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14 June 2004

Design for stable electronic Earth Fault protection in an electrically noisy environment

Electronic devices are susceptible to EMC (Electro-Magnetic Compatibility) problems.

Following are some examples:

your computer interferes with FM radio reception
operating your vacuum cleaner causes "snow" on your TV
your car radio buzzes when you drive under a power line
a helicopter goes out of control when it flies too close to a radio tower
you pick up CB radio conversations on your stereo
your telephone is damaged by lightning-induced surges on the phone line
the screen on your video display jitters when the flourescent lights are on
your new memory board is destroyed by an unseen discharge as you install it
the clock on your VCR resets everytime your air conditioner kicks in
your laptop computer interferes with your aircraft's rudder control
the airport radar interferes with your laptop computer display
your pacemaker picks up cellular telephone calls
a hospital's EKG machine picks up Channel 5

In automated plants especially, electronic equipment that fails to operate correctly can cause enormous damage. Where an electrical installation serves a plant where the integrity of the supply is critical (e.g. production plant or hospital) it is important that an Earth Fault protection device meets the following criteria:

(a) reliable protection: the supply is interrupted when there is a real earth fault which endangers human life
(b) dependable protection: the supply is not interrupted in the absence of an earth fault which endangers human life

When the protection device has determined that action is needed, it normally sends a trip signal to the circuit breaker that feeds the electrical supply in which the fault was detected.
Both criteria can be violated by electrical noise:
In case (a) above by jamming the electronic circuitry such that when a trip signal should be sent to the breaker, it is not sent.
In case (b) above by causing a trip signal to be sent to the breaker when there is no real fault condition and no trip signal should be sent. This is often called nuisance tripping and is the more serious of these effects. As unnecessary interruption of the electrical supply often causes high losses in production it can lead the maintenance personnel to disable the protection device, e.g. by disconnecting or bridging its output.

Both these effects are normally caused by an EMC (Electro-Magnetic Compatibility) problem which consists of unwanted interfering signals (EMI = Electro-Magnetic Interference) coming from sources via a coupling path like wiring, direct or induced (conducted EMI) or electromagnetic radiation (radiated EMI).
Each of the three elements: the source of EMI, the coupling path and the affected device, must be present for the EMC problem to occur.
EMC problems are generally solved by identifying at least two of these elements and eliminating (or attenuating) one of them.

Often, the sources of EMI are expensive or impossible to remove and the coupling path usually cannot be removed. However, where this can be done it is usually considered to be the better solution, the rule being to remove the EMI as close to the source as possible.

For the designer of the protection device, however, these elements are also outside his control. Therefore it is important that the electronic protection device filters out as much EMI as possible.

The EMI coupling path can be the following:

- Conducted (electric current)
- Inductively coupled (magnetic field)
- Capacitively coupled (electric field)
- Radiated (electromagnetic field)

Coupling paths often utilize a complex combination of these methods making the path difficult to identify even when the source and receptor are known. There may be multiple coupling paths and steps taken to attenuate one path may enhance another.

The following sources of EMI are often encountered in systems where protection devices are installed:

- inductive currents oscillating in the associated wiring at the moment a circuit breaker interrupts the supply of an inductive load (switching noise)
- the inrush current when a breaker closes onto a heavy load inducing voltages in other wiring (switching noise)
- Arc welders
- other power transients
- Electric motors
- Lightning, solar flares
- Other electronic equipment (e.g. variable speed drives, lamp dimmers)
- radio transmitters, e.g. cell phones or walkie talkies – in such cases it may be feasible to apply shielding, reroute the cables which pick up the radiation or filtering the signals inside the device.

The degree to which the protection device filters out the EMI can be measured against existing standards. Such standards exist for protection devices to ensure an acceptable degree of EMC, or immunity of the device to EMI. The applicability of each standard depends on the intended application and on the degree of EMC of other critical equipment in the same system.

The following standards are currently used by EPC to test the level of EMC of protection devices:

(1) IEC-255-22-1 surge immunity

With regard to equipment-damage hazards, the most stringent test is that of high-energy transients–the so called SURGE test. In this test, the mains supply lines, unshielded signal lines, or cable shields are driven via low-value series resistors with long-duration, high-voltage pulses. The pulses have approximate 2µsec rise times and 50µsec fall times (to 50% of peak value), with amplitudes ranging from 0.5kV to 2kV for mains lines and to 1kV for signal lines.

For supply lines, the SURGE test galvanically couples the test signal using a 9µF DC decoupling capacitor in parallel with a series resistance as low as 10Ω (and in some cases, with no resistor at all). Unshielded signal lines are tested with a series resistance as low as 40Ω, line-to-line or line-to-earth. Adding 90V gas arrestors in series prevents capacitive loading of the signal lines between tests (Figure 1a, 1b).

