Introduction to Surge Mitigation Techniques

Foreword

Recently there has been a great deal of discussion about what constitutes surge protection. For the reasons explained in 2, this document takes a more global view and discusses how surges can be mitigated (reduced in severity) by the various techniques available. This view point is purely my own and should not be considered the policy or approach of any organisations I belong to. Should any reader wish to discuss the content of this document my contact email address is m.j.maytum@ieee.org.

This document is mainly the result on a discussion on isolation transformers, see http://pes-spdc.org/content/isolating-transformer-surge-protective-component-spc

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Contents

Introduction to Surge Mitigation Techniques

1 Introduction

This document describes the various surge mitigation (reduction) techniques available to the designer. The use of non-linear voltage amplitude limiting functions is the most commonly thought of approach for surge protection. However, today there are non-linear current amplitude limiting functions along with extensively used linear surge attenuating functions. Surge protection gurus like Ronald B. Standler (*Protection of Electronic Circuits from Overvoltages, Chapter 13*) and François Martzloff (*Diverting Surges to Ground: Expectations versus Reality, Proceedings, Open Forum on Surge Protection Application, NISTIR-4654, August 1991*) have both discussed the use of filters in surge protection and Standler (*Protection of Electronic Circuits from Overvoltages, Chapters 12 and 14*) has also analysed the common-mode surge protection given by EMC chokes and isolation transformers. Linear attenuating functions like filters and transformers do provide surge mitigation and could be classified as performing surge rejection.

The various types of surge mitigation only briefly described. References are given for more in depth descriptions of the mitigation functions.

2 Surge protection or surge mitigation?

The terms “protection” and “protective” are part of the surge protection engineering discipline vocabulary. It should be remembered that these terms imply that, under specified conditions, the surge is reduced to a level below the impulse withstand capability of the following circuit or equipment. However, in the field the incoming surge parameters are the result of many factors, rather than conforming to the standardized impulses from the generators specified in various standards. Likewise the following circuit or equipment impulse withstand can be unknown.

The inclusion of a surge protective function should reduce the onward level of the incoming surge, but not necessarily to the withstand level of the “protected” item as that withstand level may be unknown. For these reasons the ITU-T often uses the term “surge mitigation” (make (something bad) less severe, serious, or painful) instead of “surge protection”. If surge protection is achieved then it is a successful case of surge mitigation.

3 Definitions

The term definitions given in this clause apply to this document and occur in the discussion thread “*Is an isolating transformer a surge protective component (SPC)?*” at http://pes-spdc.org/content/isolating-transformer-surge-protective-component-spc.

Some term definitions are not the standardised term definitions as they were found to be specific to a particular application or a traditional limited approach. A discussion illustrating the shortcomings and conflicts of certain definitions is covered in the discussion thread “*Is an isolating transformer a surge protective component (SPC)?*” at http://pes-spdc.org/content/isolating-transformer-surge-protective-component-spc

3.1 common-mode surge

surge appearing equally on all conductors of a group at a given location.

NOTE 1—The reference point for common-mode surge voltage measurement can be a chassis terminal, or a ground terminal.

NOTE 2— Also known as longitudinal surge or asymmetrical surge.

3.2 differential-mode surge

surge occurring between any two conductors or two groups of conductors at a given location.

NOTE 1—The surge source maybe be floating, without a reference point or connected to reference point, such as a chassis terminal, or a ground terminal.

NOTE 2— Also known as metallic surge or transverse surge or symmetrical surge or normal surge.

3.3 impulse withstand voltage

highest peak value of impulse voltage of prescribed form and polarity which does not cause breakdown of insulation under specified conditions

NOTE—See Technical Report IEC/TR 60664-2-1:2011, ed. 2.0

3.4 Insulation

that part of an electrotechnical product which separates the conducting parts at different electrical potentials

NOTE—See Technical Report IEC/TR 60664-2-1:2011, ed. 2.0

3.5 insulation coordination

mutual correlation of insulation characteristics of electrical equipment taking into account the expected micro-environment and other influencing stresses

NOTE—See Technical Report IEC/TR 60664-2-1:2011, ed. 2.0

3.6 insulation resistance

resistance under specified conditions between two conductive bodies separated by the insulating material

NOTE—See Standard IEC 62631-1, ed. 1.0 (2011-04)

3.7 isolating transformer

transformer with protective separation between the input and output windings

NOTE—See Standard IEC 60065, ed. 7.0 (2001-12)

3.8 lightning overvoltage

transient overvoltage at any point of the system due to a specific lightning discharge

NOTE—See Standard IEC 60664-1, ed. 2.0 (2007-04)

