Assessment of Present Electric Utility Electromagnetic Compatibility Needs

Hardware, Software, and Technology Gaps

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Hardware, Software, and Technology Gaps

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ABSTRACT

This work provides an introduction to the application of electromagnetic compatibility (EMC) to the electric power utility sector. There is a significant technology gap of a knowledge-based nature since, traditionally, power grid engineering has not been significantly affected by EMC issues. Also recognized is the requirement for the development of an EMC standard properly tailored to present and projected near-future needs of power grid technology.

The definition of this standard and related test methods will also provide more insight into the specification of specific hardware requirements as well as software tools that are required in support of a dedicated EMC analysis for power grid systems and components. The need for the integration of current software tools, which were developed for the analysis of the power grid at the system level, with EMC-related modeling capabilities has also been recognized and is being considered as one of the essential elements for guiding the development of the power grid EMC standard.

Keywords

Electromagnetic compatibility
EMC standards
Smart grid

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INTRODUCTION: EMC FOR THE ELECTRIC POWER UTILITY

This chapter outlines the main technical issues that illustrate the importance of EMC in the context of today's power grid technology.

1.1 The Definition of Electromagnetic Compatibility (EMC)

The International Electrotechnical Commission [IEC, 1990] defines electromagnetic compatibility as: "the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment".

EMC is a far-reaching discipline that affects virtually all applications in the field of electrical engineering. The term electromagnetic compatibility is commonly referred to along with electromagnetic interference (EMI). The acronyms EMC and EMI are often interchanged or used together, although they refer essentially to opposite takes on the same issue. The IEC also defines electromagnetic interference as "degradation of the performance of an equipment, transmission channel or system caused by an electromagnetic disturbance".

Following [Paul, 2006], a system is said to be electromagnetically compatible with its environment if the following conditions are met:

- It doesn't cause interference with other systems
- It is not susceptible to emissions from other systems
- It doesn't cause interference with itself

EMC deals with system or equipment (electromagnetic) emissions and susceptibility (also referred to as *immunity*, especially in European standards) both for conducted and radiated signals. The four areas that categorize the EMC standards are then: radiated emissions (RE), conducted emissions (CE), radiated susceptibility (RS), and conducted susceptibility (CS).
In general, two or more electrical devices (from a single component to a large, complex system) are considered "electromagnetically compatible" with each other when they function according to their design specifications while sharing the same environment. For this to occur, in practice, the electromagnetic signals generated by each device, or from the environment, shall be limited in amplitude in a way that avoids disturbances on all the other devices, while at the same time each device should be designed to tolerate some level of interfering signals.

Compliance with EMC standards typically facilitates the design of an electrical system, both industrial and consumer, that maintains its functionality when different components, or subsystems, share the same electromagnetic environment.

EMC always relates to a system where a "source" and a "receptor" (sometimes referred to as "victim") can be identified: the source is the device or component that produces the emissions, and the receptor is the device or component that may be affected. This condition does not necessarily require the presence of two (or more) separate devices or components. In other words, a system should also be designed to ensure "self-compatibility," that is, its own circuitry should not interfere with the system's ability to provide functionality within design specifications (as the third item of the aforementioned criteria indicates).

It is important to understand that EMC deals only with "unintentional" transmission and reception of signals, regardless of how they propagate from the source to the receptor (Figure 1.1). For example, the signal of a radio broadcasting station becomes an EMC concern only if its signal impacts an apparatus that was not tuned, or not designed to receive, that signal. The apparatus in this case is an "unintentional receiver". Similarly, a 180 Hz, third-harmonic signal present on the mains represents an EMC concern because it is a spurious signal "unintentionally transmitted" on the power line.

