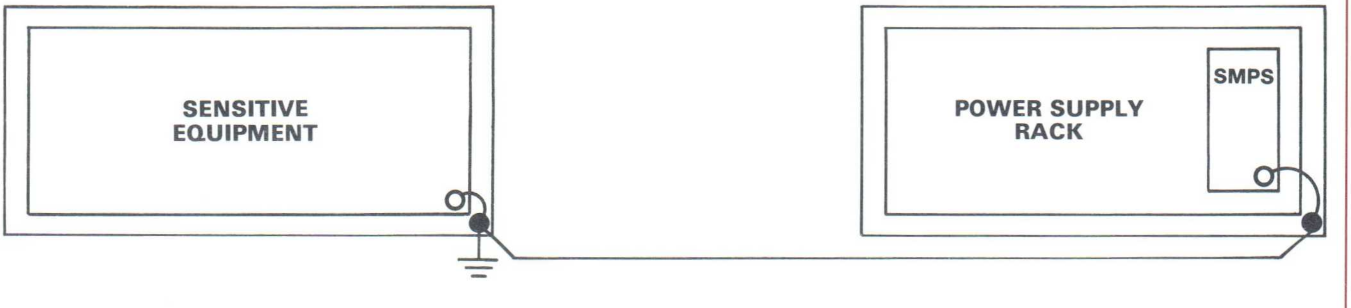


FIG. 25. SINGLE-POINT EARTHING

If it is necessary for the power supply rack and the module rack to be in the same framework, then a perfect screen is necessary between them to ensure that there are no troublesome interference fields.

Since it is virtually impossible to have cover plates without some resistance, and as ventilation holes provide a fraction of radiation, particularly at very high frequencies, then perfect screening between adjacent racks is difficult to achieve.

Therefore it is better to completely insulate the racks from each other and provide a single-point earth connection between them to prevent earth loops. (FIG. 26)

Attention must also be paid to cabling. Loops and long wires should be avoided and twisted wire used for go-and-return currents to cancel out electromagnetic fields.

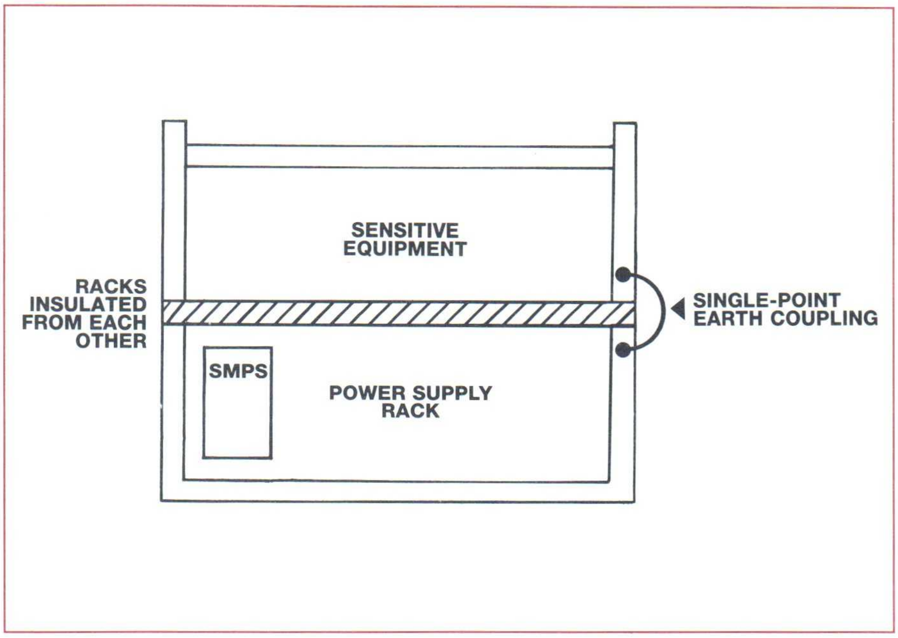


FIG. 26. ADJACENT RACKS INSULATED AND SINGLE-POINT COUPLED

5.1.2. *Far fields*

As the graph shows, the far field starts close to the source for the very high frequencies, i.e. the extremely high harmonic content of the interference. (FIG. 27)

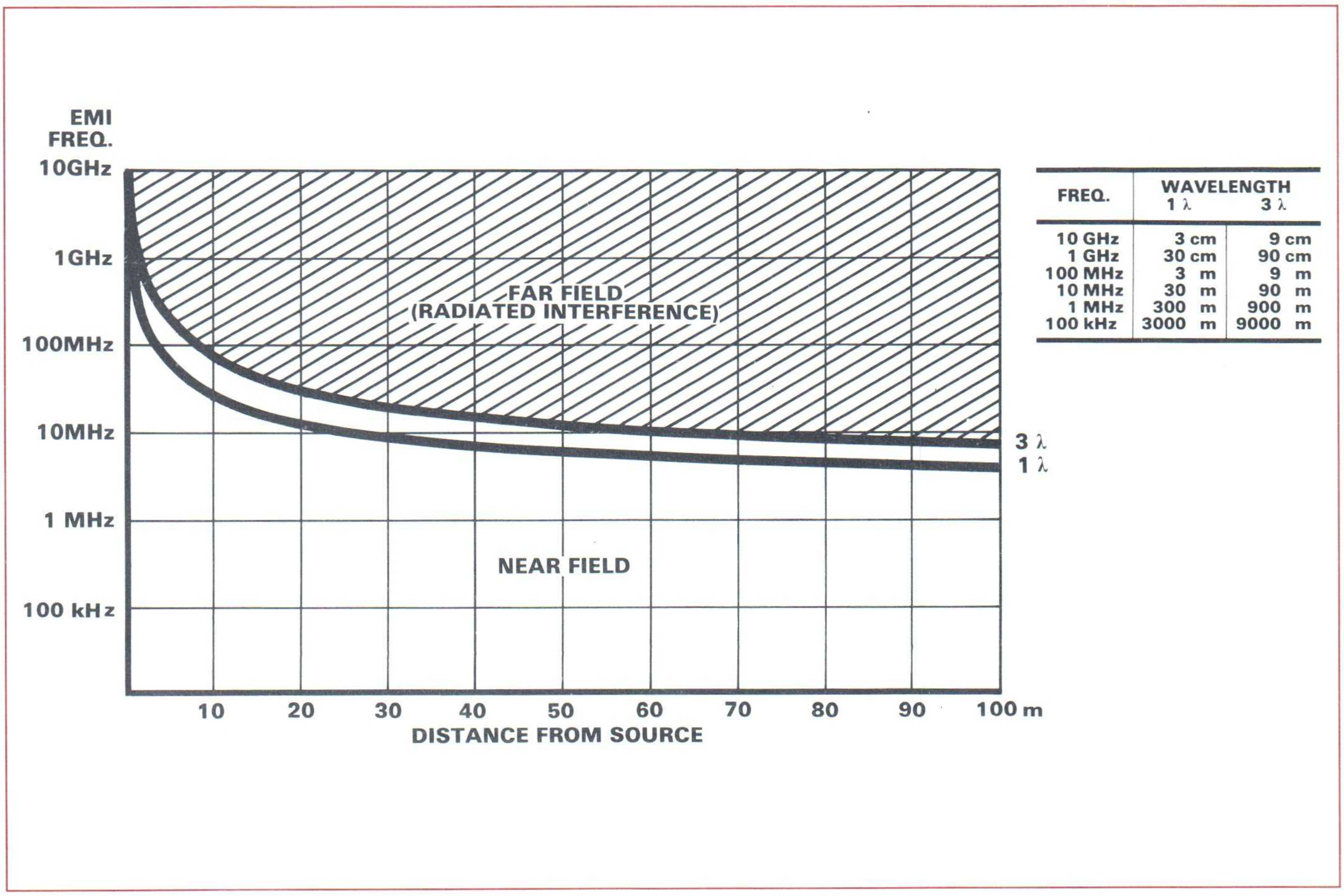


FIG. 27. FAR FIELD DISTANCES OVER THE EMI FREQUENCY RANGE

The magnitude of the field strength is dependent upon the source of radiation. As prevention is better than cure, attention must be given to the efficiency of the shielding and the balancing out of currents by using twisted wiring for the high-frequency current paths. To reduce the chance of multiple earth paths, good contact should be maintained between mating surfaces of the metalwork, covers, etc., for instance, by keeping them free of paint. When checking the efficiency of additional shielding, the field strength in the area to be protected should be measured under shielded and unshielded conditions.

5.2 Conducted EMI

As discussed in Section 4.2.2, conducted EMI from a power supply can be transmitted via the input terminals to the mains or via the output terminals to the load. The specifications mentioned in Section 3 although more stringent for conducted interference to the mains, are more easily met by filtering than those for the output ripple, as seen in the EMI level graph for the PE 1129, 1130, 1131 power supplies.

5.2.1. *Output ripple in the forward converter*

The equivalent of the LC filter circuit is represented as shown. Although the resistive component of the inductance L is of little interest, it is not so for the parasitic components of the capacitor C, namely, its series equivalent resistance Rp and its equivalent series inductance Lp.