3.9 Overvoltage

any voltage having a peak value exceeding the corresponding peak value of maximum steady-state voltage at normal operating conditions

NOTE—See Technical Report IEC/TR 60664-2-1:2011, ed. 2.0

3.10 rated impulse voltage

impulse withstand voltage value assigned by the manufacturer to the equipment or to a part of it, characterizing the specified withstand capability of its insulation against transient overvoltages

NOTE— See Technical Report IEC/TR 60664-2-1:2011, ed. 2.0

3.11 electric screen

screen of conductive material intended to reduce the penetration of an electric field into a given region

NOTE—See Standard IEC 60050-151:2011, ed. 2.0

3.12 surge

temporary disturbance on the conductors of an electrical service caused by an electrical event.

NOTE—See http://pes-spdc.org/content/isolating-transformer-surge-protective-component-spc

3.13 surge protective component (SPC)

component designed into the circuit of a device or equipment port, for the purpose of mitigating the onward propagation of overvoltages or overcurrents or both.

NOTE—The selected component should not significantly degrade the normal system operation.

3.14 surge protective device (SPD)

device that is intended to mitigate surge voltages or currents or both of limited durations at a designated port or ports

NOTE 1—The surge reduction or restriction operating modes may be common-mode or differential-mode or both.

NOTE 2— See http://pes-spdc.org/content/isolating-transformer-surge-protective-component-spc

3.15 withstand voltage

voltage to be applied to a specimen under prescribed test conditions which does not cause breakdown and/or flashover of a satisfactory specimen

NOTE—See Standard IEC/TR 60664-2-1:2011, ed. 2.0

4 Surge Mitigation Functions

Figure 1 shows the various types of surge mitigation function. The left side of the figure shows non-linear functions and the right side shows linear attenuating functions. Some functions can used to mitigate common-mode and differential-mode surges, while others are limited to differential-mode or common mode surges

