Ceramic transient voltage suppressors, CTVS

Design notes

Date: July 2014

1 Design notes

1.1 Principles of protection with ceramic transient voltage suppressors

EPCOS multilayer chip varistors (MLVs) and CeraDiodes have been used successfully for many years in a wide field of applications. During this time they have become the most popular component for ESD protection. In the mobile communication industry multilayer varistors and ESD/EMI filters meanwhile represent the world standard in ESD protection.

Advanced semiconductor technology for integrated circuits has created a very small geometry inside components which is more and more sensitive to any kind of electromagnetic interference. The integration of additional features in applications like smartphones leads to an increasing number of components. On the other hand less board space is available due to the trend to miniaturize the whole product. As a consequence smaller components with an increasing level of passive integration are required. Excessive noise levels caused by EMI (electromagnetic interference) or RFI (radio-frequency interference) can impair the proper operation and the reliability of the design. Unwanted transients, like ESD spikes, coming through the I/O ports of a device may lead to memory losses and/or IC destruction. Field rejects caused by ESD sensitivity of a device are expensive and may affect the success of the end-product.
Very fast response time and reliable ESD absorption capability over a broad operating temperature range at small sizes (0201 to 2220) have made MLVs, ESD/EMI filters and CeraDiodes the first choice in the electronics industry.

EPCOS CTVS components are available for a wide range of applications in automotive, industrial and consumer electronics as well as in smartphones, portable devices and computers. Special components with defined capacitance tolerances and integrated resistors for filter applications can be used to enable a device to comply with other EMC standards. Further, EPCOS arrays in packages from 0405 up to 0612 are able to provide ESD protection for two and four data lines while EPCOS filter arrays in 0405 and 0508 packages can offer both ESD and EMI protection in one component.

1.1.1 Protective circuits

Multilayer varistors and CeraDiodes are a reliable solution for protection against electromagnetic interference or transient overvoltages arising from ESD, EFT or surges at circuit board level.
They are very often used in low-voltage applications (operating voltage V_{DC} <50 V) for protection of data lines and power supply lines.

CTVS must on all accounts be connected parallel to the electronic circuits or devices which are to be protected against transient overvoltages, see figure 1.

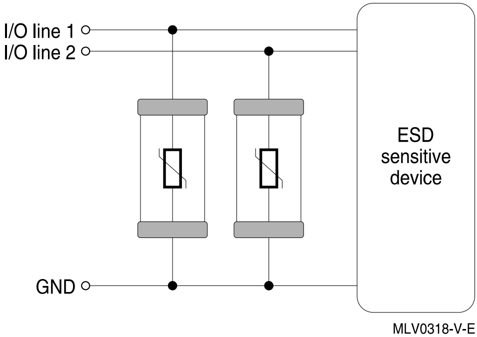

Figure 1
Typical integration of CTVS into circuits for the purpose of protection against ESD/ EMI.

Characteristic line impedance

The principle of overvoltage protection by CTVS components is based on the series connection of voltage-independent and voltage-dependent resistance. Use is made of the fact that every real voltage source and thus every transient has a voltage-independent source impedance greater than zero. This voltage-independent impedance Z_{source} in figure 2 can be the ohmic resistance of a cable or the inductive reactance of a coil or the complex characteristic impedance of a transmission line.

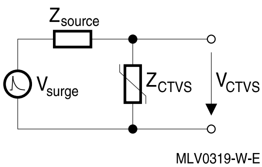

Figure 2
Equivalent circuit in which Z_{source} symbolizes the voltage-independent source impedance

If a transient occurs, current flows across Z_{source} and the CTVS that, because $V_{source} = Z_{source} \cdot I$, causes a proportional voltage drop across the voltage-independent impedance. In contrast, the voltage drop across the CTVS is almost independent of the current that flows.

Because

$$V_{CTVS} = (Z_{CTVS} / (Z_{source} + Z_{CTVS})) \cdot V_{surge} \qquad \text{(equ. 1)}$$

the voltage division ratio is shifted so that the overvoltage drops almost entirely across Z_{source}. The circuit parallel to the CTVS (voltage V_{CTVS}) is protected.

Figure 3 and 4 illustrate the principle of by CTVS components.

