ELECTRIC POWER
RESEARCH INSTITUTE

PQ Encyclopedia

*A product of the EPRI Power Quality Knowledge program*

# Electromagnetic Shielding:
# A Power Quality Engineering Perspective

Chapter 21

## CONTENTS

*Alfonso G. Tarditi, EPRI*

## SUMMARY

The objective of this chapter is to outline the relevance of the electromagnetic shielding concepts and techniques for electric grid power quality (PQ) applications. Examples are presented to show where properly implemented shielding practices are essential to ensuring the grid functionality from a PQ perspective. After a description of some basic concepts, this chapter focuses on those PQ aspects where the shielding technologies can ultimately ensure operations with minimal disruptions.

## About the Electric Power Research Institute

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery, and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety, and the environment. EPRI also provides technology, policy, and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

## About the EPRI Power Quality Knowledge program

The EPRI Power Quality Knowledge program provides a wealth of resources in well-designed, readable, and accessible formats. Paramount among these are documents covering a wide range of PQ topics, written not only for use by busy PQ professionals, but also to be shared with important end-use customers and internal utility management. The program's website, http://mypq.epri.com/, is the most comprehensive electronic PQ resource available, providing 24-7 access to proven expertise via the PQ Hotline, hundreds of PQ case studies, over 300 EPRI-authored PQ technical documents, PQ standards references, indexes, conference presentations, and a wealth of other resources.

For more information, please visit http://mypq.epri.com/.

3002002221

**The impact of shielding best practices can be significant, if not essential, to maintain the desired PQ target level during the highly variable conditions in which the grid is operating.**

## INTRODUCTION

This chapter discusses the relevance of electromagnetic (EM) shielding concepts in the context of power quality (PQ) engineering. It is not intended to be a replacement for the numerous books on electromagnetic compatibility (EMC) that provide dedicated chapters to EM shielding (such as C. A. Paul's *Introduction to Electromagnetic Compatibility* and H. W. Ott's *Electromagnetic Compatibility Engineering*) or more specialized books focused entirely on EM shielding itself (as in *Electromagnetic Shielding* by S. Celozzi, R. Araneo, and G. Lovat).[1] Thus, after a brief compendium on the basic concepts, the focus of this chapter is shifting to the aspects of EM shielding that are considered important for power quality in today's electric grid environment. Finally, selected application examples are outlined.

EM shielding is traditionally a topic that is introduced as part of the EMC engineering curricula. However, its applications are quite diverse, ranging, for example, from the traditional areas of radio transmissions and electronics design to, more recently, issues related to human exposure to EM fields and telecommunication security (where signal leaks, channel crosstalk, and conditions that would allow signal "sniffing" must be avoided).

The PQ main realm of operations is related to high-power systems (since a goal of PQ is to ensure nominal conditions on distribution or transmission power lines) and large fluctuations of electric and magnetic fields, without dealing with the propagation of electromagnetic waves. On the other hand, shielding, like most EMC topics, is traditionally focused (mostly) on techniques related to low-level EM fields, typically leaks or unintentional transmitted or received signals, and is certainly not focused on impacting large power flows. However, PQ may be affected directly by shielding issues in some situations. The impact of shielding best practices can, in fact, be significant, if not essential, to maintain the desired PQ target level during the highly variable conditions in which the grid is operating.

## BASIC CONCEPTS

### Definitions

#### EM Shielding

A standard definition of *EM shielding* can be found in *The Authoritative Dictionary of IEEE Standards Terms*, and essentially it refers to the ability of reducing the level, and therefore the effects, of electric and/or magnetic fields in a particular region of space.[2] A more general definition may be expressed as in *Electromagnetic Shielding* by stating that EM shielding encompasses "any means used for the reduction of the EM field in a prescribed region." This definition is preferred because it does not entail any reference to a specific geometry, like the presence of a specific domain or a separation boundary.

Implied in these definitions are the concepts of source, propagation channel or medium, and target, all in reference to "unwanted" EM signals. Thus shielding can be effective, in principle, if proper techniques are applied in any combination of the following possible scenarios: (1) limiting a signal at the source, (2) obstructing its propagation path, or (3) isolating the target from the incident EM energy.

Shielding, as much as the rest of the electromagnetic compatibility discipline, revolves then around "unintentional" signals versus those that are meant to be properly transferred and coupled. This distinction is typically being done on the basis of the signal frequency, although sometimes the amplitude is the discriminating factor, as in the case of surge protection.

Beyond the academic value of this classification and nomenclature definition, the concept of *unintentional versus intentional* EM coupling is important from a design and operational engineering perspective because it impacts directly, for example, the selection of components like filters, cables, protection circuitry, and grounding and bonding techniques.

### Power Quality

The International Electrotechnical Commission defines *power quality* as "characteristics of the electric current, voltage and frequencies at a given point in an electric power system, evaluated against a set of reference technical parameters."[3]

The concept of power quality has a somewhat subjective connotation, because the term *quality* requires some standard or reference to be used as a term of comparison. Following the book *Electrical Power System Quality*, a "power quality problem" is defined as "any power problem manifested in voltage, current or frequency deviation that results in failure or misoperation of customer equipment."[4] According to this definition, and for the purposes of this work, it can be stated that the level of power quality should be measured against the severity of the occurrence of undesirable behavior in an electrically powered device. This essentially provides a criterion for defining a PQ figure of merit. Its definition is obviously dependent on the specific case, in the same way as it occurs, for example, in the EMC standards specifications for emissions and susceptibility.