The effect of the series resistance Rp on the ripple is considerable. The voltage developed across Rp:

$$\Delta V_{R1} = Rp \times \Delta I_L$$

The voltage developed by Lp:

$$\Delta V_{R2} = \frac{Vi}{n} \times \frac{Lp}{Lp + L}$$

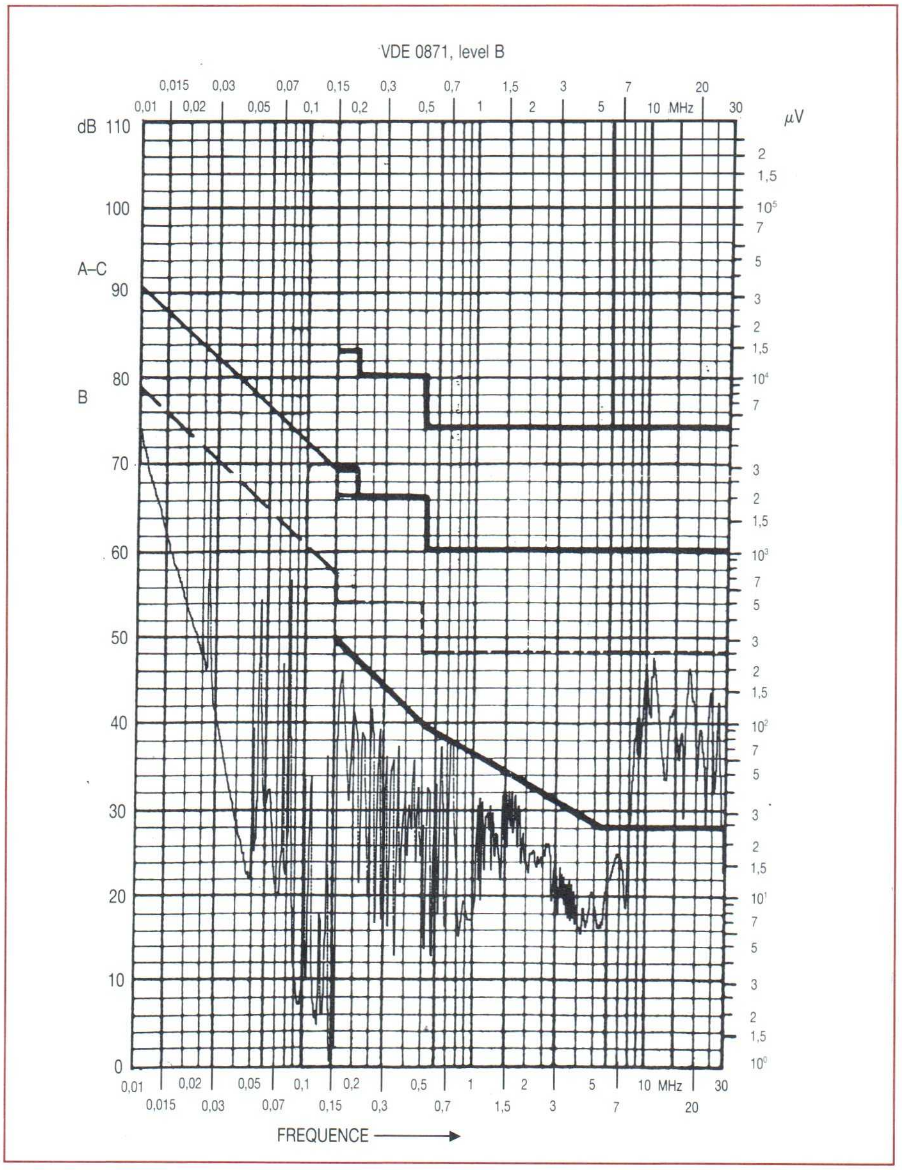


FIG. 28. GRAPH OF CONDUCTED EMI FOR PE 1129/30/31 SUPPLIES

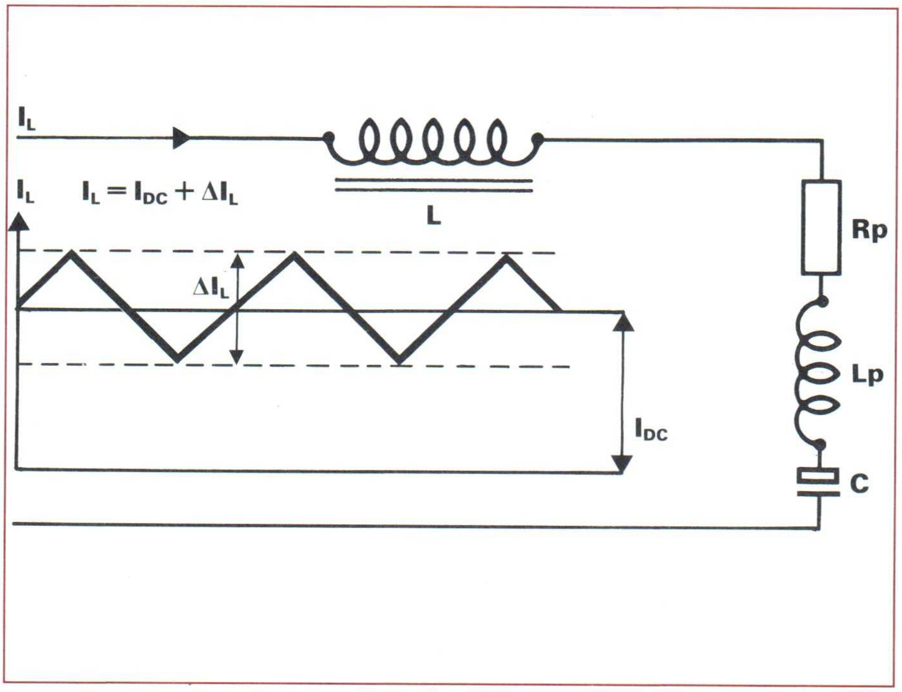


FIG. 29. EQUIVALENT CIRCUIT OF OUTPUT FILTER

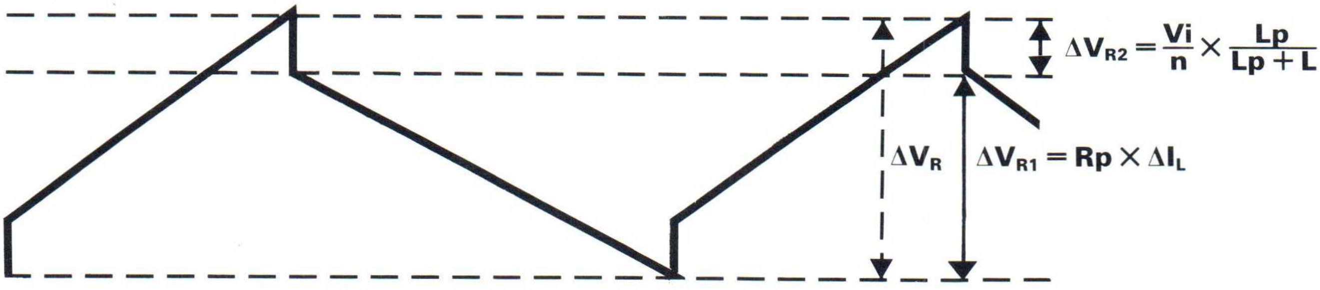


FIG. 30. COMPOSITION OF OUTPUT VOLTAGE

where the term Vi expresses the peak voltage excursion of

$$L\left(\frac{V_i}{n} - Vo + Vo\right)$$

The total ripple is

$$\triangle V_R = \triangle V_{R1} + \triangle V_{R2}$$

Conducted interference from the power supply to the load is normally attended to at the design stage (see Section 4.2.2. for details) by reducing stray capacitances to earth from conducting surfaces and by the use of bypass capacitors and adequate output filtering.
However, there are sensitive loads, for example, 100pA measurement systems and operational amplifiers, where the output ripple values are unacceptable.
In this case, an extra filter can be fitted external to the power supply to achieve the desired level. A typical filter is shown. (FIG. 31)
With a different current rating, this may also be used as an input filter.
* Ripple reduced by leakage inductance
* Asymmetrical currents reduced by two inductances

This filter should be mounted close to the output of the SMPS. The following precautions should be observed to avoid any unwanted pick-up:

- avoid placing the filter or its connections in areas of high electro-magnetic fields, as indicated in the previous examples.
- avoid loops and extra long connecting wires to the load
- mount highly-sensitive circuits in a separate cabinet where possible

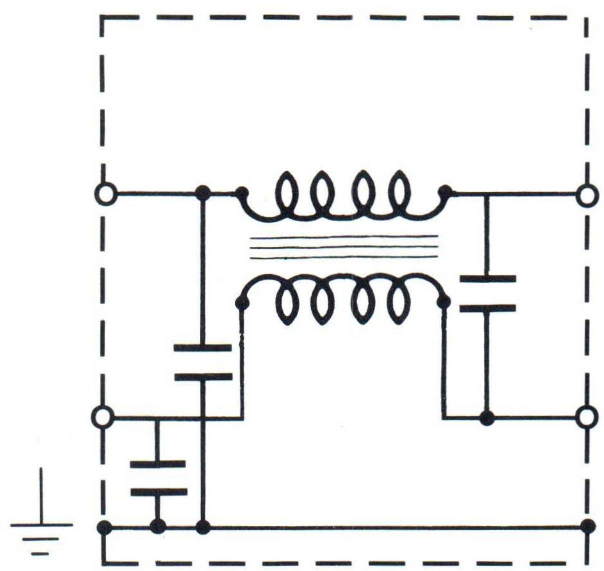


FIG. 31. TYPICAL COMMERCIAL FILTER

- connecting wires should not be at high r.f. potential with respect to earth to ensure they do not act as radiators.

Mount filter near to power supply and connect to load avoiding electromagnetic fields.
Better still, re-arrange cabinet location to avoid electromagnetic fields (FIG. 32).