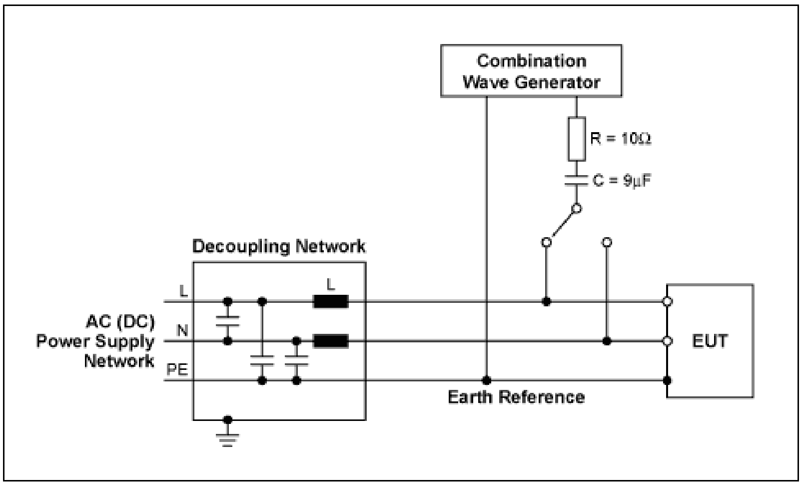


Figure 1a. Test setup: Capacitive coupling of a test signal to AC or DC lines

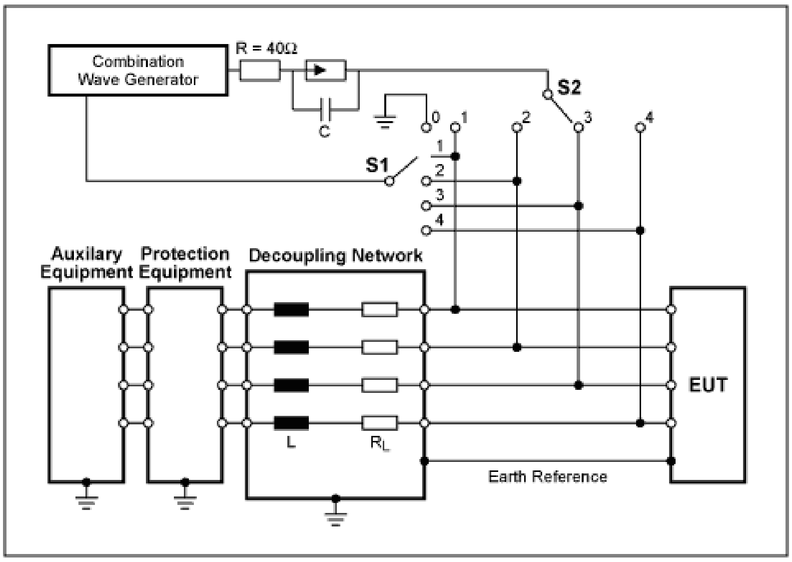


Figure 1b. Test setup: Coupling to unshielded, unsymmetrically operated lines.

(2) IEC-255-22-2 ESD (Electro-static discharge) immunity

The test generator consists of a high-voltage, 150pF capacitor that discharges via a 330Ω series resistor (Figure 2), a switch, and an electrode (shaped to simulate a finger) that discharges into the equipment under test (EUT).

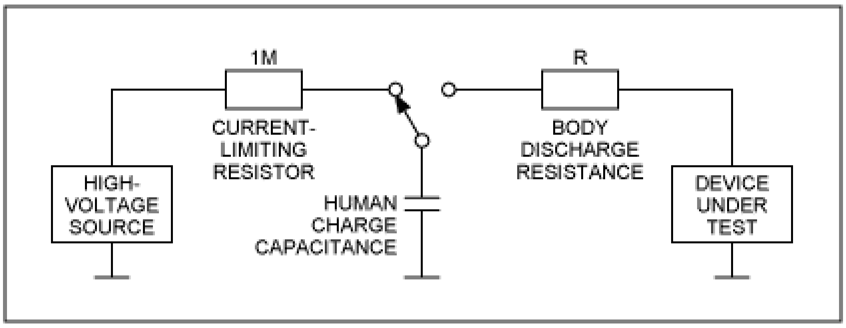


Figure 2. A simple test circuit applies controlled ESD pulses to a test device.

The test specification distinguishes between contact discharge and air discharge. Contact discharge is applied by touching the equipment enclosure with the test finger while closing the switch. This procedure exposes the equipment surface to the test voltage (±2kV, ±4kV, ±6kV, and ±8kV), minus a voltage drop caused by current flowing through the series resistor. The resulting short-circuit currents are depicted in Figure 3.

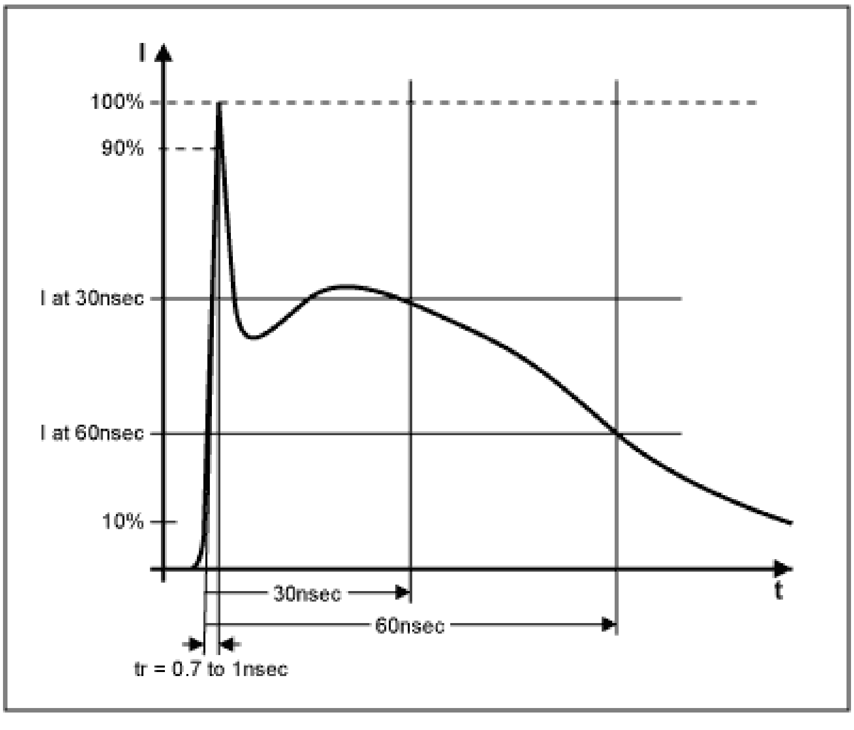


Figure 3. An ESD zap from the circuit of Figure 1 produces this current in the device under test.