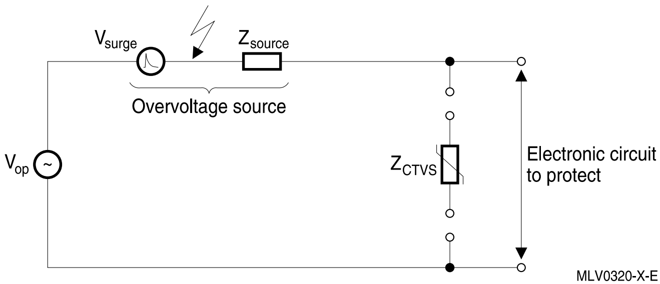

Figure 3
Typical equivalent circuit to show how a CTVS protects an application. The overvoltage surge is represented by an additional source element.

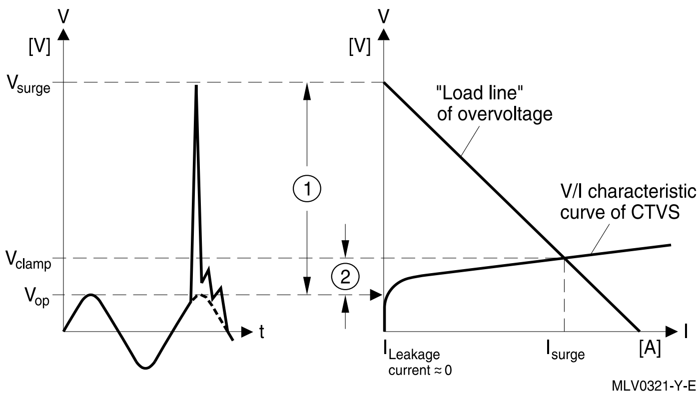

Figure 4
Typical CTVS protection scenario: An overvoltage event superimposed over the normal operating voltage causes a shift in the CTVS operating point, which is at the intersection of the overvoltage load line and V/I characteristic curve of the CTVS, and the overvoltage is effectively clamped.

The intersection of the “load line” of the overvoltage with the V/I characteristic curve of the CTVS is the “operating point” of the overvoltage protection, i.e. surge current amplitude and protection level.

The overvoltage ① is clamped to ② by a CTVS.

V_{op}	Operating voltage
V_{surge}	Superimposed surge voltage

For selection of the most suitable protective element, one has to know the surge current waveform that goes with the transient. This is often, and mistakenly, calculated by way of the (very small) source impedance of the line at line frequency. This leads to current amplitudes of unrealistic proportions. Here you have to remember that typical surge current waves contain a large portion of frequencies in the kHz and MHz range at which the relatively high characteristic impedance of cables, leads, etc. determines the voltage/current ratio.

Figure 5 shows approximate figures for the characteristic impedance of a supply line when there are high-frequency overvoltages. For calculation purposes the characteristic impedance is normally taken as being 50 Ω. Artificial networks and surge generators are designed accordingly.

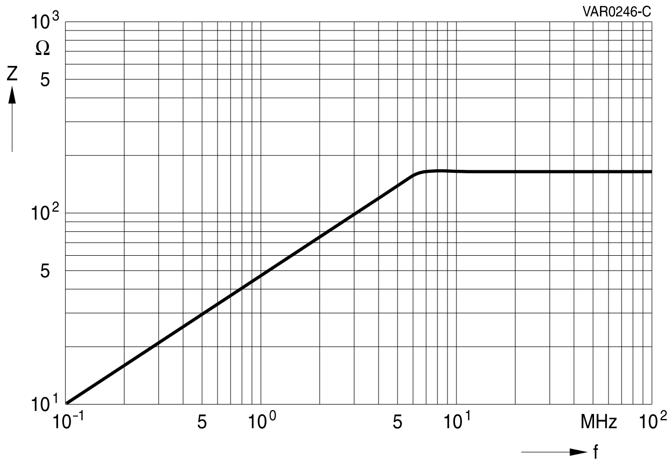

Figure 5
Impedance of a supply line for high-frequency overvoltages

1.1.2 Transient overvoltages

Transient overvoltages are distinguished according to where they originate. They can be divided into internal and external overvoltages.

Internal overvoltages

Internal overvoltages originate in the actual system to be protected, e.g. through

- inductive load switching
- arcing
- direct coupling with higher voltage potential
- mutual inductive or capacitive interference between circuits
- electrostatic charge
- ESD

With internal overvoltages the worst-case conditions can often be calculated or traced by a test circuit. This enables the choice of overvoltage protective devices to be optimized.