5.2.2. *Filtering and Stability*

In feedback amplifier design, a voltage derived from the output is superimposed upon the input in such a way as to oppose the applied signal.
From basic principles, it will be recalled that the requirement for stability is that the phase shift around the loop should be less than 180° when the feedback factor is greater than 1. This feedback principle is applied in power supplies for load voltage sensing. Any variations in the load are sensed and fed back to correct the switching output from the power supply. (FIG. 33)

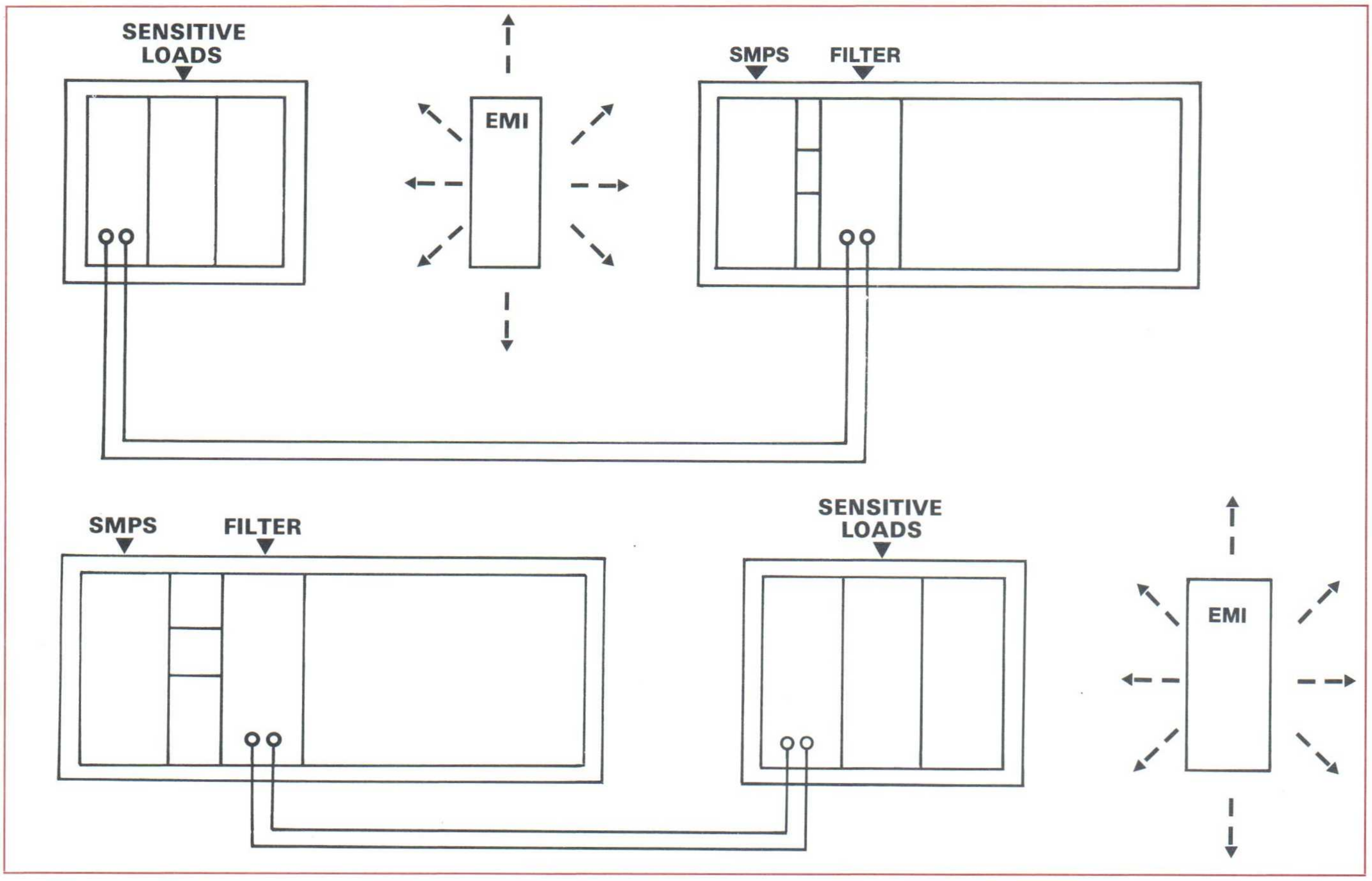


FIG. 32. RACK-MOUNTING ARRANGEMENTS FOR FILTER

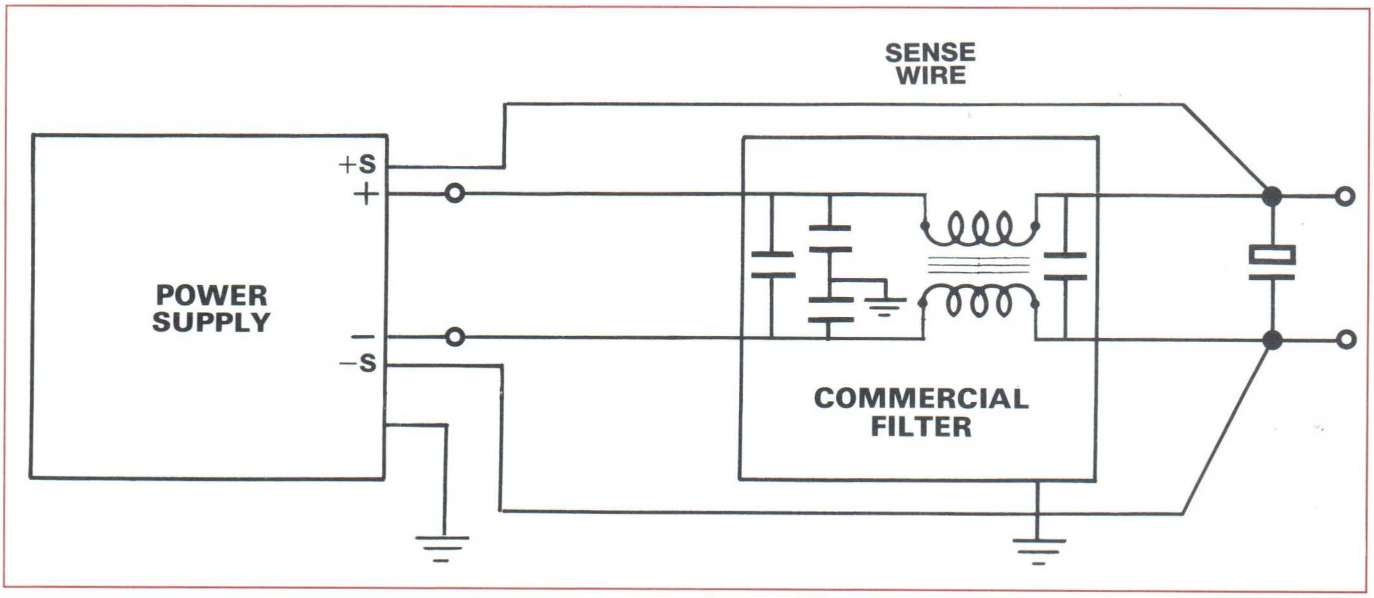


FIG. 33. FILTER WITHIN THE SENSING LOOP

When an additional filter is used, this may be included within the sensing feedback loop; i.e. the sense wires will be across the load.

Ensure that the addition of a filter does not cause instability. Also remember that voltage drops occurring in the filter will reduce the static stability at the load if not remotely sensed.
By careful design of the feedback amplifier the stability can be controlled over the required operating conditions.
A.C. analysis tests on a PE 1145 (5V/10 A) switched-mode power supply with a commercial filter on its output have been plotted as shown, and prove that by attention to design, the stability can be successfully controlled. (FIG. 34)