Air discharge is applied to insulating surfaces by bringing the test tip toward the surface as rapidly as possible. . The test requires at least 10 measurements, spaced at least one second apart, at each level of standard test voltage (±2kV, ±4kV, ±8kV, and ±15kV). The object is to find the weakest point within the equipment's enclosure by testing to the limit specified for that class of equipment. Using the same test generator, an additional capacitive-coupling test is implemented by connecting the test tip to a metal plate positioned close (about 10 cm) to the equipment casing. This test applies only to those parts of the equipment that are touched by users during normal operation and maintenance.

(3) IEC-255-22-3 Radiated EMF immunity

In the test for this standard continuous radio signals are transmitted which are scanned from 80 - 1000 MHz such that the unit under test receives 10V/m.

(4) IEC-255-22-4 Fast transients (FTB) immunity

An FTB test capacitively couples a test signal onto the mains line or the signal line. It employs a coupling device shaped like a tube and enclosing the line under test for about one meter. The test signal consists of bursts of approximately 75 high-voltage pulses, delivered in bursts at a 3Hz repetition rate. Each pulse has an approximate rise time of 5nsec, and a fall time (to 50% of peak value) of 50nsec with a 50Ω load or 100nsec with a 1000Ω load. The time between pulses is 10µsec or 200µsec (Figure 4).

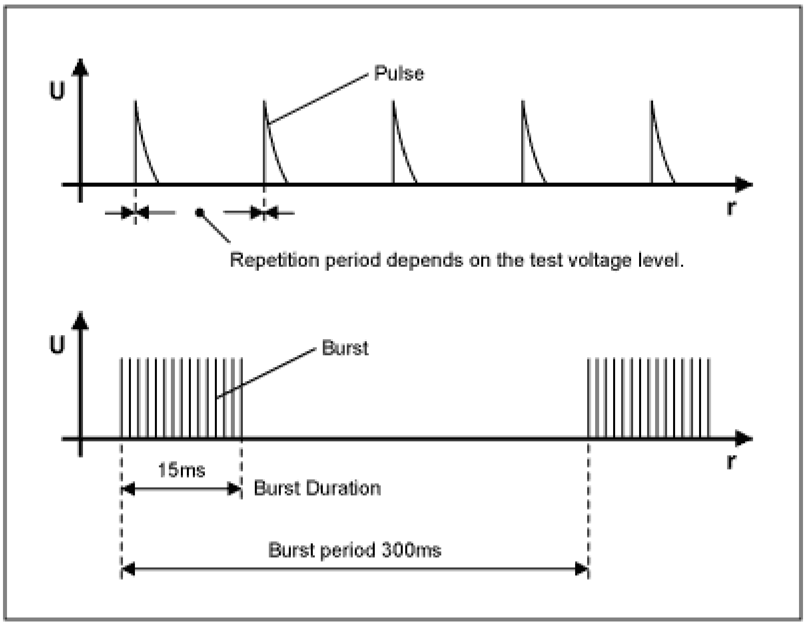


Figure 4. The test pulses in an FTB burst are specified as shown.

To create the high voltage required for low load resistance, the output resistance of this generator is much lower than that of an ESD generator. Peak amplitudes for the test pulses range from ±0.25kV to over 0.5kV, and (at 50Ω load) from 1kV to 2kV. At 1000Ω the load amplitudes are 0.5kV, 1kV, 2kV and 4kV. A decent cable shield, connected properly to ground/earth on the equipment side, can remove a lot of trouble from this test.

(5) IEC-255-22-5 Insulation requirements, voltage tests etc.

(6) IEC-255-22-6 Immunity to conducted disturbances induced by radio frequency fields

These standards are fairly stringent. If the various types of EMI covered therein have not received special attention in the design of the electronic protection device, it has a very slim chance to comply to any of these standards.
Further to EMC considerations the following environmental standards are usually applied to electronic devices like a protection device and also need to be kept in mind by the designer:

- IEC-68-2-1	low temperature immunity
- IEC-68-2-2	dry heat immunity (where applicable)
- IEC-68-2-3	damp heat immunity
- IEC-529	IP code for enclosure
- IEC 255-21-2	shock and bump (where applicable)
- IEC 255-21-3	seismic immunity (where applicable)

EMI considerations in the design of electronic devices deal with the following:
Electrical disturbances can be conducted by the power lines or conveyed through the air by capacitive, magnetic, or electromagnetic radiation. Most difficult to cope with (usually) is the interference conducted over signal lines connected to the equipment. In any case, one must distinguish between the need to protect against damage or malfunction, and the need to prevent signal or data distortion resulting from (for example) a disruption in the sequence of a microcontroller program. The first problem is attacked via hardware design, the second via a hardware watchdog and software algorithms.

With the above in mind, the following general design rules should be followed:

- EMI protection should be considered while designing the circuit, not added afterwards.
- disturbances should be blocked as near to the source as possible, preferably before they enter the equipment, and redirect them to ground.
- All sections that may be exposed to EMI disturbance, even electrically isolated sections, should be located as far as possible from sensitive circuitry.

Design considerations for various types of EMI

Because signal circuitry cannot withstand kV-level voltages, such disturbances must be excluded from the input, converted to current, and then to heat e.g. by a transzorb, zener, MOV or gas arrestor.