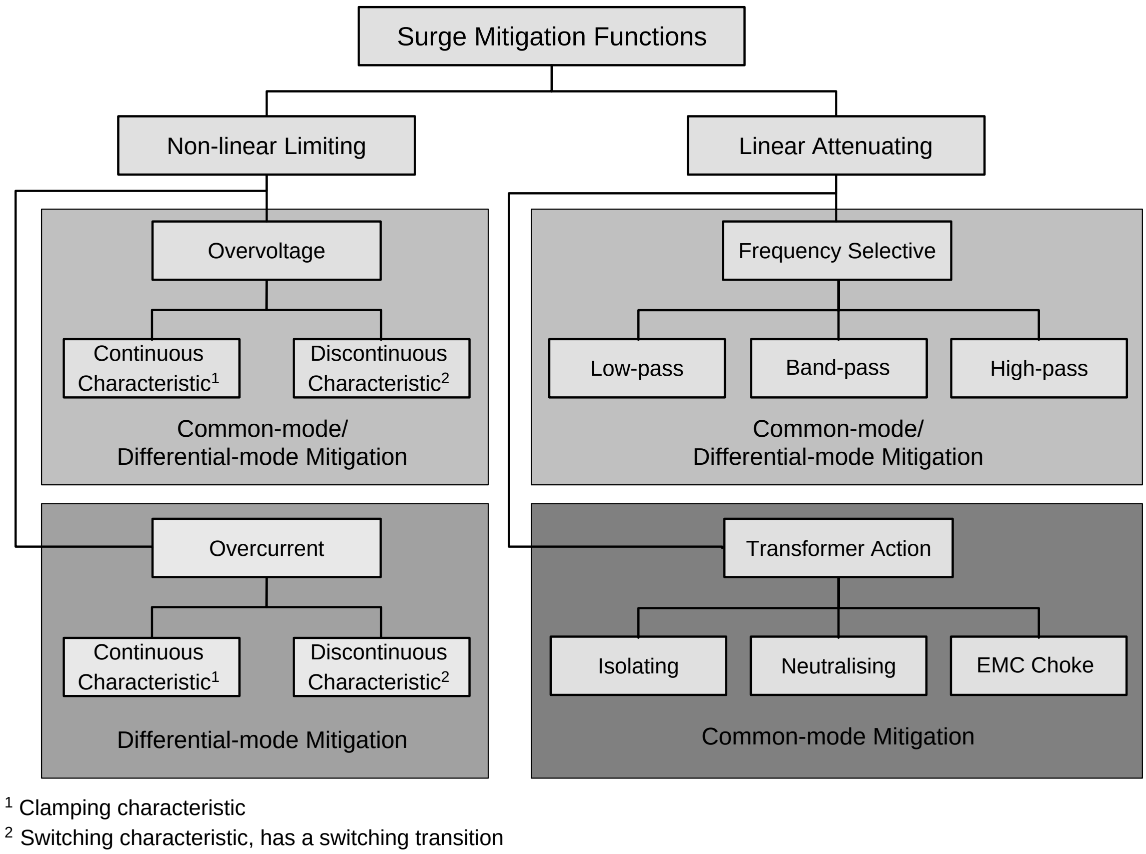

Figure 1—Common Surge Mitigation Functions

5 Non-linear limiting

This form of surge mitigation operates by limiting (clipping) surge amplitudes that exceed a predetermined threshold value to values either close to that of the threshold or much lower than the threshold.

Surge mitigation controlled by an integrated circuit (IC) and a power element can be multimode. For example in a DC supply feed using such an arrangement the IC can maintain the conditioned voltage to a fixed level for various combinations of surge voltage and time, but when these combinations are exceeded, the power element is switched off to prevent over-dissipation and the conditioned voltage falls to zero. This sophisticated form of surge mitigation is not covered by this document.

Gated thyristors are used to provide a combined over-current and overvoltage protection component, see IEEE Std C62.37 (1996): *IEEE Standard Test Specification for Thyristor Diode Surge Protective Devices* and IEEE Std C62.37.1 (2012): *IEEE Guide for the Application of Thyristor Surge Protective Device Components*

More detailed information on the various technologies mentioned here will be available in the forthcoming C62.42.x series of surge protective component (SPC) application principles

5.1 Overvoltage limiting

Voltage limiting components draw little current until the voltage exceeds the predetermined threshold voltage of the component.

5.1.1 Continuous characteristic

These components use solid-state materials. Metal-oxide varistors (MOV) use the properties of sintered material and silicon semiconductor components use the properties of PN junctions. All components have a clamping vi characteristic, but the clamping characteristic varies with technology, see Figure 2 for two examples. References: IEEE C62.33-1982 (R2000), *IEEE Standard Test Specifications for Varistor Surge-Protective Devices*, IEEE C62.35-2010, *IEEE Standard Test Methods for Avalanche Junction Semiconductor Surge-Protective Device Components.*

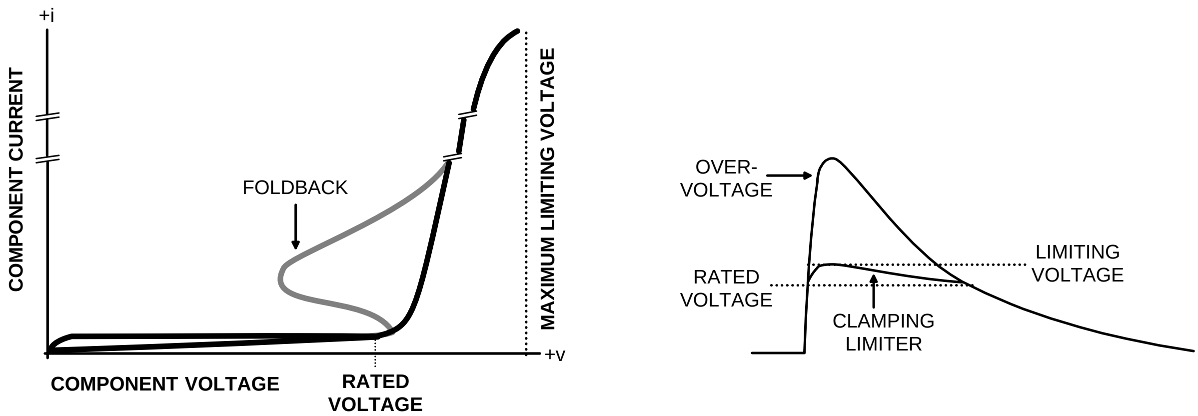

Figure 2—Overvoltage limiting—Continuous (clamping) characteristics

Technologies with these characteristics are:

- metal-oxide varistors (MOV)
- forward biased semiconductor PN junction diodes
- zener breakdown semiconductor PN junction diodes

- avalanche breakdown semiconductor PN junction diodes
- punch-through semiconductor PNP or NPN junction diodes
- fold-back semiconductor PNP or NPN junction diodes

5.1.2 Discontinuous characteristic

These components use solid-state materials or gases. Figure 3 shows the vi characteristics for a solid-state thyristor and a gas discharge tube (GDT). The vi characteristic is not continuous but has a break or breaks where switching occurs. see Figure 3. References: IEEE Std. C62.31-2006 (R2011), *IEEE Standard Test Methods for Low-Voltage Gas-Tube Surge-Protective Device Components*, IEEE Std C62.37 (1996): *IEEE Standard Test Specification for Thyristor Diode Surge Protective Devices.*