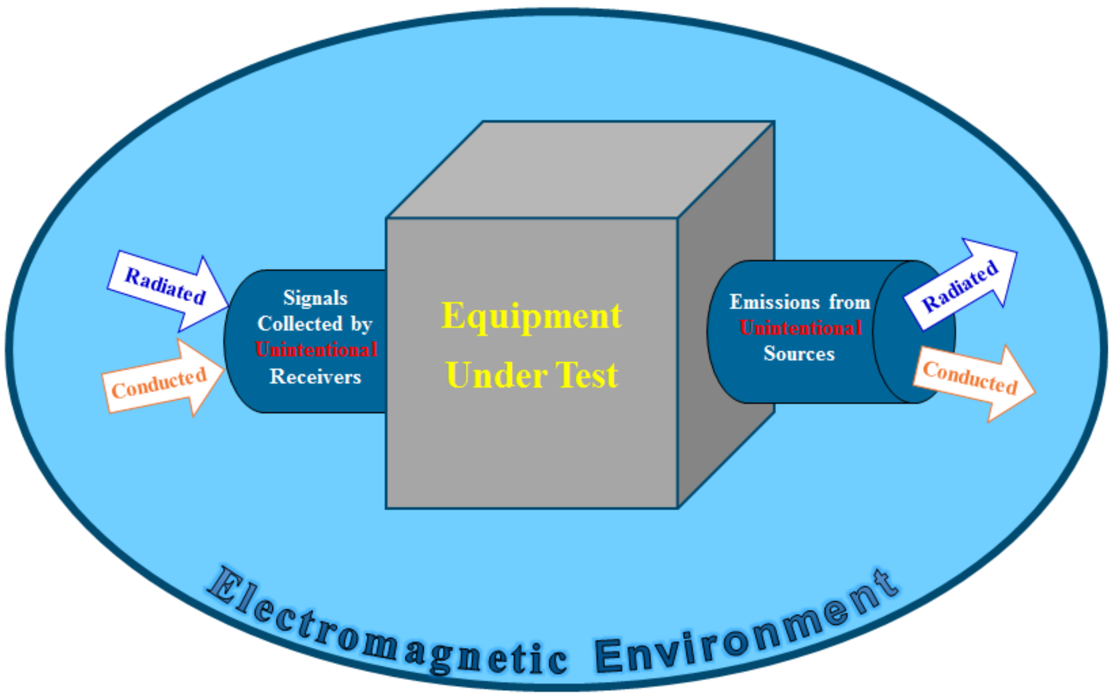

Figure 1-1
General Scenario for Electromagnetic Compatibility

1.2 EMC Relevance in Different Industry Sectors

EMC plays a well-established, essential role in different engineering sectors (for example, aerospace, defense, and electromedical devices). In all of these cases, the essential function of EMC is to provide properly-customized standards to which any design should comply to prevent potential malfunctions. As part of the standards, test methods are described to allow for compliance verification (a typical example is the widely adopted MIL-STD-461 standard, [DoD, 2007]).

The overall rationale of this “EMC system” is that, in an environment where all the devices meet the limits prescribed in the standard, the operations should be not affected by EM interference. There are two important *caveats*, however.

One is a subtle issue about the “consistency” of the EMC standard (considered for a particular class of products/systems): the standard prescriptions, in fact, will typically ensure that the emission levels (measured at a given distance) are much less than the susceptibility thresholds. However the system cannot be “fail proof” in that two systems can be close enough to each other to cause interference.

The second one is related to the definition of the environment: typically, the electromagnetic environment is defined within certain parameter ranges such that systems in that environment would function properly. However, for situations that fall outside the description of the environment itself, one or more devices may be subject to interference.

An example could be the case of a lightning strike: if the definition of the environment does not include lightning (or only up to a certain level) it is quite possible that the consequence of a strike of sufficient magnitude would affect the functionality of some devices.

The last consideration is related to the relevance of EMC: the typical outcome for all fields of engineering where EMC has important application has been that, with the increase in electronic complexity of devices, EMC moved from being a useful tool to a necessity.

1.3 Growing Presence of EMC Issues in Power Grid Engineering

Based on the previous considerations, it is possible to identify several areas of technology for the power industry where EMC is becoming increasingly important.