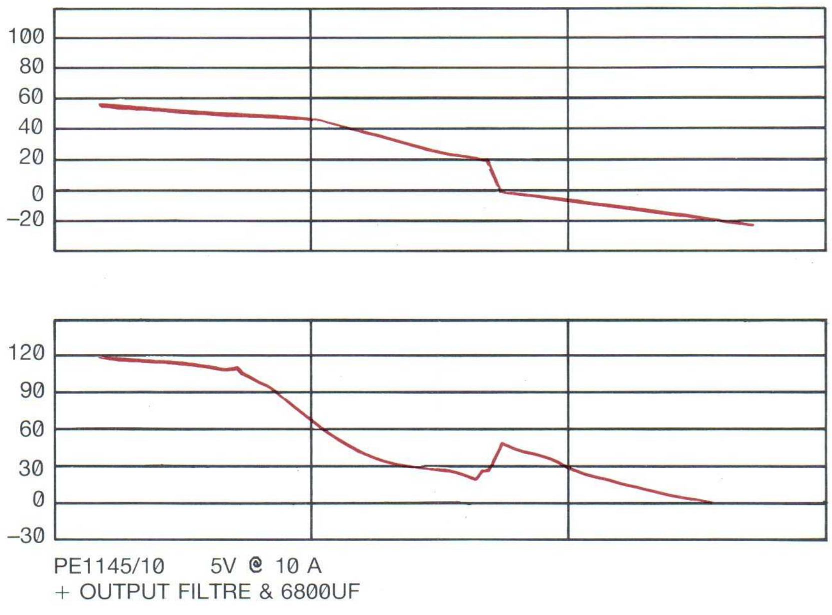


FIG. 34. GAIN/PHASE PLOT OF PE 1145 + COMMERCIAL FILTER

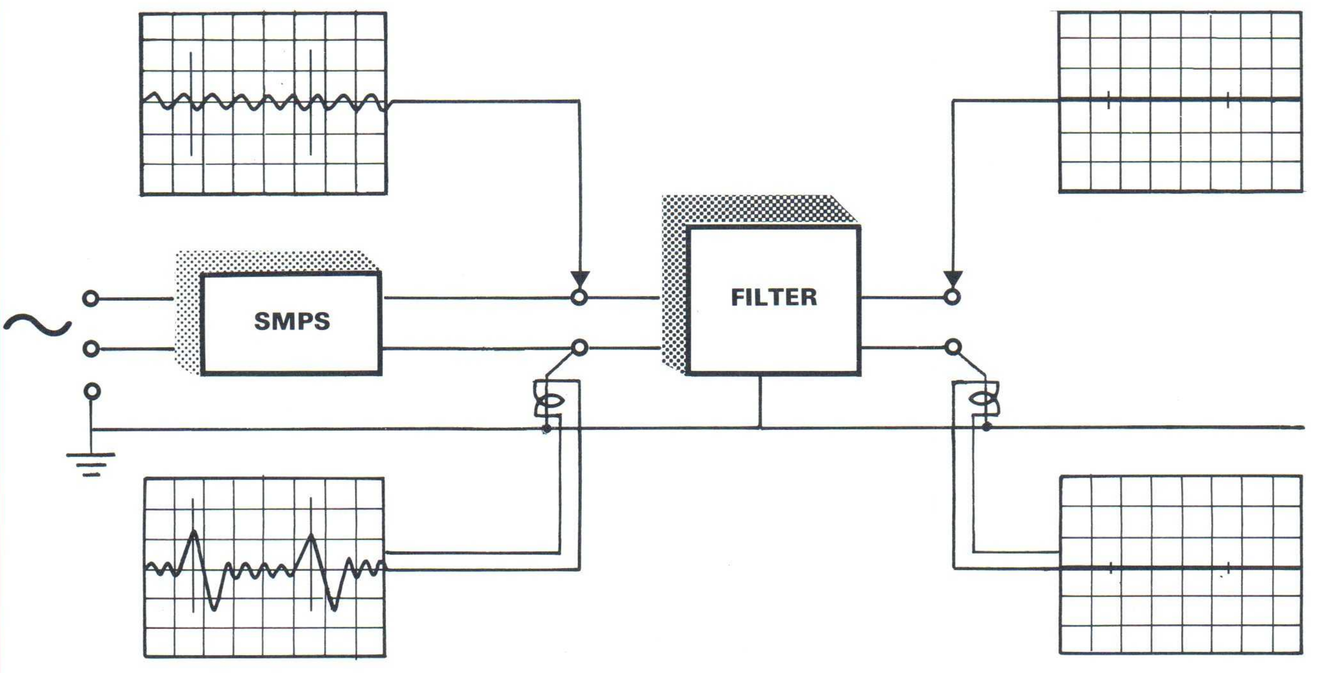


FIG. 35. OSCILLOGRAM OF EMI CURRENTS BEFORE AND AFTER FILTERING

5.2.3. *EMI conducted to input*

Unwanted interference from a power supply to the mains input source are easier to filter out at the design stage compared with output ripple, as the operating parameters are more readily determined in advance. These design features are outlined in Section 4.2.2. Conducted Interference.
In practice, precautions mainly consist of ensuring that earth loops and resistive earths are not formed that could transfer common-mode interference to other equipment using the same supply lines.

For instance, a mains extension lead supplying the SMPS and other equipment could be the source of common-mode interference as any EMI developed in the resistance of the cables is common to all circuits fed from the extension lead. The effect of a resistive earth lead is shown as an example. (FIG. 36)

6. USER GUIDE-LINES

6.1 Defining the Problem

Radio frequency interference has been around a long time – "sparked off" in 1896 when Marconi connected a Ruhmkorff inductor to a battery and by means of a morse key established a wireless connection over a distance of two miles, long before the switched-mode power supply was introduced – a point worth remembering before blaming the SMPS when tracking down noise in a system.
Unshielded or badly placed transformers, long unscreened leads, multiple-earth loops, poor system design all add their quota of noise to small-signal circuits. And switching transients, generated in other parts of the system or mains-borne, occurring perhaps only once every few minutes, can play havoc with digital equipment, yet may not be detected by the measuring instruments.

Although radiated interference can travel long distances, as indicated, by effective shielding of the equipment it is simple to control.
Conducted interference is more easily measured, but harder to suppress.
Interference can be very elusive, but if treated with a healthy respect at both the system design stage and during construction, it can be kept within acceptable limits.
If the level of EMI is unacceptable, it can nearly always be remedied by the methods described in the previous sections, using a logical, systematic approach as suggested in the flow-chart.