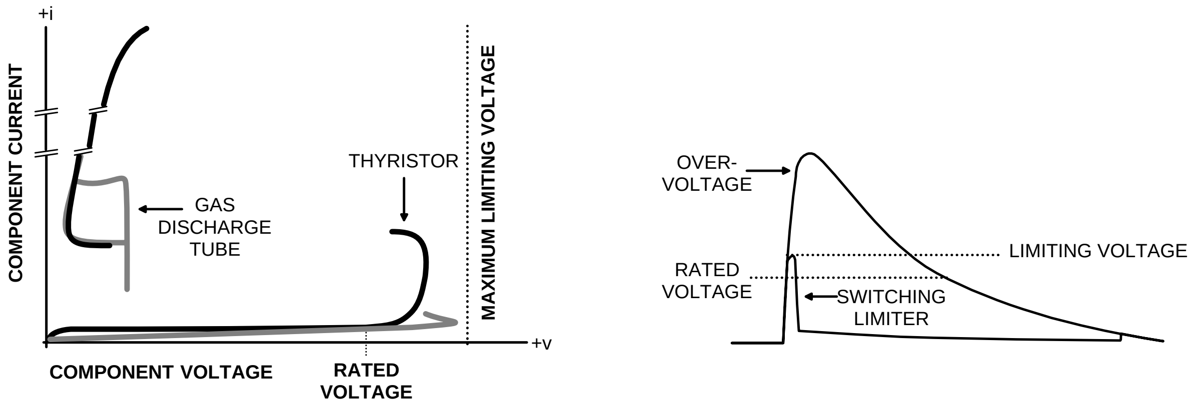

Figure 3—Overvoltage limiting—Discontinuous (switching) characteristics

Technologies with these characteristics are:

- spark gaps
- gas discharge tubes
- fixed voltage and gated thyristors

5.2 Overcurrent limiting

Current limiting components develop comparatively little voltage until the current exceeds the predetermined threshold current of the component. Reference: IEEE Std. C62.39-2012, *IEEE Standard for Test Methods and Preferred Values for Self-Restoring Current-Limiter Components Used in Telecommunication Surge Protection*.

5.2.1 Continuous characteristic

These components can be electronic circuits or materials whose resistance increases with temperate rise caused by self heating. Electronic circuits, Electronic Current Limiters (ECL) can be made with constant current or re-entrant characteristics, see Figure 4. Reference: J.L. Sanchez, Ph. Leturcq, P. Austin, R. Berriane*, M. Breil, C. Anceau** and C. Ayela**, Design and fabrication of new high voltage current limiting devices for serial protection applications, 8th International Symposium on Power Semiconductor Devices and ICs, 1996. ISPSD '96 Proceedings, pp 201 – 205.

Thermally operated components, Positive Temperature Coefficient (PTC) thermistors have a re-entrant characteristic under d.c. conditions. Under short duration surge conditions, PTC thermistors don't usually change in resistance. Under longer term a.c. surge conditions, the PTC thermistor temperature rise causes an increase in resistance gradually decreasing the current flow. Thermal equilibrium is reached when the PTC thermistor voltage and the circuit current flow results in the appropriate component dissipation to maintain the temperature.

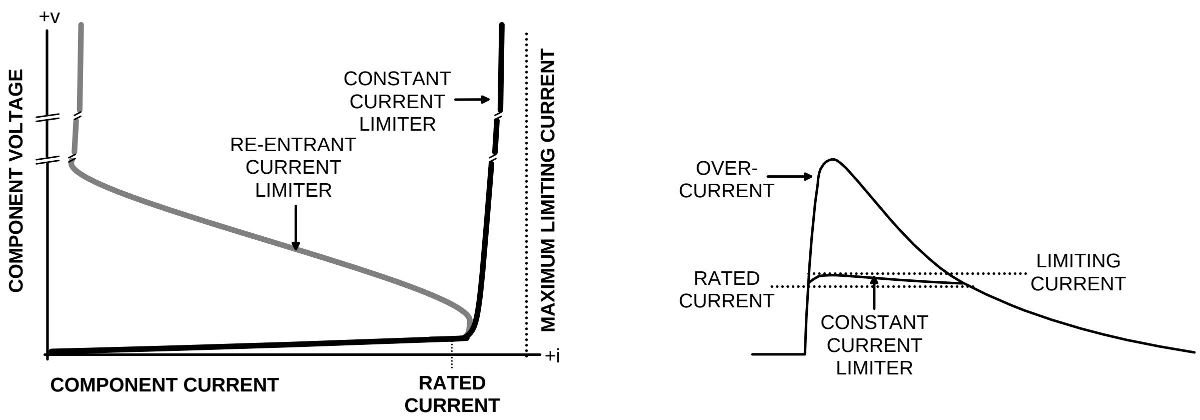

Figure 4—Overcurrent limiting—Continuous (clamping) characteristic

Technologies with these characteristics are:

- electronic current limiters (ECL)
- polymer positive temperature coefficient (PTC) thermistors
- ceramic positive temperature coefficient (PTC) thermistors

5.2.2 Discontinuous characteristic

These components can be electronic circuits, called Electronic Current Limiters (ECL), or one operation components like fuses. The iv characteristic is not continuous but has a a break where switching occurs. see Figure 5. Unlike fuses, ECLs operate under impulse conditions, see Figure 5. Reference: J.-P.Laur;J.L. Sanchez; M. Marmouget; P. Austin; J. Jalade; M. Breil; M. Roy, A new circuit-breaker integrated device for protection applications, The 11th International Symposium on Power Semiconductor Devices and ICs, 1999. ISPSD '99 Proceedings, pp 315- 318.

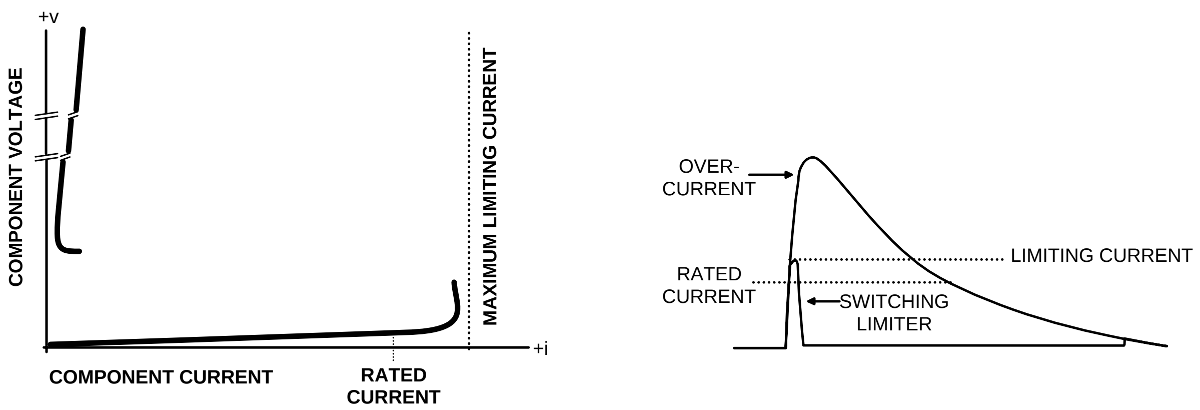

Figure 5—Overcurrent limiting—Discontinuous (switching) characteristic

Technologies with these characteristics are:

- electronic current limiters (ECL) (self-restoring)
- fuses (one shot)

6 Linear attenuation

Linear attenuation circuits or components reduce all levels of surge by a given reduction factor.

More detailed information on the various technologies mentioned here will be available in the forthcoming C62.42.x series of surge protective component (SPC) application principles

6.1 Frequency selective

Filters select out or reject certain parts of the frequency spectrum. Reference: Ronald B. Standler Ph. D., *Protection of Electronic Circuits from Overvoltages*, Dover Publications, December 2002, chapter 13: Filters.

For frequency filtering to be effective there must be little or no overlap of the service and surge spectrum. Figure 6 shows the Fast Fourier Transform (FFT) spectrum obtained from 1.2/50 and 10/1000 impulses of unity amplitude. The “knee” of these particular spectrums is roughly at a frequency period of ten times the surge duration.