## EM Shielding General Scenario

### EM Coupling

**The ultimate purpose of shielding is, in general, to avoid electromagnetic coupling between a source of electromagnetic field and a target to be protected.**

Although, according to the definition adopted here, shielding consists of reducing the level of the EM field (in a particular region), its ultimate purpose is, in general, to avoid EM coupling between a source of EM field and a target to be protected.

In some cases, this source is not necessarily well specified, such as for a sensitive device to be shielded against noise (the noise source could be anywhere and may vary). Conversely, in other examples the target is not well specified, as for the case of shielding a transmitting antenna power cable (which has the primary purpose of delivering all the available power to the antenna, preventing any radiation along the connection) or for the shielding of a high-security area outside of which casual or intentional signal reception must be avoided. Finally, in some cases, both source and target are well defined: for example, the primary and secondary windings of a shielded isolation transformer, or sections of a heterodyne radio where different stages are operating at different frequencies.

EM coupling in the form of unintentional transfer of electromagnetic energy from one electric circuit to another is then the basic physical phenomenon that shielding is attempting to prevent.

An EM perturbation (a "signal") can travel through conducting media (typically wires, but also pipelines, railways, and ground paths) and in space. The distance through which these signals can propagate, and their levels at the location of interest, are affected both by the frequency and by the characteristic impedance of the propagation medium.

This, along with the EM susceptibility characteristics of the equipment or system to be protected, is what fundamentally determines the shielding requirements. In other words, the necessity for shielding implies that there is some form of undesired EM coupling between a "source" and a "victim" (referring to common EMC jargon).

This coupling can occur, in general, everywhere in the EM frequency spectrum, all the way down to DC. For electrostatic fields, for instance, the protection against electrostatic discharge is a very common example, and for magnetic fields, there are many instances where sensitive instruments—for example, electro-medical devices or precision manufacturing devices using electron beams—need to be magnetically

Static electric and magnetic fields refer to an established pattern in space of EM potential energy, often visualized through “field lines of force” or vectors.

Shielding is a complementary engineering practice to filtering.

shielded (not just from static but also from low-frequency magnetic fields) to ensure the required level of performance.

## Propagation of EM Signals

The general features of the propagation of the EM signals from static fields to high frequencies are here reviewed to provide a direct reference for the concepts that are being discussed.

**DC (Direct Current, Static Fields).** Static electric and magnetic fields (thus not including any transient required to set them up) refer to an established pattern in space of EM potential energy, often visualized through “field lines of force” or vectors. This pattern is determined by the distribution in space of the field sources (charges for the electric field and electric currents[5] for the magnetic field) and, for the electric field, by the presence of conductors and the ground (that, conceptually, is just another conductor). Similarly, the topology of a static magnetic field pattern is affected by the presence of materials with high magnetic permeability.

There is no “propagation” issue in reference to a static field: The field levels measured at the target location (that is, the equipment or area to be shielded) will determine the shielding requirements at the lower end of the frequency spectrum.

**Quasi-static, Power Frequency, and Audio Frequency Range.** For very low frequencies, the scenario is similar to that of static fields, in that the propagation effects are negligible compared to the space scale determined by the EM wavelength[6] that in this case is much larger than the characteristic dimension of any structure or equipment under consideration. This holds for most applications, including transmission power lines extending for several hundreds of kilometers.

In other words, quasi-static fields can be considered as if their time variations were propagating instantaneously in a region significantly smaller than the wavelength. However, unlike the static case, the time-dependent character of the fields determines the presence of magnetic induction effects that increase, in general, the complexity of the shielding requirements.

From the perspective of signal propagation, the lack of (meaningful) radiative effects implies that almost no energy will be transferred at a long-range distance (many wavelengths) as an EM wave. The transfer of energy at low frequencies occurs typically through conduction currents (in wires) and via magnetic induction, thus occurring on a short range (much less than a wavelength).

**Radiating, Low-Frequency Range.** Electric and magnetic field oscillations at frequencies approximately in the 100-kHz range and higher begin to manifest radiative effects that are significant for practical-sized structures. At the same time, conduction currents begin to be affected by parasitic reactances present in long conductors, which may provide a filtering effect at some frequencies, in some cases. In general, at these (and higher) frequencies, the propagation in a conductor should be accounted for from the point of view of a transmission line, the properties of which can be impacted by a particular choice of shielding technique.

**High-Frequency Regime.** Above the 10-MHz range, the dimensions of most equipment and systems are comparable or larger than the wavelength. In this situation, unshielded conductors easily become efficient radiators. At the same time, the propagation along wires becomes more heavily affected by the parasitic reactances, and signals are carried through shielded cables that are chosen by design as the proper transmission line.

## The Physics of EM Shielding

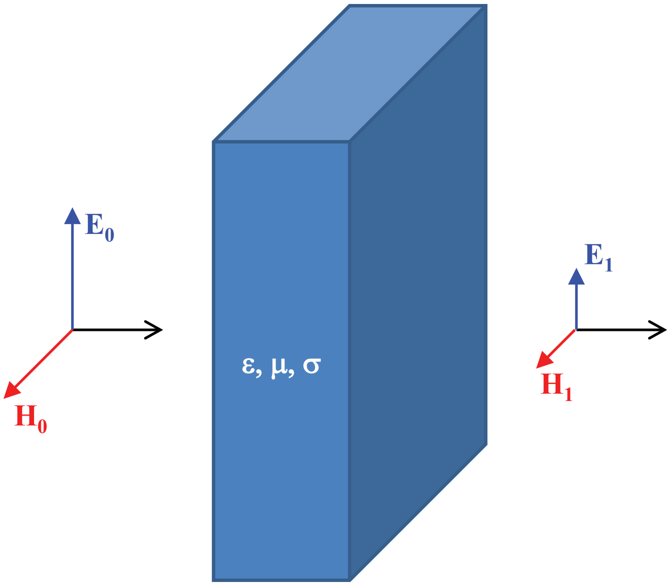
Shielding is a complementary engineering practice to filtering. Where shielding starts to become ineffective, a filter can be inserted in the circuit to be protected. Conversely, if filtering is not effective enough—for example, when noise in some frequency range is conducted away from the source—shielding can be introduced to minimize undesired effects.