Ground-loop currents, which can enter an interface and run throughout the circuit, are often thwarted with galvanic isolation. Isolation is especially useful for the longer lines and high ground-loop currents that may occur in industrial systems. This is usually achieved by a transformer (e.g. CT = current transformer) or an optocoupler.

An ESD current pulse of 30A peak may produce only tens of millivolts of resistive voltage drop on a ground trace, but its extremely steep rise time (>30A/nsec) may induce hundreds of volts of inductive drop on the same trace (assuming roughly 1nH/cm of wire inductance)—more than sufficient to cause data errors. Skin effect applies at these high frequencies, increasing wire resistance dramatically by forcing current to flow only within microns of the conductor surface. To counteract this effect, ground connections need a large surface area to maintain low resistance.

Fast rise times can enable capacitive coupling of FTB and ESD disturbances from noisy sections to supposedly quiet ones. In this context, a frequent mistake is to provide galvanically isolated supplies by adding additional windings (these are capacitively coupled) to the main power-supply transformer. This arrangement allows "infected lines" (ground returns for the external signal) to contaminate the entire circuit.
A switch-mode supply offers better FTB and ESD protection because its transformer, which is much smaller than a 50/60Hz one, has less capacitive coupling.

Other commonly used EMI-protection components are as follows:

Gas Arrestor: A kind of dish-shaped capacitor filled with gas, frequently neon. Overvoltage in excess of 100V or so creates a plasma that limits the voltage at low levels and carries high currents. Gas arrestors absorb high-level transients, but are not suitable for fast transients because the emergence of plasma takes some time, usually a few milliseconds. They are not suitable for mains protection and are difficult to use with low source impedances. Leakage currents in normal operation are very low.

Varistor (MOV): An arrestor made with metal oxide (mostly zinc), usually shaped like a tablet with two connectors, one on each side. With behaviour similar to that of a zener diode, it responds much faster than the gas arrestor, but exhibits high leakage currents especially when the signal approaches the clamping voltage.
MOV's should only be used where surges are expected no more than 3-4 times in the lifetime of the device and where these surges are guaranteed to be below a certain maximum energy. MOV's degrade every time they absorb a surge and can eventually blow open-circuit which leaves the device unprotected.

Suppressor (Transzorb) Diodes: Used to limit fast transients at low voltage levels, their power-dissipation capability is limited according to their form factor. As for varistors, they exhibit significant leakage currents in the vicinity of their breakdown voltage but have a much flatter voltage-current response. Junction capacitance is also significant, so in fast systems using high bandwidth or fast rising signals they are usually decoupled with diode bridges.

ESD Structures: Novel designs that behave somewhat like diacs are integrated in some RS-232/RS-485 transceiver ICs (and recently, in analog multiplexers as well). Exhibiting low capacitance and low leakage currents, they are suitable for both ESD and FTB protection.

Chokes, Ferrites: Can attenuate high frequency and fast voltage peaks, but don't absorb much energy. Beware of resonant effects, and always use with attenuating capacitors (commonly an LC filter in a T-structure). These devices are frequently used to protect against common-mode disturbances and for mains filtering.

Capacitors: Perhaps the most important protective element. Its important features are equivalent series resistance (ESR), inductance, high current capability, and voltage capability. Careful selection is needed depending on target frequency, current and voltage.

Series Resistors: Also among the most important and cheapest of protective elements. Properly selected according to resistance and power dissipation, they can replace more costly elements, with comparable results.

General design measures to be taken to ensure a high level of EMC of an electronic circuit board (PCB)

In a device for an industrial environment, the power supply circuit (auxiliary supply) will almost always include an RC-filter, transzorbs and possibly varistors and/or zeners to block or absorb the "hard" noise like surges in order to protect the power supply circuit components as well as to prevent the noise from affecting the processing circuitry. The RC filtering also limits the dv/dt of the EMI to which amplifying power components like transistors and SCR's are sensitive.

In a protection device as part of an electrical installation, signal frequencies are relatively low with 50/60 Hz being the basic frequency, although where variable speed drives are involved large currents can be observed at frequencies in a range like 10 – 200Hz while harmonics of 10% or more are often found in the range 150 - 2500Hz.
For the signal paths, the frequency range of interest should be decided on (in our case this is usually 0-70Hz but can be up to 2500Hz) and, especially near the board I/O, the signal should be filtered accordingly – usually by low-pass RC filters.
The anti-aliasing filter which is needed where an A/D converter is involved, can often double as an EMI filter but then its high-frequency response (above about 30 MHz) should be double-checked.

The electronic cicruit itself usually generates EMI by its SMPS, oscillators, logic circuit and other switching functions, affecting other parts of the device. Even voltage regulators can generate a high frequency response to current changes. Switching currents can cause voltage drops on PCB tracks and induce signals on other PCB tracks or act like a transmitter antenna.
Since the LV supply lines (e.g. +5V) are usually affected most by these interferences, decoupling capacitors should be placed between the supply rail and Ground as near as possible to each alone standing logic IC (including microprocessor, PLA etc) or a group of them (more than e.g. 3cm from the next decoupling capacitor). These capacitors will prevent the switching pulse from travelling along the PCB tracks by supplying its fast rising current to the nearest load. Provided, of course, the capacitor is large enough to supply most of the increase in current and small enough to have a low enough inductance to be effective. A good increase in the level of EMC can be achieved for a microprocessor with two ceramic SMD capacitors of values 1nF and 10nF across the supply rails.
In terms of frequency response, a ceramic SMD capacitor of size 1206 reaches its lowest reactance value (before the inductance takes over) typically at the following frequencies:
100pF: 350MHz, 1nF: 120MHz, 10nF: 45MHz, 100nF: 15MHz (data from AVX)

It is also a good idea to prevent FTB's from demodulating in p-n junctions, by connecting a small decoupling capacitor (e.g. 100pF) to each bipolar base, e.g. the input of a bipolar-input op-amp except where some other part of the circuit already fills this function.
Where a microprocessor is part of the circuit, all its digital I/O connections should also be filtered or at least decoupled since outputs can also conduct EMI into the logic circuitry.