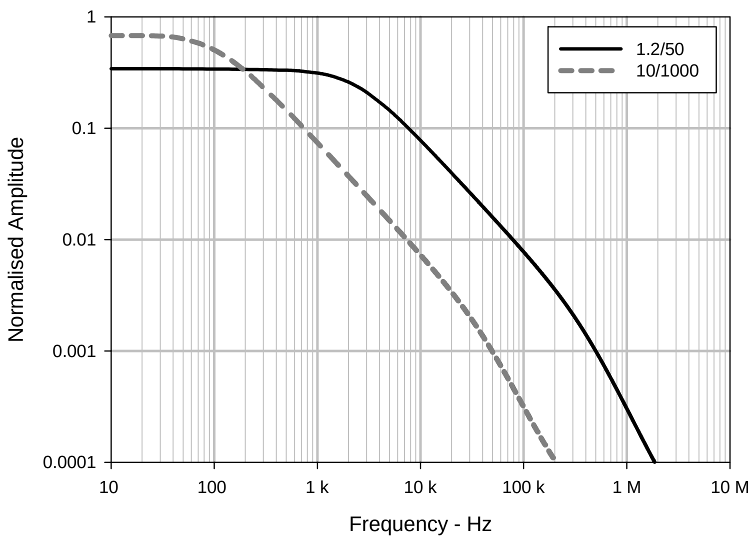

Figure 6—1.2/50 and 10/1000 surge waveform frequency spectrums

6.1.1 Low-pass filter

Because the surge frequency spectrum overlaps power service frequencies, like 50 Hz and 60 Hz, low-pass filters can only remove some of the surge frequency spectrum appearing on the power service. In addition, during power faults, when higher than normal power frequency voltage occurs, a low-pass filter is ineffective in reducing the level of power fault. Figure 7 shows a low-pass filter characteristic with the Figure 6 surge frequency spectrum overlaid.

A low-pass filter can be used in equipment to reduce self-generated switching spikes such as in switching mode power supplies and inverters used in photo-voltaic systems.

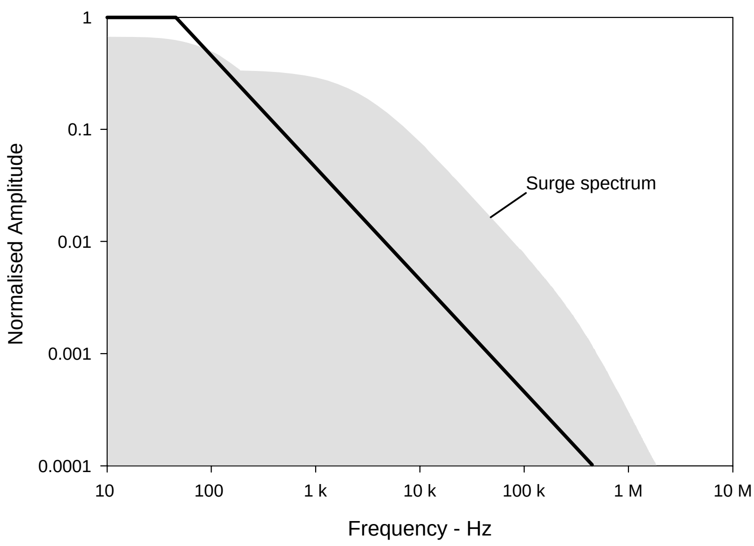

Figure 7—Low-pass filter characteristic

6.1.2 Band-pass filter

Where the service frequency spectrum is narrow, a band-pass filter can essentially remove the surge. An example of a band-pass filter is the quarter-wave stub surge protector used in high frequency coaxial systems. In addition, the quarter-wave stub protector has lower intermodulation distortion than a conventional protection approach using a gas discharge tube (GDT). Figure 8 shows a band-pass filter characteristic with a surge frequency spectrum overlaid.