**Shielding effectiveness is one of the basic parameters to characterize how well a shield is performing.**

Shielding effectiveness is one of the basic parameters to characterize how well a shield is performing. This general concept was originally developed in S. A. Schelkunoff's *Electromagnetic Waves* from the perspective of a transmission line.[7]

Considering the general shielding scenario that refers to the reduction of the EM field in a particular region, let $E_0$ be the amplitude of the electric field component of the EM wave incident on the shield, and let $E_1$ be the corresponding component that is measured in the protected region, past the shield (that is the "transmitted" field component). Let also $H_0$ and $H_1$ be defined in a similar fashion for the magnetic field component (see figure below). Then shielding effectiveness is defined as $SE_E = E_0/E_1$ and $SE_H = H_0/H_1$, respectively, for the electric and magnetic fields.

**Geometry of Shielding Effectiveness**



The basic geometry for defining the shielding effectiveness is shown with electric and magnetic field wave components before ($E_0$, $H_0$) and after ($E_1$, $H_1$) passing through a shielding material.

For notation simplicity, the shielding effectiveness for the electric field will be discussed and referred to as *SE*. As it is customary in EM engineering, SE is often expressed in decibels (dB), thus $SE_{\mathrm{dB}}=20\cdot\log_{10}(E_0/E_1)$.

The concept of shielding effectiveness can also be analyzed more in detail by considering the example of a shield made of a solid, homogenous material of constant thickness (thus, neglecting imperfections, apertures, and boundary effects). In this case, the SE can be derived observing that transmitted field $E_1$ is attenuated as the result of three combined effects: an energy loss of the EM wave due to absorption in the material (its attenuation in dB will be indicated with $A_{\mathrm{dB}}$), a reflection due to the discontinuity at the shield surface (indicated with $R_{\mathrm{dB}}$), and a combined effect due to multiple reflections occurring along paths in the interior of the material thickness ($M_{\mathrm{dB}}$). In summary, it can be written $SE_{\mathrm{dB}} = A_{\mathrm{dB}} + R_{\mathrm{dB}} + M_{\mathrm{dB}}$.

The analysis of these three different terms provides a description of the shielding properties of a generic ideal shield. The first two, absorption and reflection, are the most relevant ones and are discussed here in more detail; the contribution from multiple reflections can be neglected when the shield thickness is much greater than its skin depth, as defined below.[8]

In general, the shielding effectiveness is a function of the frequency $f$ of the incident EM wave, of the material thickness and of its fundamental electromagnetic properties: the dielectric constant ε, the electric conductivity σ, and the magnetic permeability μ. These properties characterize completely a particular material from the point of view of its interaction with EM fields.

The absorption loss as the EM field traverses a material through a distance $x$ decreases exponentially as $\exp(-x/\delta$, where $\delta = \sqrt{(2/\omega\mu\sigma)}$ is called the skin depth, and $\omega = 2\pi f$ is the angular frequency (see, for example,

**For a good conductor, the shielding contribution due to energy losses in the material is larger than for an insulator and these losses become more pronounced at higher frequencies and for "magnetic" materials.**

*Classical Electrodynamics and Introduction to Electrodynamics*).[9] Thus $A_{dB} = 20 \cdot \log_{10}(e^{-x/\delta})$.

From this expression, it can be easily seen that for a good conductor, the shielding contribution due to energy losses in the material is larger than for an insulator and that these losses become more pronounced at higher frequencies (where the skin depth gets smaller) and for "magnetic" materials, where the permeability $\mu$ is higher. For example, for copper, at 60 Hz it is found $\delta = 0.85$ cm. Thus, to provide even a factor of 100 in absorption loss (40 dB), a thick sheet of almost 4 cm would be required, clearly not an economical choice. On the other hand, at 1 MHz, copper has $\delta = 76\mu m$. Thus, a shield of only 0.35 mm provides an attenuation of 40 dB.

The particular pattern of the incident field must be taken into account for the description of the shielding effect due to the EM field reflection (the "reflection loss"). The analysis of the EM field propagation across a discontinuity (as in *Introduction to Electrodynamics*, for example, in this case applied to the vacuum-shield interface) yields a simple expression for the reflection loss contribution $R$ to the shielding effectiveness expressed as proportional to the ratio between two wave impedances. More precisely, it is found that $R = Z_w / (4Z_s)$, where $Z_w$ is the norm of the wave impedance of the vacuum (or other medium where the wave is propagating) and $Z_s$ is the norm of the impedance of shield material.[10]

In the conditions where the EM field propagates, even approximately—as a plane wave radiating in space (typically referred to as far-field conditions)[11]—the wave impedance $Z_w = E/H$ is equal to the constant $Z_0 = \sqrt{(\mu_0/\varepsilon_0)} = 377$ ohms (in a vacuum, but in air as well). The impedance of a good conductor (defined as a material where, for a given frequency, $\sigma >> \omega\varepsilon$) is $Z_s = \sqrt{(\omega\mu/2\sigma_0)}$.[12] Because $Z_w$ is a constant, $R$ can be determined by the dependence of $Z_s$ on the physical parameter of the shield material.

Thus for an EM wave incident on a conducting shield, $R$ gets larger for higher conductivity but decreases both for higher frequencies and for higher magnetic permeability materials.