For several reasons, but mainly to minimise resistive voltage drop and inductive coupling it is good practice to keep PCB tracks as short and wide as possible, especially power supply lines, signal tracks and those which carry fast changing currents, e.g. the supply for a thermal printer head.

Another reason for having wide tracks – especially large pad areas – is to help conducting the heat away from components which may heat up above a few dozen degC. This is especially effective when the PCB is going to be potted.

The concept of keeping connections as short as possible also applies to the placement of external wire terminations and connectors by which the geography of the interconnection between PCB's or other parts is affected.

For keeping PCB tracks as short as possible it is often a good strategy to first place the components much like on the circuit diagram and then moving them to satisfy other design considerations. It is also useful to identify functionally or logically related groups of components and move them together.

A Ground plane should be used on PCB's inside a plastic enclosure or when no other shielding to RF is provided. The Ground plane also has a small capacitive decoupling effect and its low ESR will minimise Ground loop effects. The shape of the Ground plane can lend itself to an antenna effect, so it should be as homogeneous as possible.

Finally, for immunity to HV breakdown due to unintended static or intended voltages, sufficient clearance is to be provided between copper parts which may have a high voltage potential between them. At this stage it should also be known whether the PCB will be coated with an insulating layer or potted or left open.

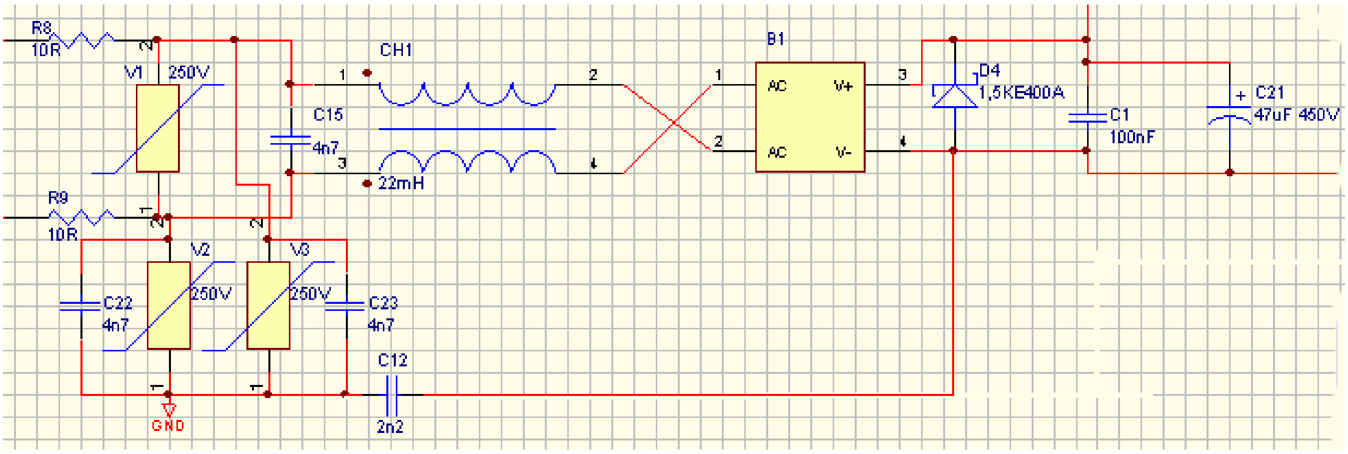
Summarising, the following are issues to be considered to ensure a good level of EMC when designing an electronic circuit on a PCB:

- absorption of high energy surges
- filtering of high-frequency EMI with low-pass filters
- LV supply rail decoupling
- RF modulation decoupling
- tracks to be short and wide
- component placement geography
- Ground plane and its geography
- clearance for HV

Special design measures taken to increase the level of EMC by examples of some EPC products