External overvoltages

External overvoltages affect the system to be protected from the outside, e.g. as a result of

- line interference
- strong electromagnetic fields
- lightning

In most cases the waveform, amplitude and frequency of occurrence of these transients are not known or, if so, only very vaguely. And this, of course, makes it difficult to design the appropriate protective circuitry.

Some overvoltages and their corresponding voltage and duration are depicted in figure 6.

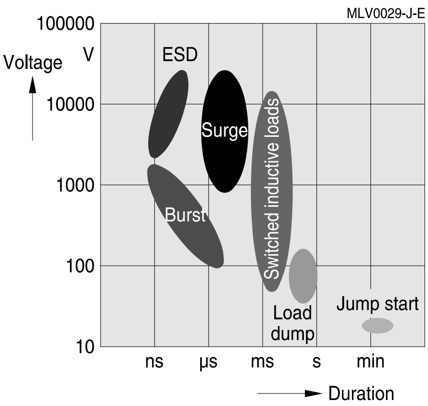

Figure 6
Overview of transient overvoltages

1.2 ESD protection

The trend to miniaturized components and lower signal levels increases the susceptibility of electronic circuits to interference from electrostatic. Simply touching a device may lead to electrostatic discharge causing functional disturbance with far-reaching consequences or to component breakdown. Studies have shown that the human body on an insulated ground surface (e.g. artificial fiber carpeting) can be charged up to 15 kV and higher.

To ensure immunity to interference and CE conformity, measures are needed to prevent damage due to electrostatic discharge (ESD). This applies to both circuit layout and the selection of suitable overvoltage protection.

Suitable overvoltage protection components must meet the following requirements:

- response time <0.5 ns
- bipolar characteristics
- sufficient surge current handling capability
- low protection level

In addition, the following requirements are desirable:

- smallest possible component size
- low inductive SMD design
- stable capacitance values for RF interference suppression
- low capacitance values for systems with high-speed data transmission rates
- wide operating voltage range
- high operating temperature

All EPCOS multilayer varistors, CeraDiodes and ESD/EMI filters are suitable for ESD protection: they fulfill at least compliance level 4 to IEC 61000-4-2.

1.2.1 ESD protection requirements

The table below acts as a guideline for how much ESD protection is required at PCB level under specific environmental conditions:

Compliance level to IEC 61000-4-2	Antistatic material	Synthetic material	Relative humidity as low as	Maximum test voltage	
				Contact discharge	Air discharge
1	x		35%	2 kV	2 kV
2	x		10%	4 kV	4 kV
3		x	50%	6 kV	8 kV
4		x	10%	8 kV	15 kV

Applied voltage kV	Peak current to IEC 61000-4-2 A
2	7.5
4	15
6	22.5
8	30

Automotive standard AEC-Q200, Rev. D (see also chapter "Protection standards," section 1.3.1.1 "AEC-Q200, Rev. D") defines further ESD component classification levels that exceed those acc. to IEC 61000-4-2 in terms of maximum test voltage, see table below:

Component classification to AEC-Q200, Rev. D	Maximum test voltage	
	Contact discharge	Air discharge
5C	–	16 kV
6	–	25 kV

1.2.2 Susceptibility of semiconductors

Almost all semiconductive components are susceptible to ESD. The sensivity however depends on many different factors such as integrated low-power ESD protection, the capacitance and layout of the specific circuit. These factors may help to reduce the risk of damage by ESD. In most cases it is, therefore, not necessary to select the external ESD protection component with the lowest clamping voltage. As explained in chapter "Selection procedures" (section 1.3.2) other selection criteria such as low leakage current or capacitance should be considered to select the optimal protection device. As a general guideline the table below lists the typical ESD susceptibility of common semiconductors devices.

Semiconductor type	Typical ESD susceptibility
VMOS	30 ... 1800 V
EPROM	100 V
MOSFET/ Power MOSFET	100 ... 300 V
GaAsFET	100 ... 300 V
LED	100 ... 500 V
JFET	140 ... 7000 V
OP-AMP	190 ... 2500 V
CMOS	250 ... 3000 V
Schottky diodes	300 ... 2500 V
Bi-polar transitors and structures	380 ... 7000 V
Schottky TTL	1000 ... 2500 V

1.2.3 Principles of ESD protection

The following aspects must be taken into consideration when designing ESD protection circuits.