When the field is not propagating as a radiated wave, the near-field conditions are being considered and typically occur at a distance from the source that is small compared to the wavelengths. In this case, the field pattern cannot be properly represented as a wave, and the electric and magnetic fields ($E$ and $H$) are primarily determined by the characteristic of the source (antenna), rather than by the propagation medium.

For near-field conditions, the wave impedance $Z_w$ can be higher than $Z_0$ for "electric" sources, like a dipole or a straight-wire antenna, in the vicinity of which the field is predominantly electric ($E/H > Z_0$), as near a capacitor. Conversely, for a magnetic loop antenna, $Z_w$ is lower than $Z_0$, and the near field is predominantly magnetic, as near an inductor.

Because the reflection loss $R_{SE}$ is proportional to $Z_w$, then for a given shield material, a magnetic field in the near field ("large" wavelength, thus lower frequency) is less attenuated than the magnetic field for a wave in a far field (higher frequency), because $Z_w < Z_0$.

Considering also the previous discussion about the absorption losses, this explains why low-frequency magnetic fields are not shielded well by conductors (both absorption and reflection terms are low). On the other hand, the low-frequency electric field in the near-field region is reflected more than in the far-field for an EM wave ($Z_w > Z_0$), and thus the conductors are very good electric shields for low-frequency and electrostatic fields.

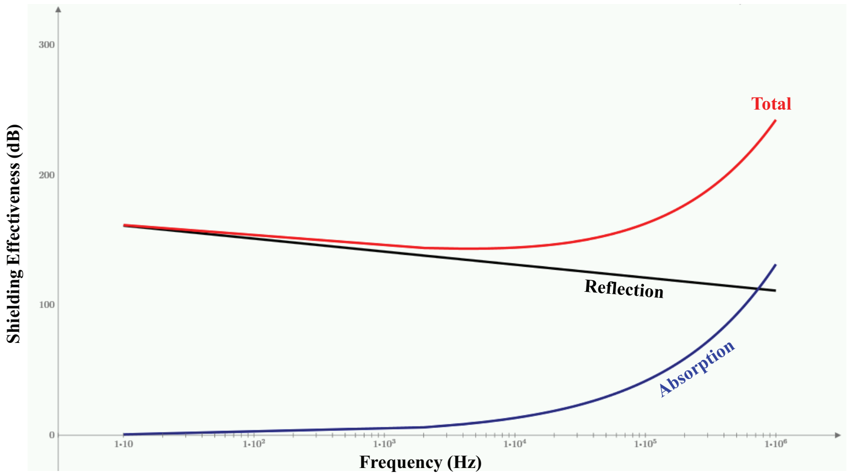
The use of high-$\mu$ materials improves the magnetic shielding performances. However, it is important to consider that the magnetic permeability in general decreases with the

**The presence of a good shielding material does not necessarily guarantee good shielding performances.**

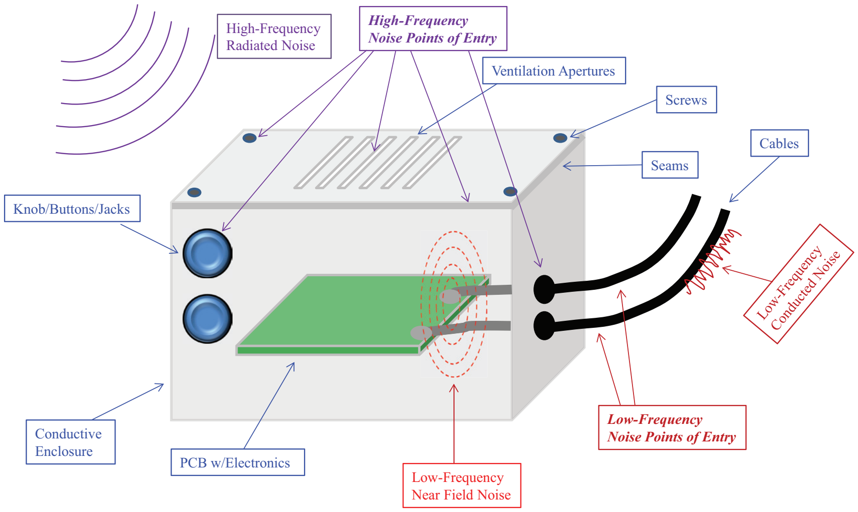
frequency, and it has a nonlinear response to the magnetic field intensity. Typically, high-µ materials are not very effective above 10 kHz.

A summary of the overall shielding effect, including both absorption and reflection, for a particular case of a copper layer is shown in the figure below.

**Shielding Effectiveness vs. Frequency for a 1 mm-thick Layer of Copper**



**Access Points for Noise in Electronics Shielding Enclosure**



This electronics shielding enclosure shows the typical entry points for high-frequency and low-frequency noise.

## Non-Ideal Effects in EM Shielding

### Apertures, Joints, and Gaskets

The presence of a good shielding material does not necessarily guarantee, in practice, good shielding performances. Non-ideal effects must be taken into account, such as the presence of apertures, due to the necessity of the insertion of cables through the shield, ventilation, and accessibility. Other examples of these non-ideal conditions arise from other mechanical constraints that prevent the utilization of a continuous layer of material and require the presence of joints of conducting surfaces and/or electrically conductive seals (gaskets or soldering).

The necessity of providing shields in the low-frequency range (typically considered less than 10 MHz) arises mainly due to the presence of cables and wiring that can carry undesired low-frequency signals from a long distance all the way to the "victim" circuitry, as a conducted emission. This can then become a source of noise due to radiated emission in the near field. In other words, the low-frequency propagation is typically less important due to typical poor efficiency of "unintentional" radiator structures. When higher frequencies become a concern, the apertures and discontinuities in the shielding structures should be considered primary sources of signal leakage. A summary of this discussion is illustrated in the figure to the left.