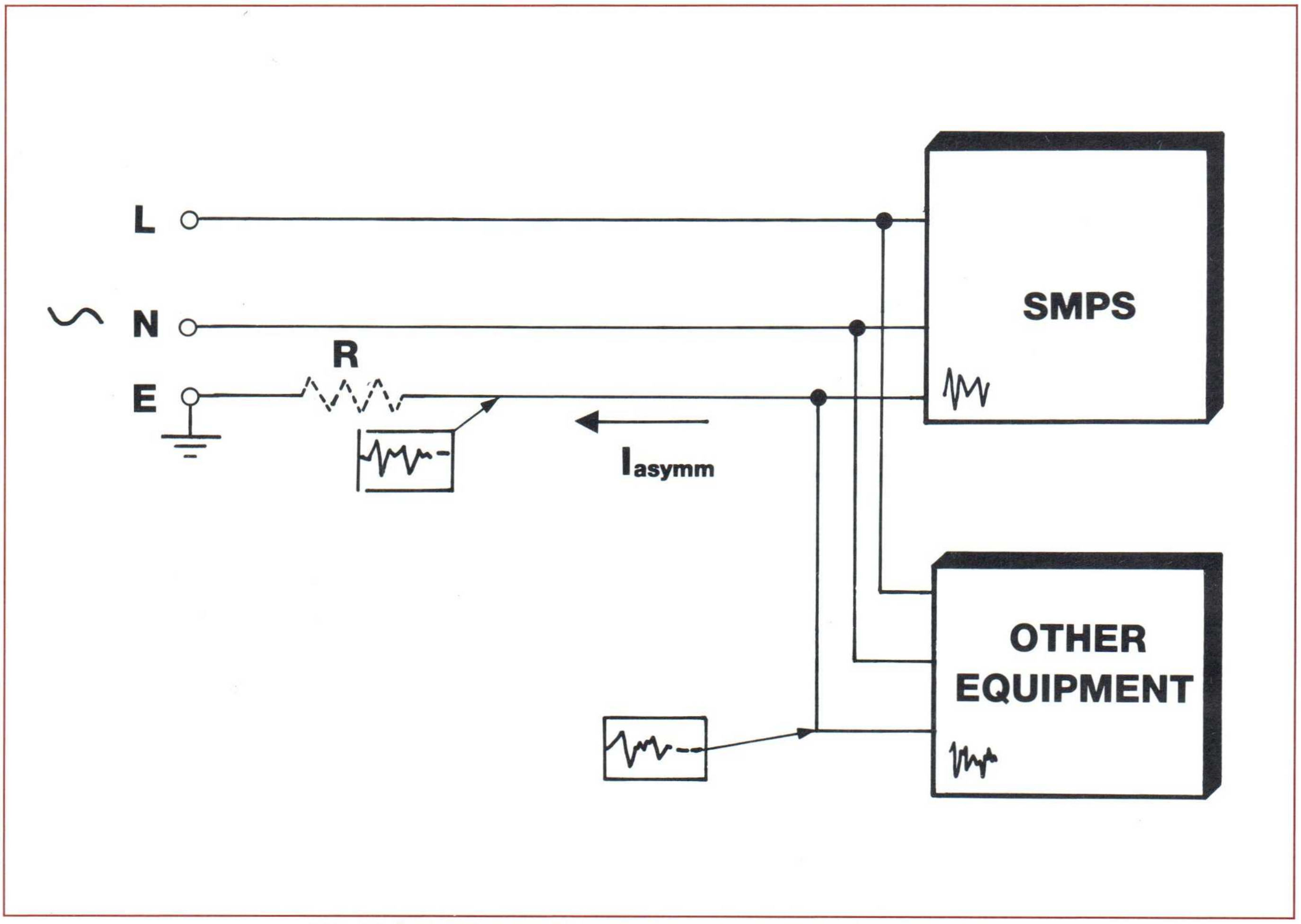


FIG. 36. RESISTIVE EARTH LINE PRODUCING COMMON-MODE EMI

6.2 Trouble-shooting

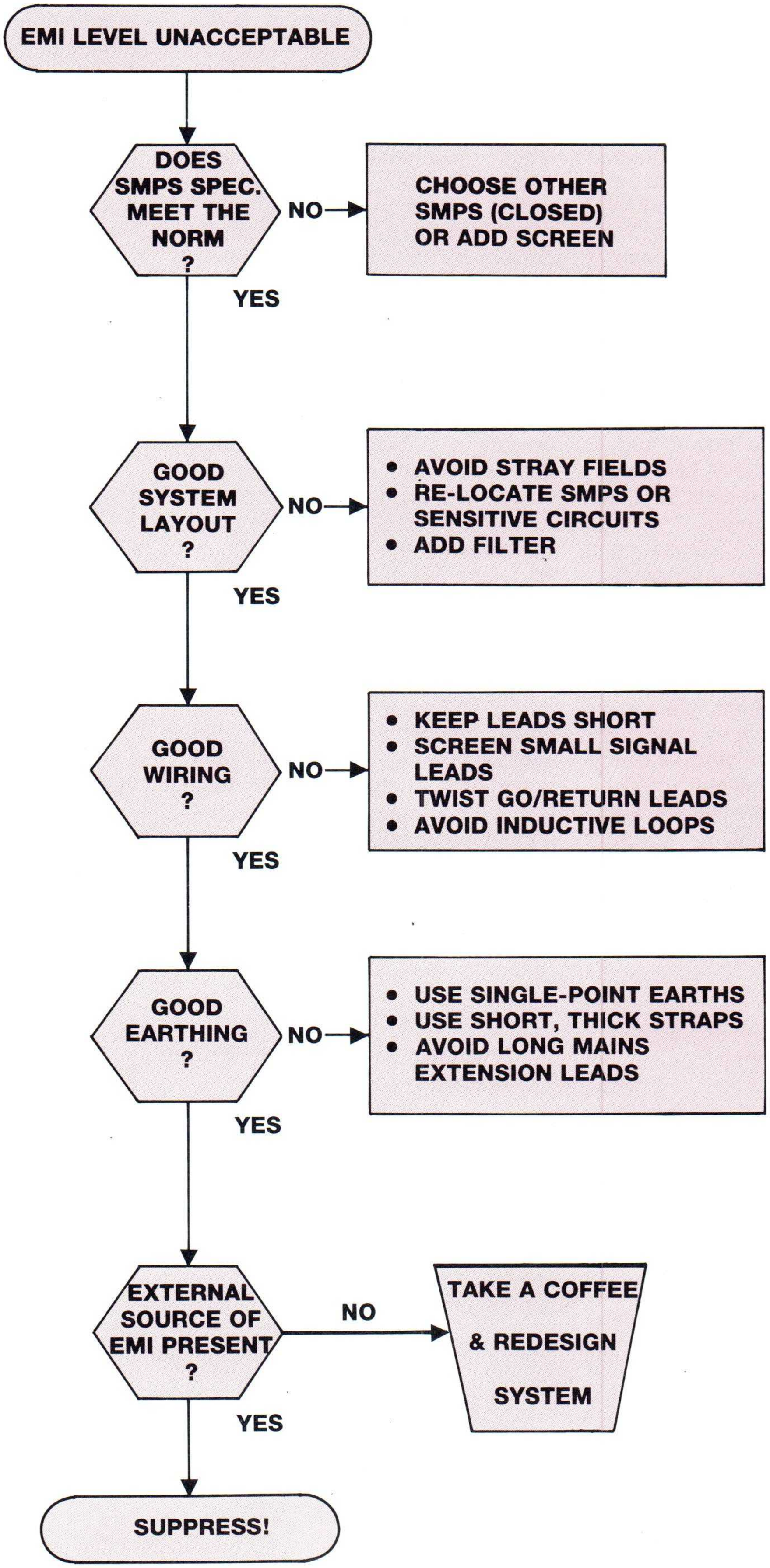


FIG. 37. TROUBLE-SHOOTING FLOW-CHART

7. MEASURING EMI

7.1 General Aspects

There are obviously two distinct methods of measuring EMI depending on whether it is radiated or conducted interference. Whatever measuring device is used, the points at which the EMI is picked-up will either be in the space surrounding the instrument under test, for radiated pick-up, or in the connections to its input or output circuit, for conducted pick-up.

In either case, evaluating the emissions from the instrument under test (switched-mode power supply), requires a virtually EMI-free environment if the results of the test are to be meaningful.

Under the laboratory conditions required for Quality Assurance testing, this means a heavily filtered mains and a screened room. Mains filters must pass heavy currents at 50/60 Hz without any appreciable attenuation, yet provide a high insertion loss over the interference band of frequencies with a low resistance earth path. Furthermore, the filter must not reduce the reliability or safety aspects of the system it serves. This demands careful design, but on the plus side, a filter does prevent transfer of noise between the equipment and mains in either direction.

When selecting a suitable filter, the emphasis can be on eliminating either common-mode or differential interference components depending on circuit requirements. These two noise components can be measured using a current-summing barbell transformer coupled to a spectrum analyser. This adds or subtracts the noise levels in the individual lines, thereby measuring the two noise modes.

Even when testing power supplies on site it is advisable to check their source of power and other equipment in the vicinity beforehand to make sure that they are not worse EMI offenders.

As far as possible, the measuring instruments themselves must be noise-free below specified levels. This is particularly difficult to achieve at extreme frequencies and at high sensitivities where the small interference signals can easily be swamped by the receiver noise. At least, the noise contribution of the measuring instrument should be known and taken into account.

The level of signal measured is also dependent on the bandwidth of the measuring instrument. The greater the bandwidth, the higher the noise reading for broadband signals. Conditions for measurements are quoted in the various standards. For example, the VDE norms specify a 200 Hz bandwidth up to 150 kHz, and a bandwidth of 9 kHz for the 150 kHz - 30 MHz range.

7.2 Quick Checks

Several quick-check methods can be used as an indication of the EMI levels.

7.2.1. *For h.f. spikes on output*

Measurement of the output ripple is altered by two disturbance factors:

1) Electromagnetic fields near the power supply (mainly H fields), which will induce h.f. current in the measuring loop of the oscilloscope probe.
2) Common-mode voltage between the output power leads of the power supply and earth.

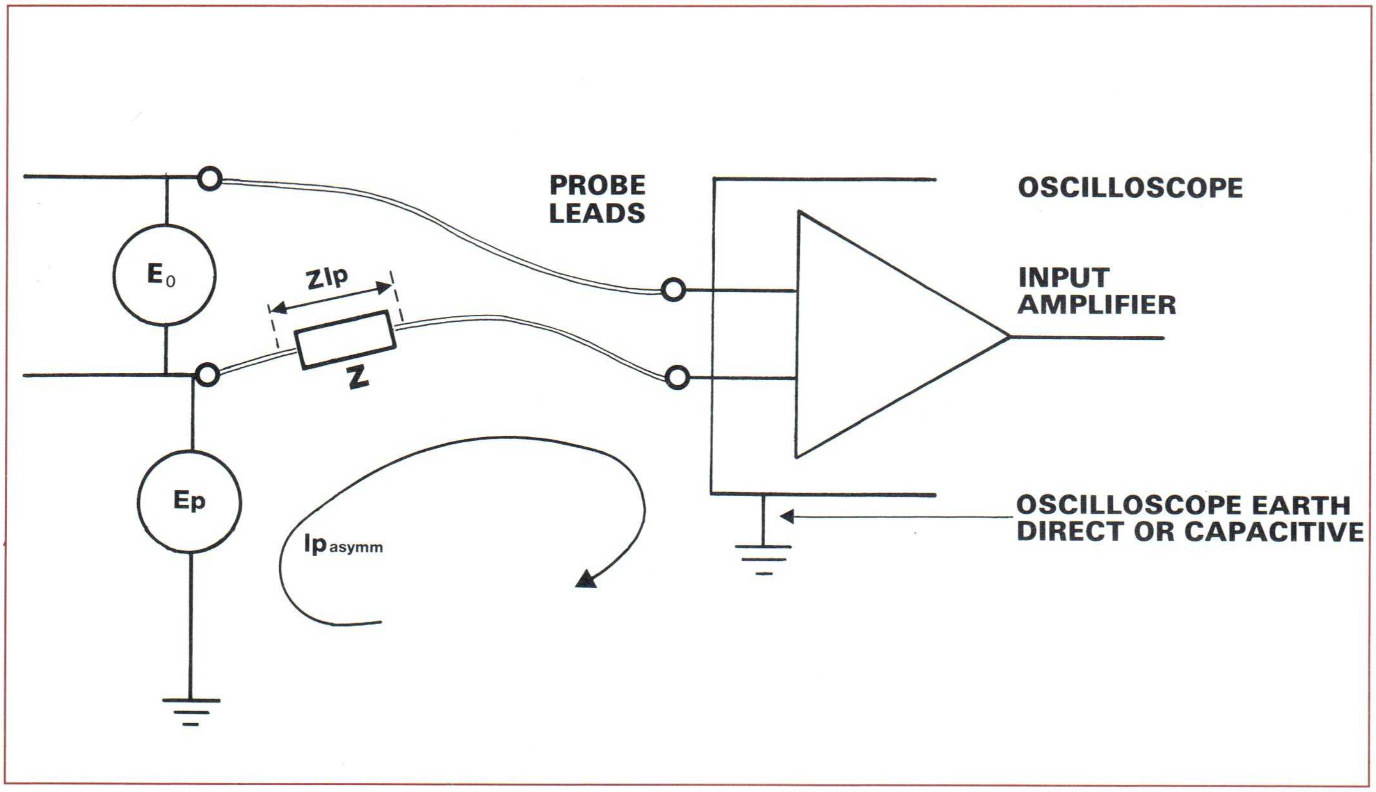


FIG. 38. OUTPUT MEASUREMENT ERROR SOURCES

Any h.f. current Ip flowing in the probe impedance Z will produce a voltage ZIp which is seen by the oscilloscope input amplifier as an h.f. ripple superimposed on the voltage Eo. (FIG. 38)
A simple method of measuring h.f. ripple at the output is shown in Fig. 39.

A wire of 30 cm is sufficient distance from the h.f. magnetic field source to reduce any measuring error caused by h.f. current being induced in the measuring loop. Any h.f. current induced in the 30 cm length of wire is short-circuited by capacitor C at the measuring point. For most power supplies, the Z of the earth loop can be reduced sufficiently by soldering the coaxial probe directly on the load to avoid contact errors and thus eliminating common-mode.
The impedance of the wire and the capacitor at the measuring point will also partly filter out any h.f. spikes that might be present in the power supply.
However, this coupling is a good simulation of the power distribution leads and the decoupling capacitor across the load, which also filters out most h.f. spikes.