For example, utilities are considering potential issues regarding the increased use of wireless communication devices in power plants and substations: because of their increasingly large numbers, the transmitting power levels, and the broad range of frequencies utilized, there is concern regarding interference between analog and digital control systems in close proximity.

These concerns are especially critical for nuclear power plants and are closely related to the issue of *exclusion zones*—areas where equipment having EM transmitting capabilities is not allowed. The definition of *exclusion zones* will affect where nuclear power plant operators can have wireless communication devices. The cost of implementing such limitations in nuclear power plants, especially near critical safety systems, is high due to the level of testing required and the complexity of the systems.

Nuclear power plants continue to rely on analog control electronics. EMC potential issues were considered when fossil plants were upgrading to digital controls. Nuclear plants require higher safety standards and the installation of digital systems requires approval by the US Nuclear Regulatory Commission (NRC). Specifically, the NRC requirements call for the EMC mapping of the entire plant before a new device that is potentially sensitive to EM field can be installed.

Because of technology improvements and demonstrated advantage in term of speed and control capability in a variety of industrial processes, digital systems are now being installed in nuclear power plants as well; however, a large amount of analog legacy systems remain in place and would need to be upgraded.

There is also a need for standards for emissions control and susceptibility requirements in the 2-150 kHz frequency range where inverters, adjustable speed drives, and switched-mode power supplies create conducted disturbances on power lines. Such disturbances have been found to affect *smart* meters, communication systems, and electronic controls (There is in fact a current IEC effort in progress on this matter towards a standard under the classification number 61000-4-19).

New challenges also arise for power quality (PQ). To be discussed more in detail in Section 2**,** PQ needs a broader context for identifying the solutions required by the fast-evolving grid technology. As the substation begins to more resemble a data center than a conventional electric grid facility, the goal of maintaining a high level of power quality now becomes more dependent on ensuring electromagnetic compatibility (EMC) of grid components and systems that control the substation operations. In this context, as it will be illustrated in Section 3, EMC guidelines are required to support a smooth implementation and growth of smart grid technologies.

In general, from an electric utility perspective, EMC issues can be referred to as:

- Grid system-level EMC: power grid EM interaction with the environment

  Examples are:

  - (emissions) power line affecting railway electronics in a shared right-of-way corridor
  - (emissions) possible impact on human health of power grid-generated EM fields
  - (susceptibility) EM events from the natural environment (lightning, geomagnetic disturbances)

- Grid subsystem-level EMC (grid self-compatibility): emissions and susceptibility limits required for different components linked together or sharing the same environment

  Examples are:

  - generation of harmonics affecting end-user loads
  - local power line fluctuations causing faulty reading on sensors connected to a remote load-optimization control hub

1.4 EMC for the Electric Utility: Historical Perspective on EPRI R&D

EMC may not be an established area for the electric utility sector, but it is not a new area, either: several EPRI projects span more than 20 years. Typically, this work was supported mainly on an “as needed” basis, rather than being part of a well-defined program. A chronology (to be considered non-exhaustive) is presented in Table 1-1.

Table 1-1
EPRI Projects with EMC Focus

1994:	EPRI TR-102400, "*Handbook for Electromagnetic Compatibility of Digital Equipment in Power Plants, Volume 1 and 2*"
1999:	EPRI TR-113093, "*Power Quality and Electromagnetic Compatibility Case Studies for the Healthcare Industry*"
2002:	EPRI 1005416, "*Electromagnetic Interference Emission Measurements Near FACTS Devices"*
2004:	EPRI *1008709,"Measuring & Managing Substation EMC"*
2006:	EPRI 1012652, "*Power System and Railroad Electromagnetic Compatibility Handbook*"
2008:	EPRI *1016729, "Program on Technology Innovation: Minimizing the Risk of Electromagnetic Interference in Modifying Power Plants and Mixed Control Equipment"*
2010:	EPRI 1021092, *"Technical Guidance for Achieving Higher Levels of Electromagnetic Compatibility for Advanced Nuclear Power Plants: Addressing the Electromagnetic Compatibility Challenges for Reliable Plant Operation."*
2011:	EPRI 1022984 "*Assessment of Electromagnetic Interference Events in Nuclear Power Plants*"
2013:	EPRI 3002000102*, "Turbine-Generator Topics for Power Plant Engineers: Fundamentals of Electromagnetic Signature Analysis"*