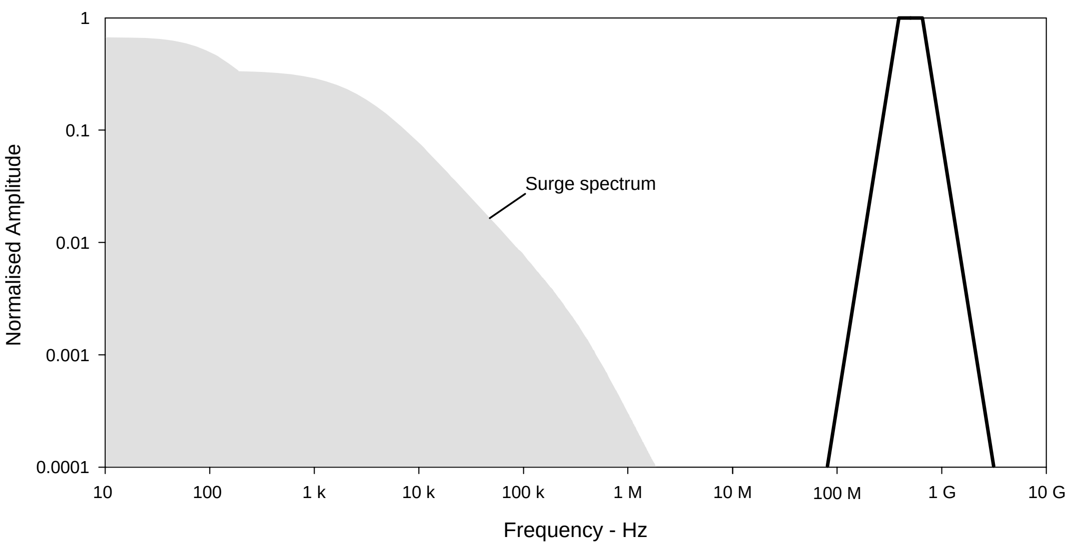

Figure 8—Band-pass filter characteristic

6.1.3 High-pass filter

Where the service frequency spectrum is above the surge frequency spectrum a high-pass filter can essentially remove the surge. Figure 8 shows a band-pass filter characteristic with a surge frequency spectrum and a.c. power service overlaid. A high pass filter can be used to filter out both the a.c. power service and the surge spectrum for applications like Power Line Communication (PLC).

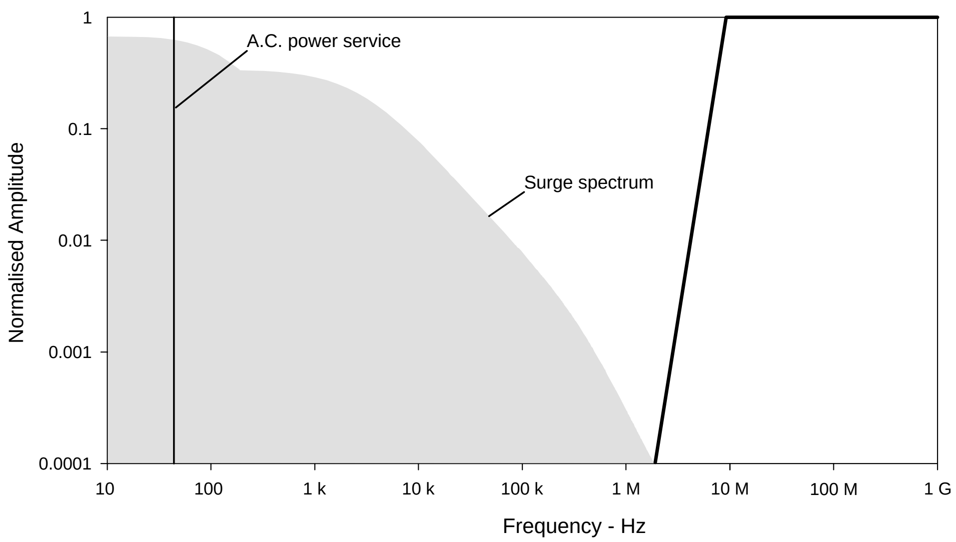

Figure 9—High-pass filter characteristic

6.2 Transformer action

All the transformers describe here mitigate common-mode surges. Additional protection must be added if differential-mode surges occur.

6.2.1 Isolating transformer

The isolating transformer reduces the propagation of common-mode surges, not through any transformer action, but by withstanding the common-mode surge across its insulation barrier. Reference: Ronald B. Standler Ph. D., *Protection of Electronic Circuits from Overvoltages*, Dover Publications, December 2002, chapter 14B: Isolation transformers. A typical application of an isolation transformer is in Ethernet ports.

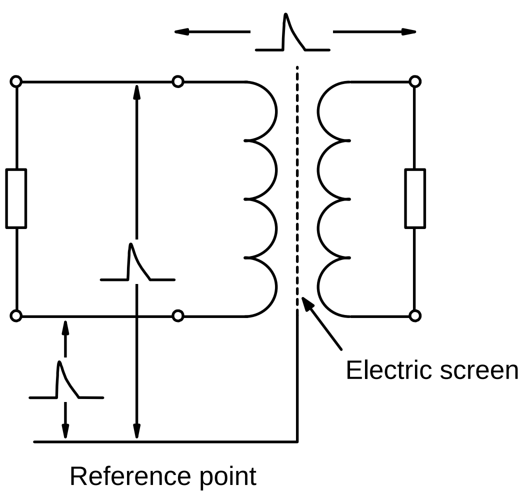

Figure 10—Isolating transformer common-mode surge mitigation

6.2.2 Neutralizing transformer

The neutralising transformer is a 2n + 1 winding, voltage operated transformer that reduces the propagation of a common-mode surge in a communications wire pair. It transfers primary winding voltage to the communications wire pair, which opposes the common-mode surge voltage on the communications wire pair. Reference: Brunssen, J.E., *Performance of the*

Neutralizing Transformer from a Volt-Time Area Approach, IEEE Transactions on Power Apparatus and Systems, Volume:PAS-97 Issue:2, pp 392 – 398, March 1978.