1.2.3.1 Provision of an alternative current path

Figure 7 illustrates the principle involved. The protective element must have the electrical characteristics required for effective ESD protection as specified in chapter "Protection standards," section 1.2.1.

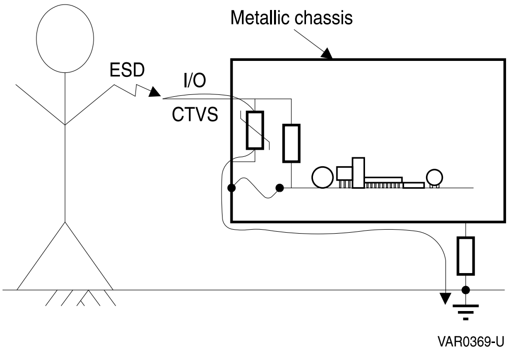

Figure 7
Alternative current path
for draining an ESD pulse

1.2.3.2 Circuit board layout

The following criteria must be observed when designing PCB layouts:

- Minimize the trace length
- Keep the suppressor conductor paths and lead lengths to an absolute minimum
- Place the CTVS as close to the input terminals or connectors as possible
- Avoid running protected conductors in parallel with unprotected conductors
- Never run critical signals (clocks, resets, etc.) near card edges, because these areas are especially sensitive to induced ESD voltages
- Minimize all conductive loops, including power and ground loops
- Keep the ESD transients return path to ground as short as possible, and avoid shared transient return paths to a common ground point
- Use ground planes whenever possible

1.2.3.3 Shielding

The extremely steep leading edges of short electrostatic discharge pulses induce extremely high electromagnetic fields, which should be contained, i.e. shielded by metal casings or other measures.

1.2.3.4 Series and parallel connection of two CTVS components

- **Series connection**

CTVS components can be connected in series for more precise matching to uncommon voltage ratings or for voltage ratings higher than those available. For this purpose the types selected should be of the same series (i.e. same case size). The maximum permissible operating voltage in series configuration is produced by adding the maximum DC or AC voltages of the CTVS.

- **Parallel connection**

CTVS components can be connected in parallel to achieve higher current load capability or higher energy absorption than can be obtained with single components. To this end, the intended operating point in the surge current region must be taken into account. In the worst case, two CTVS components may have been chosen for parallel connection, with the first having a V/I characteristic curve corresponding to the upper limits, and the second having a V/I characteristic curve corresponding to the lower limits of the tolerance band. This means that if unselected CTVS components are used in the surge current region, current distributions of up to 1000:1 may render the parallel connection useless. In order to achieve the desired results, it is necessary to match voltage and current to the intended operating point.

1.2.4 Multilayer ceramic technology versus semiconductor suppressor diodes

In most applications multilayer ceramic components can be used instead of semiconductor supressor diodes. A comparison of the most important parameters shows that multilayer ceramic may be the best choice for ESD protection.

- **Surge current handling capability**

The interleaved electrode arrangement of multilayer ceramic devices allows surge currents of over 1 kA to be handled, whereas semiconductors can often withstand only a few amperes. This characteristic enables multilayer products to be used not only for protection against ESD, but also for dealing with surge loads of much higher energy levels to IEC 61000-4-5.

- **Bipolar characteristics**

ESD can occur with any polarity, which poses no problems for multilayer ceramic products with their symmetrical protection characteristics, whereas two components are often required to achieve the required bipolar characteristic with semiconductor suppressor diodes.

- **Operating temperatures**

As shown in figure 8 multilayer ceramic products can be subjected to full load at temperatures of up to 150 °C, whereas the load capacity of semiconductor suppressor diodes derates from temperatures of 25 °C upwards and is frequently reduced to 25% of the rated value at 125 °C. An additional current-limiting resistor often has to be connected in series with semiconductor circuits to compensate.

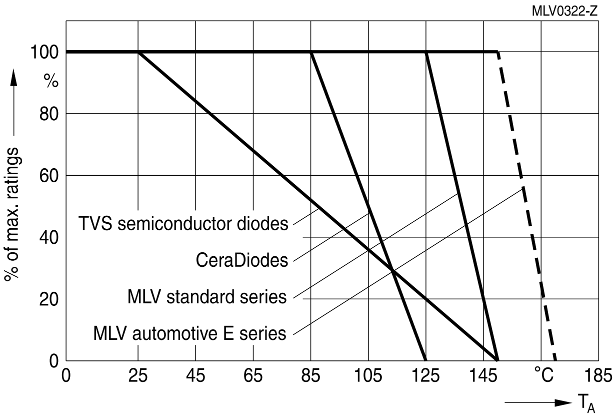

Figure 8
Temperature derating of multilayer ceramic products versus semiconductor transient voltage suppressor diodes

- **Chip size**

The ceramic material for multilayer ceramic products serves as an insulator on the exterior surfaces; the terminal electrodes are available as direct contact surfaces.