A variety of techniques allow the determination of the shielding requirements and related best practices, depending primarily on the frequency of the signal to be shielded. For example, the Institute of Electrical and Electronics Engineers (IEEE) published a document to provide guidance for the utilization of conductive gaskets and related measurement techniques in a wide frequency range (DC to 18 GHz). More in general, many publications and the references therein can be consulted for details about the analysis of processes of shields in the presence of apertures and a discussion on specialized techniques.[13]

Shielding effects are independent of grounding; however, grounding is implemented for safety reasons.

### Grounding Requirements for Shields

A shield is meant to limit the EM field in a protected area, essentially providing a Faraday cage effect for the electric field component. A shield can also reduce the amplitude of the magnetic field component, either through an oppositely directed field generated by eddy currents, or by redirecting the magnetic flux by using a high magnetic permeability material.

Thus, the described shielding effects are independent of grounding. However, grounding is implemented for safety reasons, to provide a low-impedance return current path in case of an isolation fault from the mains, for example. Grounding is also preventing the accumulation of static charge and the establishment of a potential difference between the shield and the inside components/circuitry that can become itself a source of noise or possibly cause damage to highly sensitive electronics.

The requirements for shield grounding can vary, depending on the shield topology and the frequency of operation.[14]

From an overall general grid perspective, PQ is affected only when perturbing events can impact large power flows.

### Unconventional Materials

Shielding can be performed with materials other than "conventional" conducting and/or magnetic materials; recent developments on this topic are reviewed in *Electromagnetic Shielding.*[15] These technologies refer to "active" magnetic shielding (mainly for power frequency fields) that work by injecting currents in properly designed coils to cancel the resulting field in a target area. Other examples are "partial shielding" techniques and "chiral shielding," where materials, both natural and artificial, have complex constitutive relations that link electric and magnetic field vectors with each other; a related concept is referred to as "metamaterial shielding," artificial material with specific EM properties built in by design.

## IMPACT OF SHIELDING ON POWER QUALITY

### Shielding and PQ: Different Typical Areas of Influence

In first approximation, the electric grid can be considered a network of high-power generators. In other words, a first-approximation Thevenin-equivalent of the power grid can be considered an ideal voltage source with a very low resistance in series. Thus only events involving sufficient power levels are going to produce noticeable variations of its main nominal parameters (voltage and frequency). For example, from a PQ perspective, the grid voltage control requires countering sags and overvoltages. These are the result of "high energy events," like phase faults, large loads switched on- or off-line, or power factor corrective actions.

Frequency fluctuations are also the result of "high energy events" that affect large generation plants. Thus, it can be concluded that, from an overall general grid perspective, PQ is affected only when perturbing events can impact large power flows.

On the other hand, at the same general level EM shielding is typically related to "small energy" events, since the amount of energy in EM field leaking from a source or unintentionally present in a particular location is typically small (except for large-scale accidental events, against which shielding is not likely to be effective). While shielding is also part of power installations, like long-range radio transmitters, for example, the shielding process itself does not typically require modifying intense EM fields.

In general, then, it appears that PQ shielding and EM shielding are focused on separate electrotechnology areas: the former high-power, and the latter low-power. Upon a more careful analysis, however, important correlations can be identified, as outlined in the following sections.

**Any correlation between PQ and EM shielding should refer to how shielding techniques can impact the ability to control the line voltage, the power frequency, and the harmonic content.**

## Links Between Shielding and PQ

Power quality engineering ultimately is focused on controlling three main parameters: the line voltage, the power frequency, and the harmonic content. (For the first two the goal is to maintain the nominal level; for the third the goal is to keep it at the minimum level.) Thus, any correlation between PQ and EM shielding should refer to how shielding techniques can impact the ability to control these three parameters.

Voltage sags and swells are the large-scale manifestation of loss of PQ affecting the line voltage; these phenomena are primarily due to:

- Load variations (utilization-level triggered events)
- Current faults (mainly environmental-triggered events)
- Reactive power compensation banks insertion (utilization-level triggered events)

While the first case, load variations, is no factor for the purpose of this discussion, since it does not relate to the presence or effectiveness of any shield, the second and third cases are relevant.

For the case of current faults, partial shielding techniques implemented for lightning protection of both transmission line and substation structures are beneficial (more details are presented later in the section Applications) to prevent large transients or faults on the grid. Also, a current fault may induce, via magnetic coupling, damaging voltages onto adjacent, unshielded circuits (such as railroads in a right of way).

In the case of reactive power compensation banks insertion, shielding is relevant, for example, when considering capacitive coupling of voltage "ringing" on power lines, to prevent potential hazards even in the case of locally grounded, adjacent conducting structures.

While evaluating the impact of these scenarios, it must be considered that, in general, as shown in the earler section on the physics of EM shielding, low-frequency magnetic fields are difficult to shield, and, at the same time, can induce hazardous voltage levels (both for humans and for electronics) in conductive structures. Capacitively coupled circuits are more easily protected (shielded) with a conductive enclosure (essentially providing a Faraday cage effect). However, proper grounding of the shield itself must be considered for safety reasons (an example for power cables is discussed in the Applications section).

Finally, in order to complete the analysis of the possible correlations of shielding concepts with PQ events, the impact of shielding on the stability of the nominal value of power frequency and harmonics will be addressed. Frequency stability is mainly affected by large load variations and generators being switched on-line. For these scenarios, shielding is not a factor. Vice versa, frequency fluctuations are not directly related to EM emissions that would require shielding.