2

A TECHNOLOGY RETROFIT: INTRODUCING EMC TO MEET TODAY'S POWER GRID NEEDS

This chapter outlines the main technical considerations making EMC an important aspect of today's power grid technology. One important justification for the interest in EMC relates to its impact on Power Quality. EMC is also becoming essential in grid operation control, for example in relation to interferences potentially affecting electronics at different levels (e.g. wired and wireless communications, digital data processing, sensors, and SCADA systems).

As mentioned in Chapter 1, electrical distribution is dealing with EMC issues for power lines next to railways, and in long, shared right-of-way corridors. Important EMC issues for power generation may be found in both conventional and nuclear plants (susceptibility of electronics in the control room and sensor links).

Finally, it is important to note that there is an open environmental issue related to the investigations on potential effects of EM fields, both low- and high-frequency, on human health; while this technically may not be an EMC problem, it falls within the realm of Electromagnetic Environmental Effects (E3, introduced in Section 2.1).

2.1 EMC in the Context of the Electromagnetic Environmental Effects (E3) Discipline Tailored for the Electric Utility

By looking at the entire span of technologies designed for the electric power grid, adopting only an EMC perspective may appear to be too restrictive, as some of the key problems simply do not belong to EMC. Arguably, the most appropriate framework for analyzing the impact of EMC-related disciplines on power grid technology may be that of the Electromagnetic Environmental Effects (E3) discipline, which includes, but is not limited to, EMC.

More specifically, and following [DoD, 2007b], the *electromagnetic environment* is defined as "*resulting from the power and time distribution, in various frequency ranges, of the radiated or conducted electromagnetic emissions*" and *electromagnetic environmental effects* are defined as "*the impact of the electromagnetic environment upon the operational capability of military forces, equipment, systems, and platforms*".

Still quoting from the U.S. Department of Defense definition, E3 "*encompasses all electromagnetic disciplines, including electromagnetic compatibility and electromagnetic interference; electromagnetic vulnerability; electromagnetic pulse; electronic protection, hazards of electromagnetic radiation to personnel, ordnance, and volatile materials; and natural phenomena effects of lightning and precipitation static*" [ibid.]

Clearly, the E3 concept is not unique to military applications and can be easily extended to other fields (as has happened in the aerospace sector)—including the power grid. In this context, from a general standpoint, typically an E3 issue is *the cause* and the PQ manifestation is the *resulting effect*. Examples are lightning strikes, insulator flashovers, and perturbations ("ringing") due to large capacitors inserted on-line. Other examples of non-EMC topics (besides those named in the DoD definition) included in the E3 approach for the power grid are, for example, corona and arc discharges and geomagnetic disturbances (GMD in Figure 2.1).

Figure 2-1
Electromagnetic Environmental Effects (E3) Topical Areas--Overview

2.2 EMC for Grid Operations

Today's grid operations are "morphing" into a smart grid environment. Guaranteeing the reliability of electronics controls against "PQ events" as well as natural disruptions becomes a priority. Furthermore, a related issue of growing importance is the vulnerability of the electric grid system to intentional electromagnetic disruptions (EM vulnerability, EMV).

In general, electronic systems operating near large power loads and transmission lines, and the coexistence of complex digital high-speed circuitry, telecommunication devices, and power electronics, represent a fertile environment for EMC problems (Figure 2.2). Increasing system dependence on electronics will also result in increased susceptibility of the system itself to conducted and radiated electromagnetic interference.

Current technologies being used that would benefit from EMC-integrated design and best practices are: solid-state relays and controllers, sensors (including their data link), SCADA electronics, and data communication (wired and wireless, not just for sensors, but typically digital information).