7.2.2. *For magnetic field induced faults*

- connect the probe earth clip to the probe tip leaving an area of loop.
- hold the loop near to the measuring point, but not in contact with it.

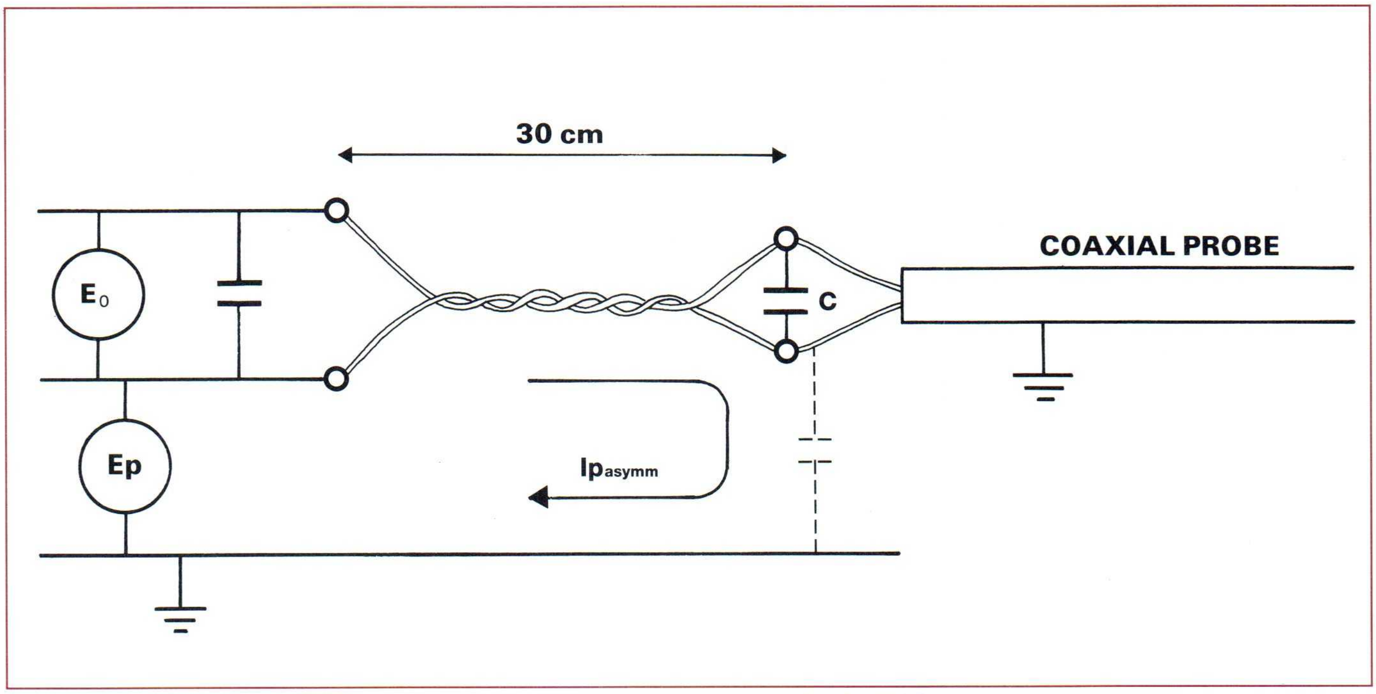


FIG. 39. MEASURING HF RIPPLE ON OUTPUT

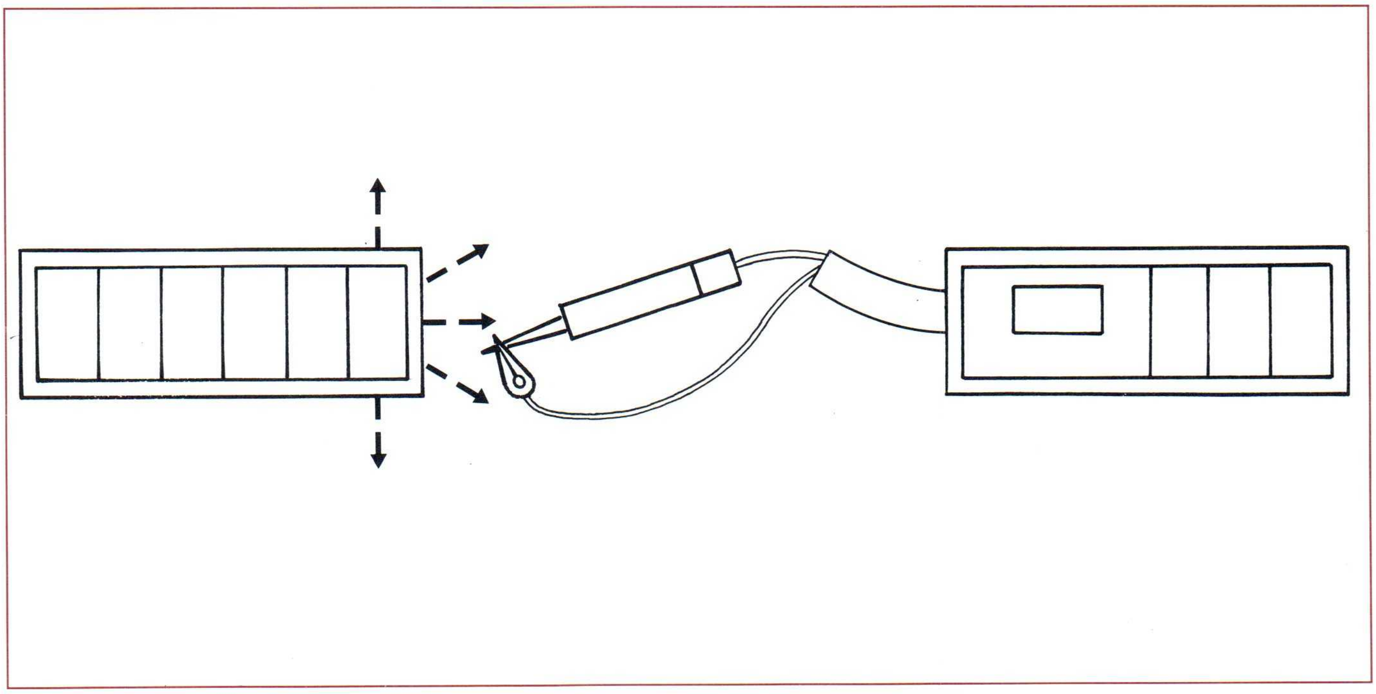


FIG. 40. H-FIELD QUICK TEST

7.2.3. *For common-mode faults*

- reduce the probe loop area and make electrical contact with one of the outputs at the measuring point.

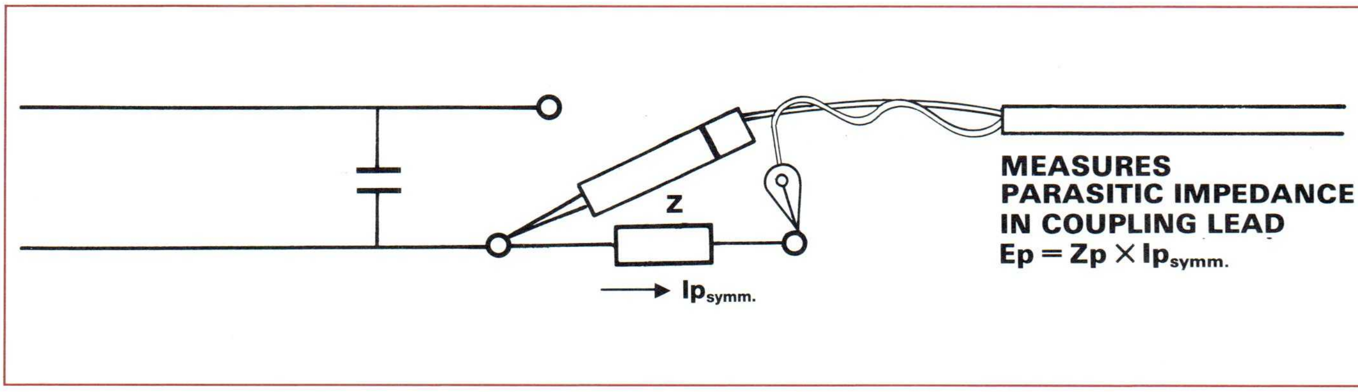


FIG. 41. COMMON-MODE QUICK TEST

7. 3 Measuring Radiated Fields

As already indicated, the method of detecting radiated interference is by the use of a loop antenna and some form of measuring instrument such as an oscilloscope or a sensitive receiver.
A practical field strength measurement was performed with two receivers, one for the low frequency range and the other for the higher frequencies:

a) up to 30 MHz:

Rohde and Schwartz ESH3 receiver, with an antenna type HFH 2-Z2 for measuring the induction(near)field that is predominant around the equipment at the low frequencies.

b) 30 MHz-1 GHz:

Ailtech Stoddart NM-37/57A receiver, measuring the electromagnetic(far)field that is present close to the equipment at these high frequencies with:
- a broadband antenna for 30-350 MHz
- a periodic log. antenna for 350 MHz-1 GHz