By comparison, semiconductor components most times require a casing. This makes them correspondingly bulky and they require more mounting space.

- **Response time**

Due to their extremely low parasitic inductances, multilayer CTVS are fast enough to handle ESD pulses with very short rise times (see also chapter "Protection standards," section 1.2.1 "Electrostatic discharge (ESD) to IEC 61000-4-2.") One can find similar results for the die of the silicon used in semiconductor protective devices like suppressor diodes. However, when the die is mounted in its package, the response time often increases to values >1 ns due to the series inductance of its package.

1.3 EMI filtering

EPCOS has created components that have two functions: in addition to serving as overvoltage protection, EPCOS multilayer components are also suitable for suppressing noise generated by electromagnetic interference (EMI). Some examples are listed below.

1.3.1 Substitution of discrete filter circuits

Usually data line protection against ESD/RFI/EMI influence will be achieved by adapting combination circuits as shown in figure 9.

In many cases, these components can be substituted by a single multilayer device with defined capacitance (figure 10). Such solutions reduce bulk and costs considerably while improving reliability.

Densely integrated multilayer component solutions for ESD/EMI applications also exhibit much better filter performance compared to filter networks consisting of discrete components because of the lower parasitic inductance resulting from the integrated package design.

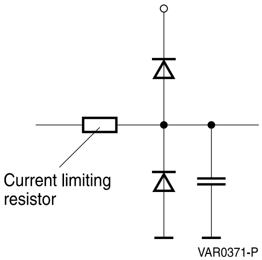

Figure 9
Before replacement: Typical ESD/ EMI filtering/ protection network.

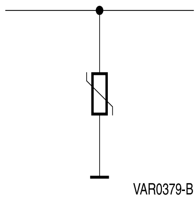

Figure 10
After replacement: One multilayer device can replace up to four discrete components.

1.3.2 Substitution of filter capacitors

In general for the protection of data lines it is of interest that the parasitic capacitance be kept low or within a defined range. If the capacitance on the signal line is too high, it will distort the signal.

On the other hand the EMC standards require filter elements that are able to suppress every unwanted noise.

To comply with those requirements EPCOS has developed multilayer varistor types with low capacitance (LC, HS, RF), controlled capacitance (CC) or high capacitance levels (HC):

- Low capacitance (LC, HS, RF) to create a lowpass filter especially needed in high-speed data lines
- Controlled capacitance (CC) to replace a capacitor for filtering purposes at I/O ports with the benefit of ESD protection plus saving additional chip capacitors
- High capacitance (HC) for noise suppression (RFI, EMI) on DC lines

The filtering properties of the integrated capacitance are very similar to class-1 capacitors. The temperature rating of the capacitance is between class 1 and class 2 with a temperature coefficient of typically 0.1%/K.

If a specific circuit calls for defined capacitance value tolerances, EPCOS is prepared to supply these specifically for the application as controlled capacitance (CC) versions.

Examples of special types with specified capacitances are:

- CT0201S4ACC2G: 0201 device with C = 4 pF ±3 pF, see data sheet for low clamping voltage series
- CT0402S5ARFG: 0402 device with C <1 pF, see data sheet for high-speed series
- CT0603S20ACCG: 0603 device with C = 80 pF ±20%, see data sheet for automotive series
- CA05M2S10T100HG: 2-fold 0508 array with C ≤15 pF and deviation of capacitance between array elements ≤3%, see data sheet for high-speed series
- CA04F2FT5AUD010G: 2-fold 0405 array with C = 270 pF ±30%, see data sheet for ESD/ EMI filter series

More details on the application of these types and on special designs with different capacitance and tolerance values can be supplied on request.

1.3.3 RF behavior of MLVs and CeraDiodes

Figures 11 and 12 show the typical RF behavior of multilayer varistors and CeraDiodes with a capacitance value that remains practically constant over a wide frequency range.