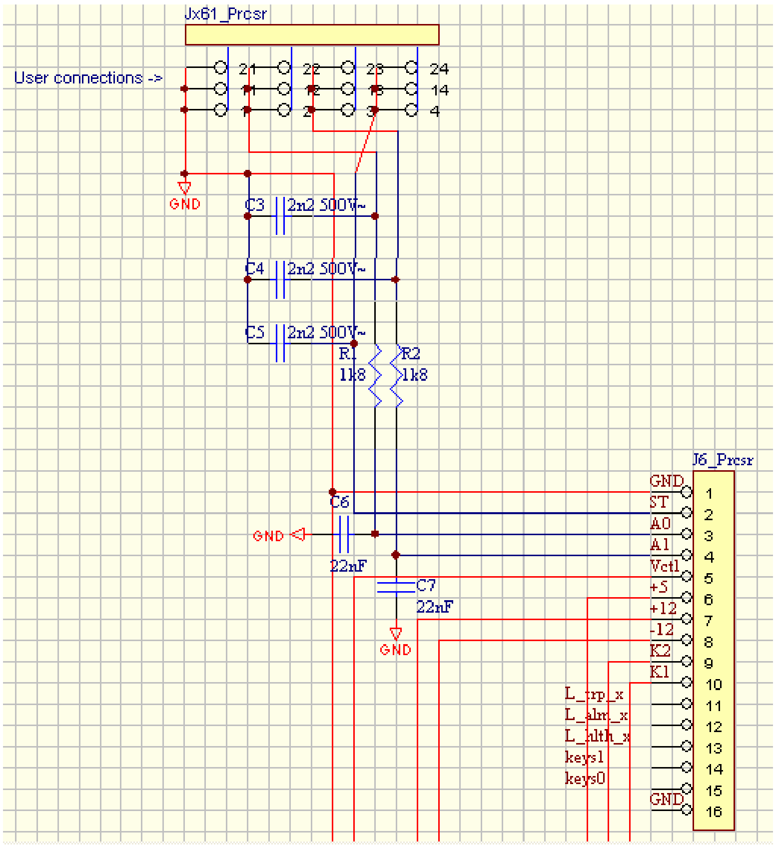
Even after all the general precautions have been taken in the design stage, after the prototype has been tested and fixed to work functionally, it will still often fail when various types of EMI are applied.
These failures are usually caused by the specific geometrics, wiring, layout and other configuration aspects of the given electronic device. At this stage special measures need to be found, usually by means of experience-driven as well as innovative diagnosis, circuit analysis, simulation, lateral thinking and trial and error. The resulting fixes are not restricted to layout and configuration changes but can include additional (or reduction of) components and different component selections, resulting in anything from 2 bridges on a PCB to a total PCB redesign.
This process often contributes a large part to the development time and the cost of the eventual quality claims for the end product.

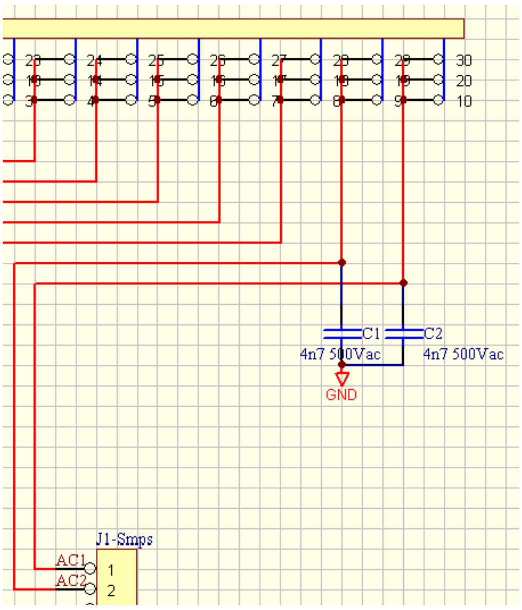
In the Elpronet the SMPS board uses resistors (R8, R9) and capacitors (C1, C15) to limit the dv/dt and a varistor (V1) and transzorb (D4) for absorption of transverse surges – see diagram below.
For common mode EMI suppression, capacitors (C22, C23), varistors (V2, V3) and the Common Mode choke (CM1) block various types of EMI, while capacitor C12 couples the internal Ground to Earth on the SMPS board to decouple the high-frequency EMI there.



Most of the following EMI fixes were taken after tests to IEC standards were done, showing deficiencies.

In this Relay the system Earth and device Ground are directly connected. The potential problem with this are Ground currents/loops which can cause sensitivity to FTB from external wiring and EMI from the SMPS. This has been minimised by having a Ground plane as a star point on the backplane PCB which accommodates the external connectors. To this Ground plane are connected suppression capacitors (C1, C2) for FTB prefiltering the auxiliary supply, capacitors for FTB on the external signal wiring (C3, C4, C5) and RC-filters for slower EMI (6) on the signal inputs (R1-C6, R2-C7). These and some of the connectors on the backplane are shown in the diagrams below.
C3, C4, C5 suppress induced EMI (6) and FTB (4) from the external wiring.