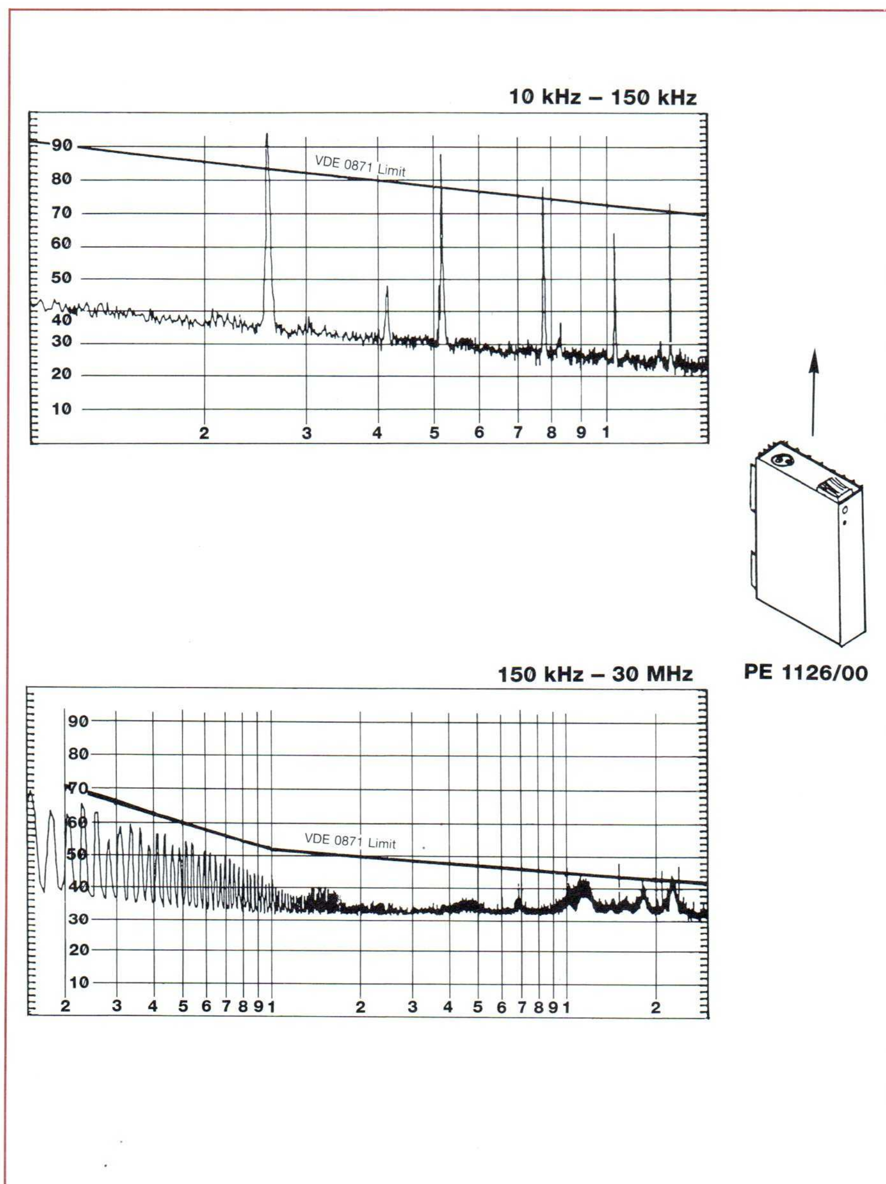
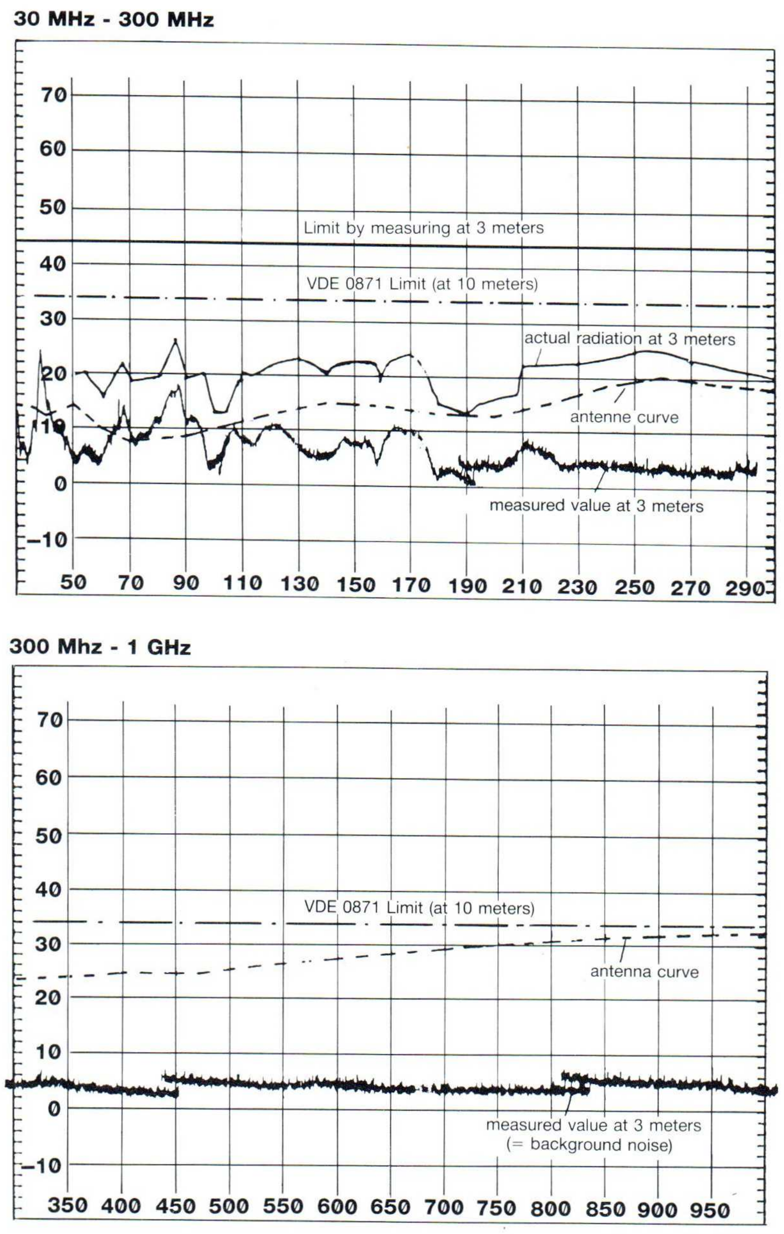


FIG. 42. PRACTICAL FIELD STRENGTH MEASUREMENTS ON A PE 1126/00



The ESH3 receiver automatically corrected the results for the response of the antenna.
For the tests above 30 MHz, the results more or less follow the curve of the antenna as shown in Fig. 42.
The limits given in this practical test were modified from the CISPR 11 and VDE 871 norms to eliminate external interference by measuring at 3 metres in a screened room. In practice the norm limits are:
10 kHz - 30 MHz: 50 μV/m (34 dB) at 30 metres
30 MHz - 470 MHz: 50 μV/m (34 dB) at 10 metres
470 MHz - 1 GHz: 200 μV/m (46 dB) at 10 metres
Results of tests on a PE 1241 (which complies with level B of VDE 871) show that the noise over the range 30 MHz to 300 MHz was less than 10 μV/metre.
Measurements on the PE 1241 at an appropriate test site showed that no radiation was detected at a distance of 30 metres and therefore this test is no longer included in the Philips Wavre Quality Assurance programme.

FIG. 42. PRACTICAL FIELD STRENGTH MEASUREMENTS ON A PE 1126/00

7. 4 Measuring Conducted EMI

To measure conducted emissions, the pick-up leads of the measuring instrument must naturally be connected across the supply input or output terminals.
Measurement methods have been laid down by the various national and international standards.
A test circuit given in IEC 478-3 for measuring interference injected into the mains is shown overleaf. The test receiver has a closely defined bandwidth and performance and is connected to the test circuit via resistor R2. The interference currents from the apparatus under test are diverted via two line impedances L1 and L2 through capacitors C3 and C4 and a polarity changeover switch to the test receiver.
In combination with the 50 ohm input impedance of the test receiver, the resistors represent the 150 ohm typical impedance of the mains supply over the frequency range 150 kHz to 30 MHz.
The accepted standards are shown graphically in Section 3. Briefly, if the EMI voltage above 150 kHz at the input terminals of a power supply is less than +54 dB referred to 1 μV then it is universally acceptable.