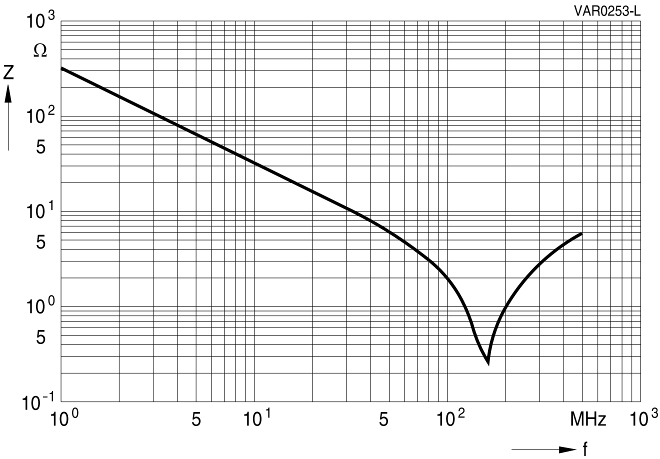

Figure 11
Typical frequency response of impedance (example: MLV standard series, type CT0805M6G)

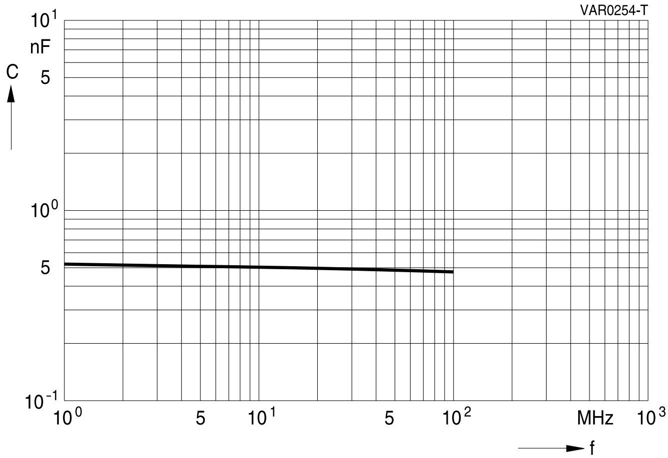

Figure 12
Typical frequency response of capacitance (example: MLV standard series, type CT0805M6G)

1.3.4 EMI filtering in mobile technology

ESD/EMI filters have two main functions. Firstly they cancel out noise from the signal lines caused by electromagnetic interference (EMI), and secondly they provide reliable protection of the circuit from the impact of electrostatic discharge (ESD).

Terms and description in the field of EMI filtering (figure 13):

- Passband
  The passband is the frequency range where signals are allowed to pass through the filter with minimum attenuation or insertion loss respectively. In the case of a lowpass filter the upper frequency limit of the passband is often referred to as the cut-off frequency.

- Rejection band
  The rejection band is in the frequency range of the expected disturbance. For lowpass filters the lower frequency limit of the rejection band is stated as f_{min}. Perturbations in this frequency band region are attenuated to a desirable level α_{min}.

- Insertion loss
  This term is used to describe the decrease in transmitted signal power between the input and output lines of the filter component. Insertion loss is usually expressed in decibels (dB).

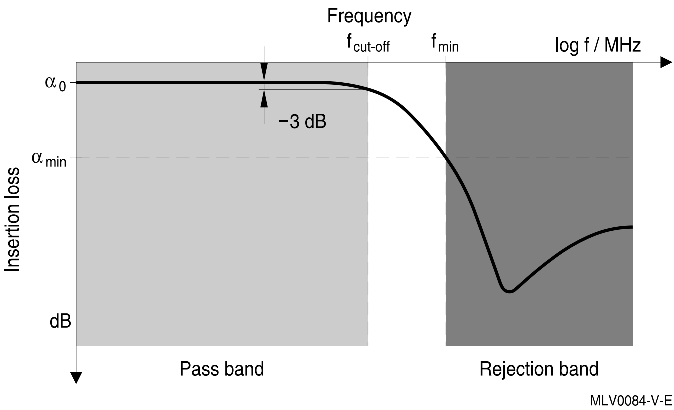

Figure 13
Filter characteristic of an ESD/EMI filter

1.4 EMC in automotive

Electronic equipment must work reliably in its electromagnetic environment without, in turn, unduly influencing this environment. This requirement, known as electromagnetic compatibility (EMC), is especially important in automotive electrical systems, where energy of mJ levels is sufficient to disturb or destroy devices that are essential for safety. EPCOS has devised a wide range of special varistor types matched to the particular demands encountered in automotive power supplies:

- extra high energy absorption (load dump)
- effective limiting of transients
- low leakage current
- jump-start capability (no varistor damage at double the car battery voltage)
- insensitive to reverse polarity
- wide range of operating temperature
- high resistance to cyclic temperature stress
- high capacitance for RFI suppression
- high-temperature (HT) versions available

EPCOS automotive varistors and SHCVs address these specific demands. These series are specified separately in the respective family data sheet.