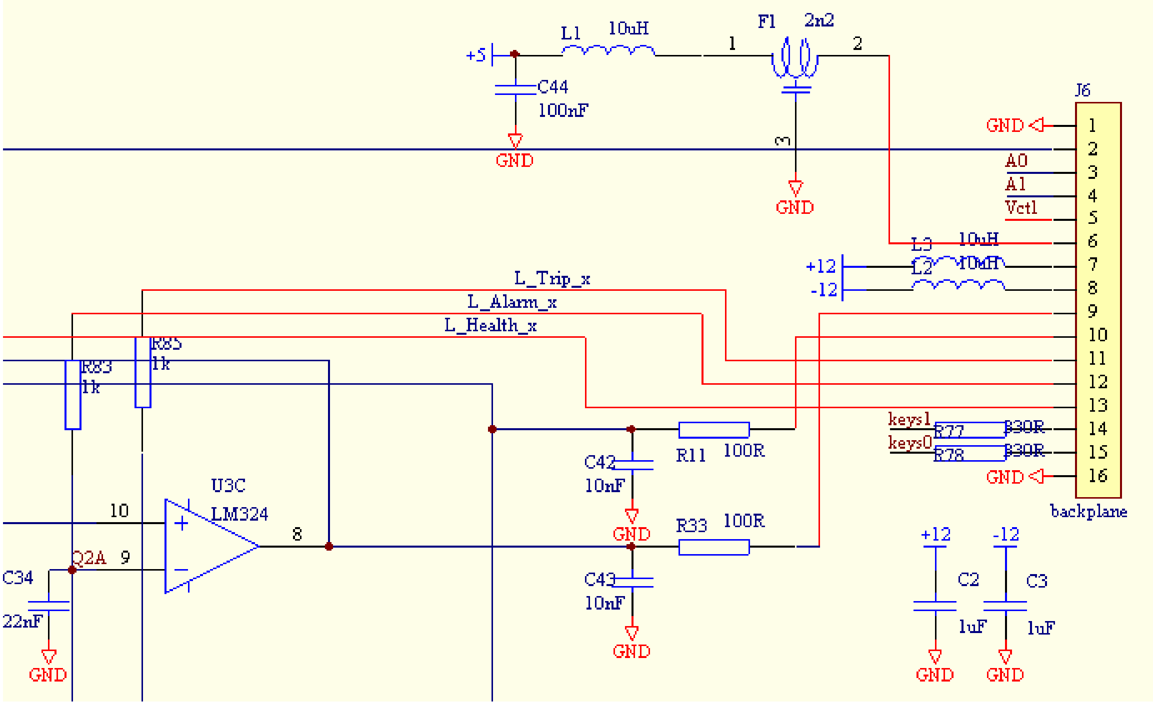


To shield off radiated EMI (3) it was found that a copper shield across the front cover provided the required immunity. Therefore the board behind the Relay front cover, holding the also display, was given a Ground plane which is connected to the star point (backplane) by one path through the processor board which is situated in-between. The processor board also has some Ground plane, so this connection has small ESR.

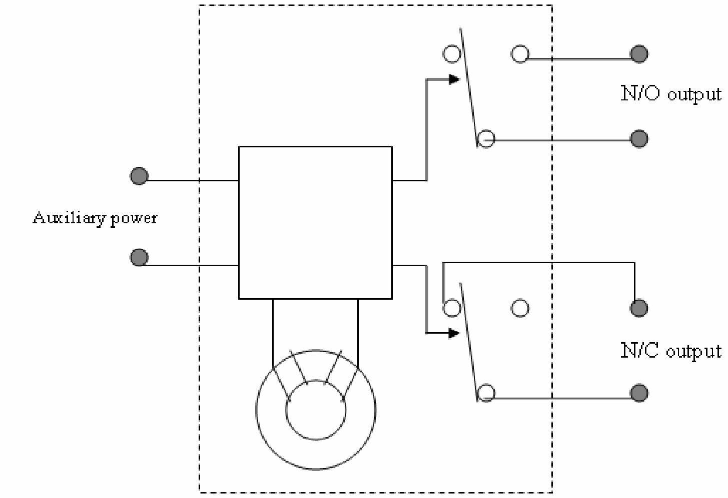
On the processor board, the power supply lines (+5V, +12V, -12V) from the switch mode board are also via the backplane. These are filtered on the processor board to ward off common mode EMI, mainly FTB (4) and surges (1) coming through the auxiliary supply. The filters consist of small inductors (L1, L2, L3) and capacitors (C44, C2, C3) and a T-type filter (F1) for the more critical 5V supply – see diagram below.

The output lines are also filtered by RC filters to block EMI from the backplane, e.g.: R11, R33, R83 together with C42, C43, C34. It is important to keep EMI from any processor pin to minimise the chances of processor hangup and restart.

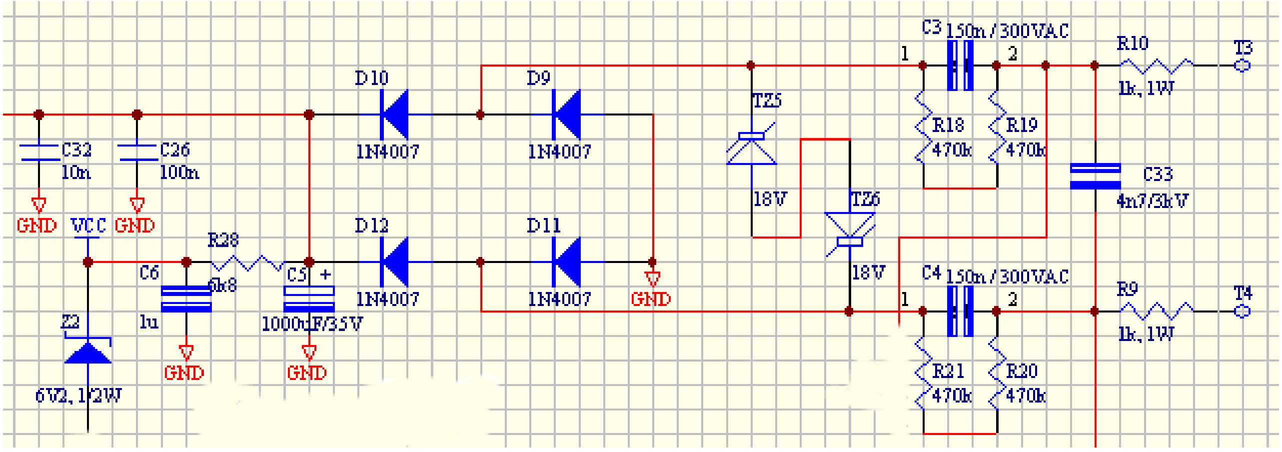
Also, the processor needs small-inductance capacitors (e.g. 1nF, 10nF and 100nF ceramic SMD) across its 5V supply as close as possible to it. The processor's clock causes the logic to draw current in steps and these capacitors will smooth the fast changes thereby preventing EMI to be transmitted to other components. They also decouple externally received EMI. To deal with large surges (1), there is also a 6.8V transzorb across the +5V supply.