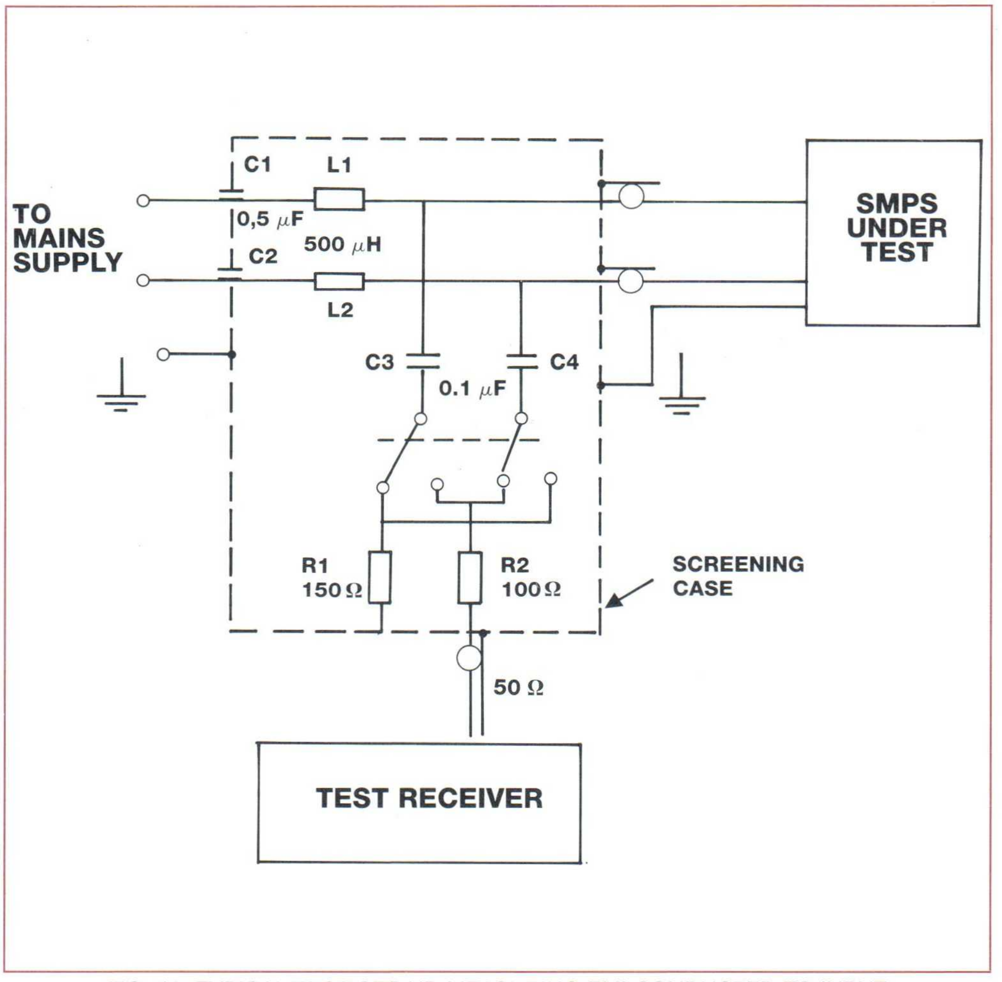


FIG. 43. TYPICAL TEST SET-UP MEASURING EMI CONDUCTED TO INPUT

Equipment used at Philips Wavre for measuring conducted EMI

Artificial network	Schwarzbeck NNLA 8120	(10 kHz - 150 kHz)
	Schwarzbeck NNBM 8112	(150 kHz - 30 MHz)
	Rhode&Schwarz ESH2-Z5	(10 kHz - 30 MHz)
Receiver	Schwarzbeck LSME 1530A	(C.I.S.P.R. 3, 10 kHz - 150 kHz)
	Schwarzbeck FSME 1515	(C.I.S.P.R. 1, 150 kHz - 30 MHz)
	Rhode&Schwarz ESH 3	(C.I.S.P.R. 1&3, 10 kHz - 30 MHz)

The ESH3 receiver is provided with an IEC (IEEE) bus interface and can perform automatic EMI measurements. The graph of Fig. 28 was measured with this receiver.

The specifications for conducted interference on all currently-manufactured closed switched-mode power supplies at Wavre are:
Conducted interference level VDE 0871

- Level A, 10 kHz to 150 kHz
- Level B, 150 kHz to 30 MHz

It is possible for system designers to achieve level B below 150 kHz by the addition of a simple external filter.

7.4.1. *Philips philosophy*

The question of filter placement has been given much thought during the research and development phases. Two major factors weighed heavily against locating a filter in the open-frame version of switched-mode power supplies.
Firstly, a customer usually requires a filter in his system anyway to reduce common-mode troubles, so a filter in the power supply would be superfluous, besides increasing the cost unnecessarily.
Secondly, where customer's equipment is not creating common-mode problems, the input leads of an open-frame power supply are still near to H-fields and are likely to pick up interference. A filter placed inside an open-frame unit would not therefore guarantee that the EMI is within the required regulation standards.
Thus the best solution is an external filter placed optimally with regard to the particular situation and conditions.
With closed power supplies a filter is fitted because the conditions are predetermined, and the H-fields are reduced by the screening effect of the housing.

In systems powered by switched-mode supplies, a lot of lower frequency symmetrically conducted EMI is also created, mainly due to the power supply. Therefore, in Philips, open-frame power supplies are equipped with sufficient symmetrical filtering to keep these disturbances within acceptable limits.
For the customer, it is sufficient to add asymmetrical filtering on the input of his system using a simple, cheap mains filter that is commercially available.

8. CONCLUSIONS

With so much written in this handbook about electromagnetic interference and switched-mode power supplies, the reader may be wondering whether the terms are inseparable. However, it is worth remembering that as the title is Electromagnetic Interference and Switched-mode Power Supplies we deliberately set out to look for trouble. It is useful, therefore, to look briefly at the trouble spots we found.

* *Interference conducted to the mains*

Easy to detect, requirements are stringent, but can easily be met by the inclusion of a commercial mains filter.

* *Interference conducted to the load*

Easy to detect, but more difficult to cure than mains conduction. Power supplies meet the norms, but for sensitive applications extra filtering may be necessary.
Problems can often be solved by good design and attention to layout and earthing.

* *Radiated interference around the supply*

Difficult to detect but easy to cure with simple shielding if the nature of radiation is well understood.

* *National and International Norms*

Well-designed equipment from reputable manufacturers meets the most stringent norms.

When buying equipment, remember that PREVENTION IS BETTER THAN CURE!

* *SENSITIVE APPLICATIONS*

Even with a decade or more of experience in the design and manufacture of high quality switching power supplies, Philips engineers state that no power supply application has come to light that is so sensitive that a customer needs to forego the obvious advantages offered by using an SMPS.
Then why the need for this handbook?

* *SENSITIVE CUSTOMERS*

Recently a customer asked for a number of 12 V, 50 A series regulators to satisfy an extremely sensitive medical application.
Fortunately, Philips diagnosed his symptoms correctly and by certain tests convinced him that the technical treatment of his problem laid in switched-mode power supplies. These technical arguments were so compelling that they were written down and now form the basis of this handbook – just in case there are other sensitive customers who have not yet waved goodbye to their series regulators!

REFERENCES

1. C.I.S.P.R.-Publication 11 (1975) – Limits and methods of measurement of radio interference characteristics of industrial, scientific and medical (I.S.M.) radio frequency equipment, with amendment no. 1
Dec. 1976 and 11A (1976) first supplement.

2. V.D.E.-0871/6.78 – Specification for radio interference suppression of electrical equipment and installations with designed generation of radio frequency.

3. V.D.E.-0875/6.77 – V.D.E. – Specification for radio interference suppression of electrical appliances and systems.

4. Federal Communications Commission Rules and Regulations
Volume II August 1976 + amendments published in Federal Registers
Volume 44 No. 201 October 16-1979/Vol. 45. no. 70-1980-04-09.

5. W.F. BAKKER: Designer's guide to EMI shielding
Machine Design – 23 march 1972 p 120 - 125

6. R.K. BOSSART: EMI testing, standards and specs
Electronics Test – may 1980 p 76 - 83

7. W.P. HOHMANN: Störprobleme bei Schaltnetzteilen
Elektronik Industrie, 5 – 1978 p 14 - 17

8. J. JORDI: Switching power supplies
EMC symposium, Brussels 22.02.1983

9. M.J. COENEN: Enkele aspecten van EMC
EMC seminar, Utrecht 31.05.1983

APPENDIX 1

Glossary of abbreviations

IEC (International Electrotechnical Committee):
various Technical Committees and Subcommittees, each for a specific field of electrotechnical interest. IEC publications are recommendations for international use and are accepted by most National Committees.

C.I.S.P.R. (Comité International Spécial des Perturbations Radioélectriques):
A specific IEC-committee for the technical view of EMC.

CENELEC (Comité Européen de Normalisation Electrotechnique): Committee for harmonising the legislation of the EEC countries.

VDE (Verband Deutscher Elektrotechniker):
Association, in West Germany, for the advances in electrotechnics and the extension of electrotechnical knowledge. The VDE draws up norms and performs tests according to VDE norms.

FCC (Federal Communications Commission):
organisation in the U.S.A., in the telecommunication field.

EMC (Electro Magnetic Compatibility):
Electrical or electronic systems have to be electromagnetically compatible. It means that they are not adversely affected by internal interference or externally generated emissions.

EMI (Electro Magnetic Interference):
Electromagnetic disturbance, which manifests itself in performance degradation, malfunction, or failure of electrical or electronic equipment.
The denomination "EMI" is more correct and more general than the formerly used "RFI".

RFI (Radio Frequency Interference):
Electromagnetic disturbance, which manifests itself as degradation in the performance of communication (or other electronic) equipment.

SMPS (Switch Mode Power Supply):
A supply in which power is converted by switching at high frequency, generally above the audio spectrum.

dB (deciBel):
The fundamental term used in EMI measurements:
$$dB = 20 \log \frac{V2}{V1}$$

dBm:
Standard unit of narrowband signal, based on a reference of 1 milliwatt.

dBμV:
Based on a reference of 1 microvolt.

For a 50 Ohm reference resistance, OdBm $\hat{=}$ 0,224 V (1mW), and therefore
OdBm $\hat{=}$ 107 dBμv or
OdBμV $\hat{=}$ –107 dBm

APPENDIX 2

Useful addresses

Information about type-testing or approvals can be obtained at:

West Germany

V.D.E. Prüfstelle
Marianstrasse, 28
BRD – 6050 Offenbach/M

France

LCIE Laboratoire Central des Industries Electriques
Avenue du Général Leclerc
F-92260 Fontenay-aux-Roses

The Netherlands

N.V. KEMA
Utrechtseweg, 310
Postbus 9035
NL-6800 ET Arnhem

Italy

I.M.Q. (Instituto Italiano Del Marchio di Qualità)
Via dei Pestagalli, 1
I-20138 Milano

Denmark

Posts and Telegraphs Denmark
Central Telecommunications Services
Radio Communications Office
Islands Brygge, 83C
DK-2300 København S

NOTES

9498 153 03111