These devices are particularly critical when operating in the following EM environments:

- Substations (due to high-voltage components with coronas, high-current surges, and switching transients)
- Transformers (for possible high-harmonic content if driven in anomalous saturation conditions)
- Proximity of high-power RF antennas (commercial radio and TV stations, cellular phone towers)
- High-voltage transmission power lines (large electric induction fields, particularly during unbalanced line conditions following a fault)
- Mobile radios in close proximity

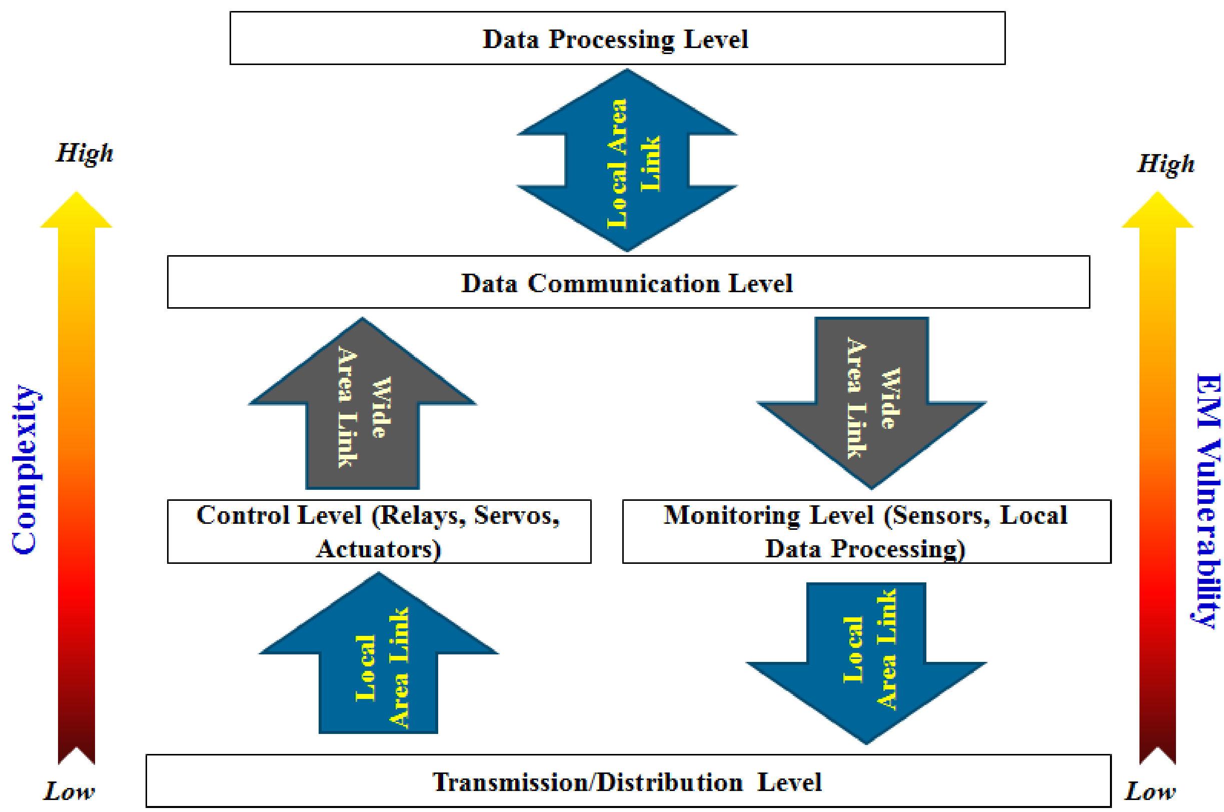

Figure 2-2
Complexity vs. Vulnerability of Multiple Power Grid Technology Levels

As a general rule (due to the propagation characteristics of EM waves), potential EMC issues affecting equipment are related to radiated susceptibility (RS) at higher frequencies, and conducted susceptibility (CS) at lower frequencies. For RS, a first-level assessment should identify possible RF point of entry (apertures, if shielded enclosures are present) and unshielded components and cables. For CS, the focus should be on any unfiltered power supply connection to mains, and other cables (especially if unshielded and long).