Generation of power-frequency harmonics (as in nonlinear loads) can lead to spurious conducted or radiated emissions that require shielding (mainly for the protection of electronics in the audio band). A case-specific analysis is required for a proper assessment of shielding requirements (in many cases, filtering may be the most appropriate choice). The analysis should consider the propagation characteristics for different frequencies on transmission and distribution lines and the actual impact of shielding in relation to harmonics generation in a nonlinear load.[16]

## The EMC Perspective: Shielding and PQ Link Through Grid Security, Communications, EMP, and EMV

The electric power grid is a taken-for-granted, increasingly critical infrastructure for almost every aspect of modern society; it is also becoming more and more vulnerable to

**As the power grid management system grows and relies increasingly on telecommunication systems, the relevant shielding guidelines must include those practices for high-frequency communication channels that used to be exclusively in the realm of the telecommunication infrastructure.**

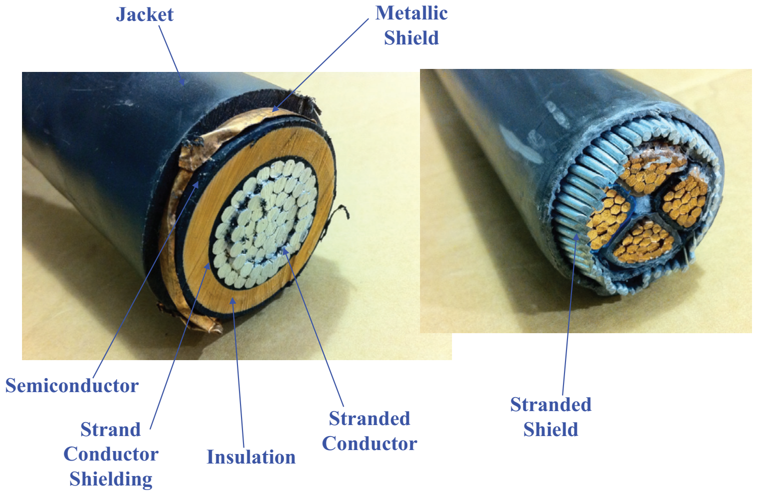
electromagnetic (EM) disruptions, from both possible intentional attacks and natural threats, as its operations increasingly rely on sensitive electronic equipment.

The timeliness of these issues is enhanced by the ongoing technologic transformation toward a "smart grid," based on a close interaction between the electric grid and telecommunication infrastructures and its reliance on electronic control and data processing.

As the complexity of the power grid management system grows and relies increasingly on telecommunication systems, the relevant shielding guidelines must also include those practices for high-frequency communication channels that used to be exclusively in the realm of the telecommunication infrastructure.

To this regard, new vulnerability factors can be identified: one is the lack of EM protection standards specifically designed for the power grid, and another is the increased availability of tools and techniques for producing intentional EM interference and a localized, small-scale EM pulse (EMP), both with high damaging potential.

**Internal Shielding of Power Cables**



These cross sections showing the internal structure of different power cables illustrate metallic and semiconductor shields

EM shielding of critical grid components is becoming an essential aspect of any technology-oriented program that aims to address the power grid's immediate and most critical EM vulnerability (EMV) issues. The impact of EMV on PQ is quite direct; in fact, PQ represents a figure of merit to gauge the relevance of potential due to EM disruptions.

Short-term significant improvements of the EM resilience of grid-critical infrastructures (both power grid and data communication) can be implemented through both shielding and filtering (such as protections against surge levels), with emphasis on critical electronics and sensors. The utilization of optical (EMI immune) technologies can also be considered as an advanced form of shielding, because the propagation medium (the optical fiber) is physically preventing the EM coupling at any frequency generated either as noise or in telecommunications.

## APPLICATIONS

### Shielding of Power Cables

Shielding is required for underground transmission and distribution power cables, for the purpose of improved mechanical strength and electrical safety. Cable shields can be made of metallic sleeves (sheaths) or tight-braided wires surrounding the primary insulator (see figure to the left).

The electrical safety aspect of the shield is related to an insulator fault condition. In this case, the shield offers a shunt path for the fault return current toward a chosen grounding location that can be effective for triggering a breaker. Furthermore, with the presence of the shield shunting effect, the ground surrounding the cable does not carry a current, which can potentially be dangerous if a sufficiently high elevated ground potential is generated.

For electrical safety reasons (not for shielding effectiveness reasons), the cable shield needs to

**A single-ended grounding of power cables would avoid losses due to high currents but presents a risk due to the high-voltage rise at the nongrounded end.**

be grounded. Otherwise, the shield would rise to a high potential due to capacitive coupling from the phase conductors. This condition, besides representing a touch-hazard for maintenance or accidental contact during excavation operations, would also cause a faster degradation of the insulator properties (for example, due to triggering of corona discharges).

If the grounding is done at both ends, there will be a current flowing through the sheath that can possibly cause excessive ohmic losses. One solution is to utilize a sheath with higher resistance and several grounding points along the cable length to minimize the potential buildup in the case of a current fault. A single-ended grounding would avoid losses due to high currents but presents a risk due to the high-voltage rise at the nongrounded end.

As long as the shield is grounded, the electric field is restricted to the region internal to the cable, surrounding the phase conductor. The presence of a shield enforces an azimuthal symmetry in the electric stress to which the insulator is subjected (the field is directed radially and is symmetric with respect to the azimuth of the cylinder). The field is then confined in a known region, where a proper insulator material, chosen by design, is present. From a transmission line impedance point of view, the shielded cable shows constant impedance per unit length, with respect to its longitudinal coordinate, which provides protection against the localized effects of overvoltages (since no localized, high potentials can be formed).