In another Earth Fault protection Relay the CT is built-in so there are no input connections:

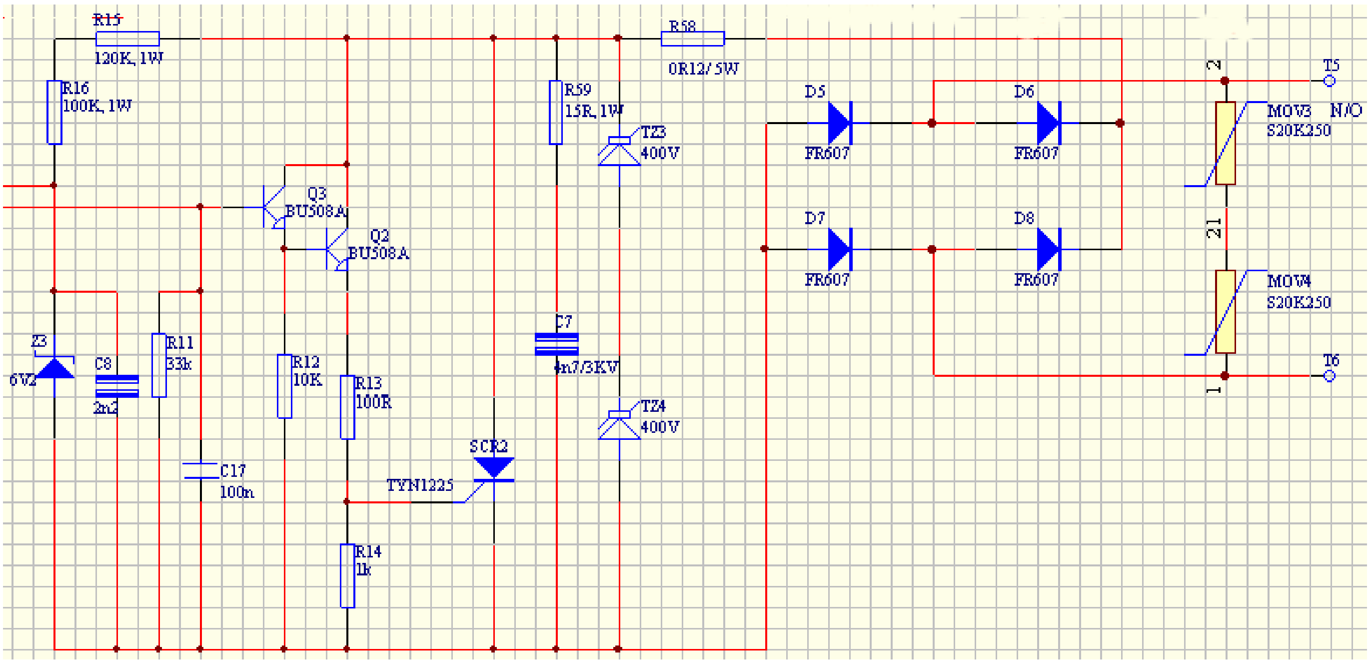


Also, there is no Earth or Ground connection although the electronics has its internal Ground.
EMC tests are therefore limited to transverse mode.
As this Relay is fully solid-state, both the auxiliary supply circuit and the output “contacts” need special protection.
Considering the auxiliary supply circuit:



For FTB’s (4) and dv/dt the RC filter (R9, R10, C33) is needed. The resistors limit the current of surges and together with the capacitor, filter out the high frequency components of the FTB.
The transzorbs TZ5 and TZ6 will absorb any excess energy from external high-voltage EMI.
Capacitors C26 and C32 are very low-inductance types to decouple the internal DC supply from high frequency components like FTB (4) and ESD (2).

The output “contacts” work as shown in the diagram below:



The two varistors are hoped to protect the diodes of the bridge rectifier.
Transzorbs (TZ3, TZ4) are meant to clamp surges and fast transients.
Capacitors C8 and C17 are meant to prevent EMI from spuriously triggering of the driver transistor Q3.

Glossary of mostly EMC Acronyms

- ACES - Applied Computational Electromagnetics Society
- ANSI - American National Standards Institute
- APLAC - Asian Pacific Laboratory Accreditation Cooperation
- CENELEC - European Committee for Electrotechnical Standardization)
- CSA - Canadian Standards Association
- CT - Current Transformer
- dv/dt - rate of rise of voltage
- E/F - Earth Fault
- EIA - Electronic Industries Association
- EMC - Electromagnetic Compatibility
  (The ability of a device or system to function without error in its intended electromagnetic environment.)
- ESA - Electrostatics Society of America
- ESD - Electrostatic Discharge\
- EMI - Electromagnetic Interference
  (Electromagnetic emissions from a device or system that interfere with the normal operation of another device or system.)
- EMP - Electromagnetic Pulse
- EPC – Electrical Protection Company (part of Crabtree)
- ESR - Equivalent series resistance
- ETSI - European Telecommunications Standards Institute
- FCC - Federal Communications Commission (U.S.A.)
- FTB - Fast Transient Burst
- HEMP - High altitude nuclear Electromagnetic Pulse
- HF - High Frequency
- HV - High Voltage
- IEC - International Electrotechnical Commission
- IEEE - Institute of Electrical and Electronics Engineers
- IEMI - Intentional Electromagnetic Interference
- I/O - Input / Output interface
- ISO - International Organization for Standardization
- ITE - Information Technology Equipment
- LF - Low Frequency
- LV - Low Voltage
- NARTE - National Association of Radio and Telecommunications Engineers
- NEMP - Nuclear Electromagnetic Pulse
- NIST - National Institute of Standards and Technology (U.S.A.)
- PCB - Printed Circuit Board
- PLT - Power Line Transient
- RES - Radiated Electromagnetic Susceptibility
- SMPS – Switch-mode Power Supply
- VCCI - Voluntary Control Council for Interference (Japan)