A hypothetical example could be a high-power, silicon-controlled rectifier (SCR) control unit with the gate being controlled by low-voltage electronics. A disturbance either near the unit or carried by a connecting cable may be interpreted by the control electronics as a signal to trigger the gate, thus closing a circuit at the wrong time.

Another critical situation could be that of a PQ monitoring and control architecture relying on a variety of sensors with itself being connected to processing electronics and to a signal transmission network (wired or wireless). In this case, a disturbance near a sensor or along the data transmission channel may trigger, for instance, an incorrect reactive power correction.

Based on these considerations, an EMC assessment related to grid operations hardware should look for the presence of:

- proper EM shielding (that includes proper grounding practices) of critical components (effective for their operation frequency range)
- EMC-aware design of the cabling layout (for both power and data) and its physical characteristics (shielded and not).

2.3 EMC for power quality

This section illustrates the correlation between EMC and PQ as one of the main drivers for bringing EMC concepts to the electric utility. As illustrated schematically in Figure 2.3, not all EMC issues affect PQ, and not all PQ events may cause EMC issues, but they are both included within the E3 perspective.

In general, power quality is actually determined by the "quality" of the voltage waveform made available at the power mains. This analysis focuses on how electrical systems and equipment design following EMC principles can positively affect and ensure PQ.

The assertion here is that, with an EMC-aware design and with testing of power grid components, fewer disturbances and outages will occur, thus improving PQ. In other words, the goal of maintaining power quality is also dependent on ensuring electromagnetic compatibility of relevant components and systems.

The utility distribution lines, even at the lowest, single-residence level, are able to support loads on the order of a few kilowatts. Disturbances that affect the quality of the wave shape at the utility line must then have fairly significant power even to be noticeable. In other words, the power line behaves like a generator with very low internal impedance—any coupling disturbance must be generated at a comparable level of low impedance to impose variations of the voltage waveform. The same point may be made from a power availability perspective: a low-power generator will not be able to support voltage waveform variations on a bus connected to a high-power source.

This reality may set aside at least some of the PQ applications from the general EMC approach: often, in fact, EMC problems are related to disturbances that are coupled to sensitive instruments, where small, stray signals may be amplified enough to produce undesired effects on equipment functionality (the interference on a radio receiver is a classic example). In the situation that has been presented, in other words, the perturbation of a power system requires another power system.

A good example is that of the lightning strike scenario: while the duration of a lightning event is very short (multiple strokes, each lasting tens to hundreds of microseconds), during the discharge, an extremely large power (not so much energy, but delivered in a very short time) is transferred to the "load" represented by the conducting path between the stroke attachment point and the ground (in reference to a cloud-to-ground discharge). Voltages in the tens of megavolts and current in the tens of kiloamperes are typical: the lightning becomes a powerful generator delivering close to a terawatt (TW or 10^{12} W) of power. The high current generated in the discharge produces an intense and rapidly varying magnetic field that couples to the local grid and induces an electric potential transient that can alter the waveform drastically.

From an EMC perspective, a lightning strike (to ground, for example) that is coupled inductively to power lines shall be regarded as a radiated susceptibility problem: the *source*, the lightning current, is emitting energy that couples inductively to the *receptor*, the power grid line. The "radiated" attribute stems from the fact that the coupling path between source and receptor is free space, not a conducting path, although the coupling actually occurs in the near field, without an actual EM wave radiation.

In the case of lightning striking the power line wires (directly or through an insulator flashover), the proper EMC framework is that of conducted susceptibility. The "susceptibility" refers to how much the grid can tolerate this "unwanted" energy from the lightning current path without losing its nominal performance conditions.