1.4.1 RFI filtering

The capacitance of CTVS devices alone (some nF) is not enough for most RFI suppression applications. Therefore EPCOS has developed SHCVs that offer transient protection and RFI suppression in very compact form. These components are comprised of a multilayer varistor connected in parallel with a multilayer capacitor. SHCVs are especially suitable for handling RFI from small motors of windscreen wipers, power windows, memory seats, central locking, etc. Figure 14 shows

an example of the suppression effect over the relevant frequency range including FM, i.e. car radio disturbances.
EPCOS has extended its product range to include capacitances of up to 4.7 µF.

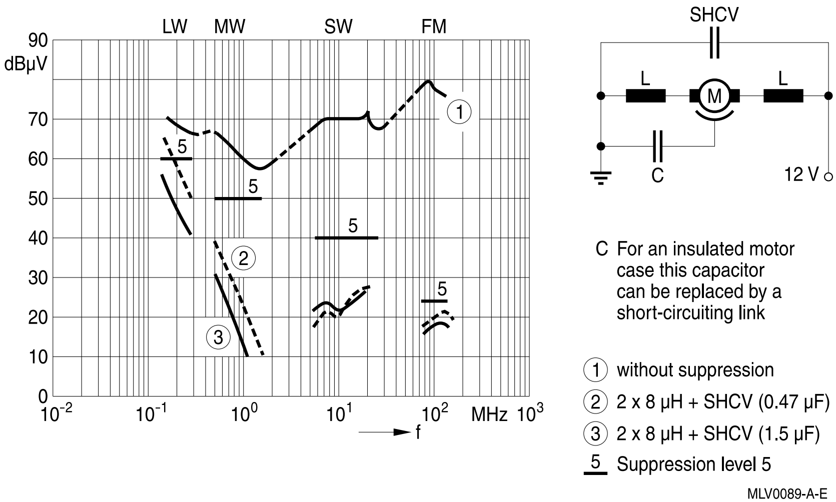

Figure 14
Example of RFI suppression in small motors with chokes and SHCVs (measured to CISPR25)

1.5 EMC for telecom equipment

Electromagnetic interference on telecommunications, signal and control lines can be quite considerable as these lines tend to be long and exposed. So the requirements are correspondingly high when it comes to the electromagnetic compatibility of connected components or equipment.

1.5.1 Surge protection CTVS series

EPCOS CTVS products are used all over the world as reliable protection components in communications terminal devices (e.g. telephones) and in switching exchange systems (e.g. line cards).

Depending on the test severity of the specifications SMD multilayer varistors in EIA case sizes 1812 or 2220 with the voltage levels K60 to K130 are used in such applications.

The preferred method of selecting a varistor for the requirement is to use PSpice simulation.

1.5.2 MLV surge protection series for telecom applications

The standard IEC 61000-4-5 additionally defines high-surge pulses for the purpose of immunity testing of telecom equipment based on International Telecommunications Union (ITU) K series standards, with wave shape 10/700 µs and test voltage in the kV region (see figure 15 for test ciruit).

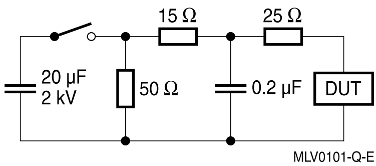

Figure 15
Circuit for generating 10/700 µs test pulse to IEC 61000-4-5 and ITU K series.

To meet these more severe test conditions, EPCOS has developed special “telecom” varistors that can absorb the energy of such 2 kV surge loads as specified in the test regulations. For further details please refer to the data sheet for the surge protection series.

1.6 EMC systems engineering

EPCOS is your competent partner when it comes to solving EMC problems. Our performance range covers:

- systems for measuring and testing EMC
- shielded rooms for electromagnetic pulse (EMP) measurement
- anechoic chambers
- EMC consultation services and planning

For further details, please contact EPCOS sales.