**The transformer electrostatic shield redirects to ground common-mode noise that otherwise would be coupled to the secondary.**

Semiconductor materials are also used for shielding in high voltage cables.[17] These materials provide a smooth cylindrical surface instead of the irregular profile given by a stranded wiring, thus avoiding the possibility of a localized electric field that may pose stress to the insulation. A variety of construction methods, materials, and design guidelines that depend on the properties of the cable exist (for details the specialized literature should be consulted).[18]

Besides power applications, the most common application of cable shielding is for low-voltage communication links, to avoid signal interference due to inductive coupling. In this case, however, grounding at both ends of the cable is required. For shielding electric (capacitive) coupling effects, grounding the conducting shield at either end is sufficient. A continuous (versus braided wire) conducting shield can provide some magnetic shielding due to induced eddy currents, although its effectiveness depends on the frequency.

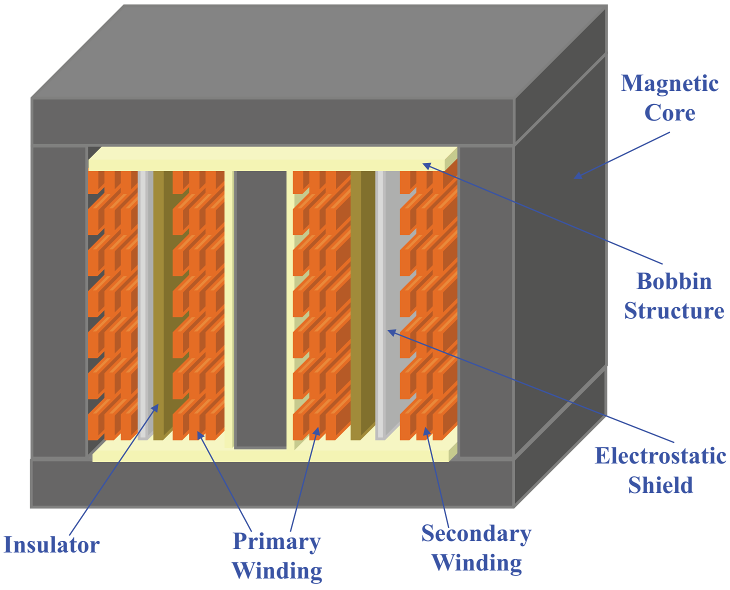
### Transformer Electrostatic Shield

In general, noise can have normal or common-mode characteristics. The former refers to a signal between the line, or “hot,” and the neutral. The latter affects both phase wires and is referred to the ground conductor. The transformer electrostatic shield redirects to ground common-mode noise that otherwise would be coupled to the secondary.

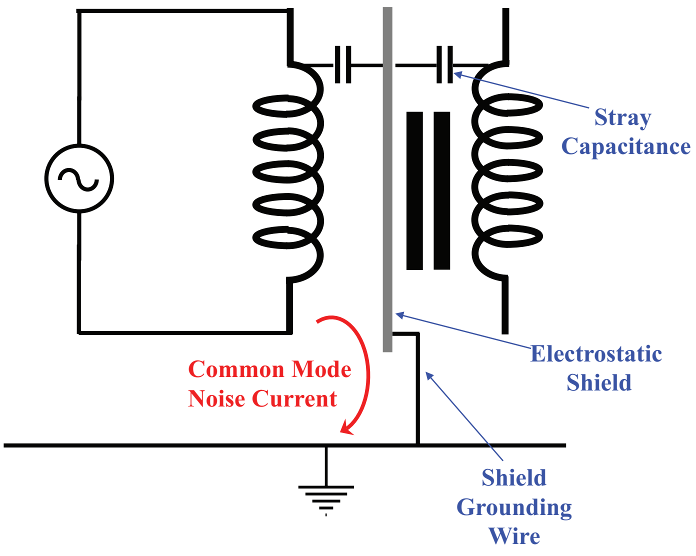
A conducting shield (typically copper or aluminum) can be inserted between the primary and secondary to prevent this coupling. In practice, the shield is wrapped around the secondary winding with the primary as the outer layer (see figure on the top of the following page). The shield is grounded so that the high-frequency noise components will find a lower-impedance path to ground through the shield (see second figure on the following page).

A shielded transformer is particularly relevant for protecting sensitive electronic systems from transients and disturbances on the mains. Noise or pulsed waveforms (like surges) with a significant high-frequency content (compared to the power frequency) can be transferred from the primary to the secondary of a transformer

**Sketch of Electrostatic Shield Inserted Between Primary and Secondary Windings**



**Basic Schematic for Transformer Electrostatic Shield Connection**



on a path different from the magnetic coupling. A capacitive coupling can in fact effectively transfer noise in the secondary (or vice versa), whereas the magnetic coupling, due to the large inductance of transformer windings, would not be effective due to its intrinsic low-pass filtering characteristics.