Neutralising transformers are typically used in power substations to buck out the ground potential rise differences between separated grounds on the communication line caused by a.c. discharges. Such transformers are large as they operate at the power frequency, see *Telecommunication Electrical Protection*, AT&T Technologies, Inc., 1985, chapter 11 Wire-line communications facilities serving electric power stations. The neutralising transformer can also buck out magnetically induced voltages on the communication line.

A phase-to-ground fault on a power transmission system can result in a ground potential rise (GPR) or increase in ground potential at the power station with respect to remote earth. The GPR can be disruptive and damaging to wire-line communications facilities entering the power station unless mitigative devices are employed. A neutralizing transformer bucks out this potential difference in communications lines.

A neutralizing transformer consists of closely coupled windings on a ferromagnetic core. The transformer primary winding is connected between power station and remote grounds. A secondary winding is placed in series with each conductor of the communications wire line pair entering the power station. The GPR voltage difference is applied to the transformer primary. The secondary windings, in series with the communications lines, are connected in anti-phase so their transformed voltage opposes the GPR voltage difference. Ideally the communication line transformed voltage and the GPR voltage difference cancel out, neutralising the GPR voltage difference.

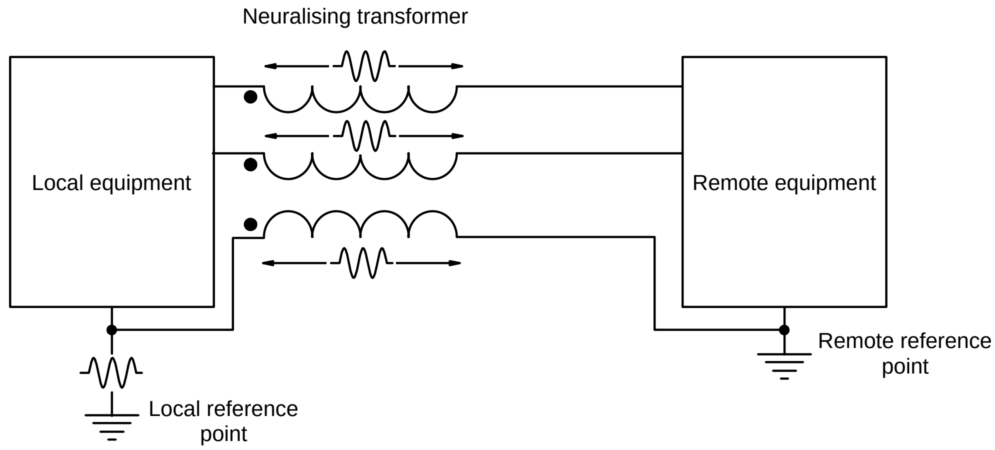

Figure 11—Neutralising transformer common-mode surge mitigation

6.2.3 EMC choke

The EMC choke is a current operated transformer that reduces the propagation of a common-mode surge. Reference: Ronald B. Standler Ph. D., *Protection of Electronic Circuits from Overvoltages*, Dover Publications, December 2002, chapter 12D: Common-mode choke.

Rather than a “choke”, EMC chokes are actually two winding transformers. For a twisted pair each winding is placed in series with a conductor and poled (phased) to give a transformer action that presents high impedance to common-mode signals and low impedance to the wanted differential signal. Coaxial cables can be wrapped round a magnetic core to give the same effect. Typically these transformers are wound on a toroidal magnet core, in Figure 12 this is shown by the “Z” shaped core symbol. A reference points at both ends of the cable provides the return path for the common-mode surge current in order for the EMC choke work.

Transformer core saturation can result in additional stress conditions as described in Maytum, M.J., Howard, K.: *Increased surge voltages caused by EMC chokes*, 1997 International Symposium on Electromagnetic Compatibility, pp 519 – 522

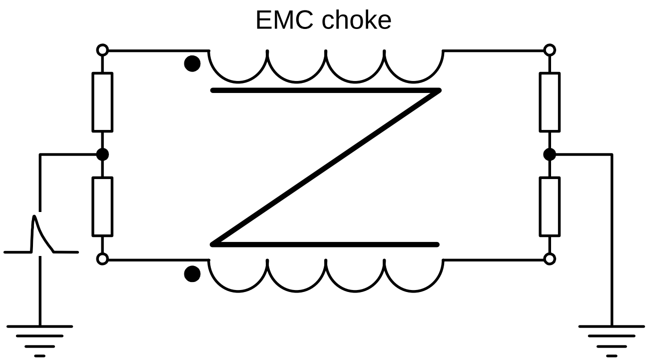

Figure 12—EMC choke common-mode surge mitigation