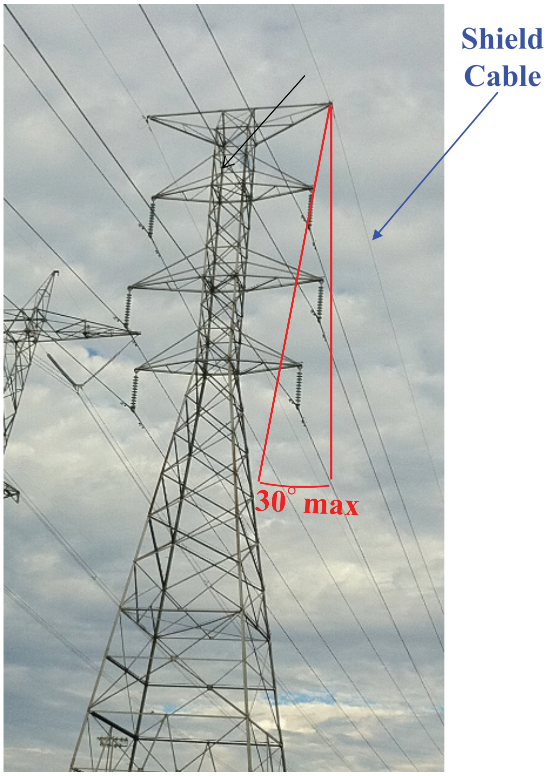
## Shielding and Lightning

Shielding is used in overhead power lines as part of an effective lightning protection system (LPS). A conducting wire properly placed above the power conductors of a transmission line, and properly grounded through the towers, provides an electrostatic shielding effect for charged clouds that may generate lightning strikes directed toward the transmission line. As a rule of thumb, the angle between the furthermost power wire and the vertical plane containing the shield wire should be 30 degrees or less.[19] This is schematically shown in the figure on the following page.

The shield wire also provides an additional parallel ground path that reduces the impact of the induced phase-to-phase and phase-to-ground overvoltages on the power lines due to direct strikes to the towers. This occurs because during the overvoltage transient some of the current is shunted by the shield wire, which provides an alternate path to ground (through the next adjacent tower).

A further protection effect is provided on the insulators. When hit by a lightning strike, the shield cable carries a voltage pulse to ground. The adjacent phase conductors are then subjected to a potential rise, due to capacitive coupling, with a similar waveform as is present on the shield, thus reducing the electric stress on the insulators near the lightning current path to ground.

### Guideline for Positioning of Lightning Protection Shield Cable on Power-Line Pylons



Similar considerations can be made for the substation protection cables. In general, an LPS provides a preferential, controlled path for a surge current through a grounded electrostatic shielding. For this purpose, the shielding does not need be a complete enclosure of the protected structure. Because of the localized character of the lightning discharge, and its predominant downward pattern, simple models have been devised that allow the design of the LPS based on the geometry of the structure to be protected (electro-geometrical models).[20]

## CONCLUSIONS

PQ and shielding technology best practices, while traditionally related to quite different areas of the grid operations, also have been shown to be strongly correlated for the purpose of managing grid-level disruptive events on a large scale.

Furthermore, an indirect link between EM shielding and PQ is related to the increasing dependence of the power grid on automatic and computer-assisted grid operation management, with particular reference to the introduction of the "smart grid" technologies. In this case, a small shielding problem, for example affecting a sensor, or on a long coaxial cable carrying information to a SCADA device, may be sufficient for triggering a wrongly directed corrective action, with a potential large impact at the power utilization level.

A fundamental contribution that can be derived from applying an EMC perspective to the power grid is a systematic approach in determining how grid components can coexist within a given electromagnetic environment.

This condition will ensure that components will not be causing mutual interactions affecting negatively the ability to provide electric service that maintains the nominal PQ parameters in all circumstances. Thus, the link between shielding technology and PQ is just part of the link between EMC and PQ: Shielding is a pervasive practice at all levels of EMC, and ultimately PQ assurance represents the goal that justifies and calls for the integration of the EMC discipline in PQ engineering.

## NOTES

1. C. A. Paul, *Introduction to Electromagnetic Compatibility*, Wiley (2006); H.W. Ott, *Electromagnetic Compatibility Engineering*, Wiley (2008); S. Celozzi, R. Araneo, and G. Lovat, *Electromagnetic Shielding*, Wiley (2006).
2. *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition, The Institute of Electrical and Electronics Engineers (2000).
3. International Electrotechnical Commission, *International Electrotechnical Vocabulary Online*, reference #617-01-05, www.electropedia.org.
4. R. Dugan, M. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power System Quality*, 3rd edition, McGraw-Hill (2012).
5. Permanent magnets and magnetized materials are still generating a magnetic field due to the presence of an electric current, albeit due to a microscopic current at the atomic level, where the elementary magnetic dipoles are produced by the net current due to the electron distribution in the atomic orbitals. While in conventional materials these dipoles are randomly oriented and their effect is canceled out, in a magnetized material (natural or induced) there is a macroscopic alignment of the atomic dipoles along one dominant direction.
6. For example, for 60 Hz the EM wavelength is about 5000 km: any practical structure will be "small" (electrically short) compared to this wavelength.
7. S. A. Schelkunoff, *Electromagnetic Waves*, Van Nostrand (1943).
8. Paul [1].
9. J. D. Jackson, *Classical Electrodynamics*, Wiley (1999); D. J. Griffiths, *Introduction to Electrodynamics*, Prentice Hall (1999).
10. Paul [1]; Ott [1]
11. Ott [1] C. A Balanis, *Antenna Theory*, 3rd ed.,Wiley (2005).
12. Jackson [9]; Griffiths [9]
13. Paul [1]; Ott [1]; Celozzi, Araneo, and Lovat [1]
14. For a detailed discussion on this matter, consult the references in note 1.
15. Celozzi, Araneo, and Lovat [1]
16. W. Thue, *Electrical Power Cable Engineering*, CRC Press (2012).
17. Thue [16]
18. Thue [16]
19. A. Baggini (editor), *Handbook of Power Quality*, Wiley (2008).
20. R. H. Golde (editor), *Lightning,* Associated Press (1977); V. A. Rakov and M. A. Uman, *Lightning: Physics and Effects,* Cambridge Univ. Press (2006).

## Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

**The Electric Power Research Institute, Inc.** (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

3002002221

**Electric Power Research Institute**
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com