The state of the power line, and therefore PQ, can be affected in other ways without requiring large power events. In some applications, power electronics may be used in devices on the grid that can be switched on or off or controlled by low-power inputs. The presence of an amplification stage of some kind (even a relay can be considered as a rudimentary amplifier) makes a system immediately more sensitive to perturbations, and standard EMC design guidelines should be applied to ensure proper functionality.

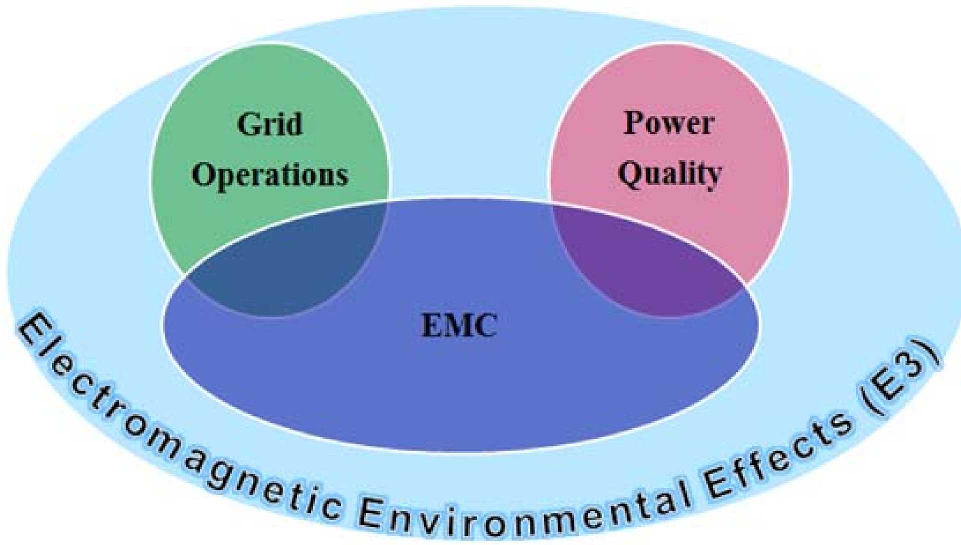

Figure 2-3
Relationship between EMC and PQ

For example, the gate of a high-power silicon-controlled rectifier (SCR) can be controlled by a sensor wired from a remote location: a disturbance either near the sensor or along the connecting line may be interpreted by the control electronics as a signal to trigger the gate, thus closing a circuit at the wrong time. The power required to produce the perturbation may be negligible, but the effect on the power system is significant. The actual disturbance coupled on the sensor could result from the interference due to conducted or radiated emissions, but the effect on the gate of the SCR is a conducted susceptibility issue (because the sensor is wired).

Continuing with this line of thought, another connection between PQ and EMC is related to PQ monitoring devices and related circuitry. The PQ monitoring infrastructure relies on a variety of sensors connected to processing electronics and to a signal transmission (wired or wireless) network. On the other side of the network, there will be a receiver/control setup (even if used only periodically). An EMC issue affecting the monitoring system (from the sensor to the control room) may also be directly reflected in the power quality. For example, the installation of a new cellular phone tower may directly interfere with a short-range wireless communication path of sensors causing unreliable or faulty readings that call for reactive power correction loads to come on or off the grid at the wrong time.

Another example could be a receiver (wired or not) for a remote current sensor near a conductor carrying a large current. Without an EMC-aware design, sudden, large current variations could cause a false reading.

Another possibility is that events similar to the last example would trigger a larger disruption (a major PQ issue). This would occur if the faulty monitoring is part of a positive feedback loop where a false reading, signaling excessive current load, would call for a generator to come on-line while the resulting transient couples to the receiver, causing an additional false reading in the same, wrong direction. If a situation like this were to occur, it would likely be a rapidly evolving instability event, where the dynamics could go undetected and the only noticeable signature would be the occurrence of a fault of some kind. Proper implementation of CS and RS standards is required to prevent these conditions.

3
EMC FOR THE SMART GRID

This chapter is focused on the relevance of EMC for the projected, near-future large-scale implementation of smart grid technologies. In general, it is expected that a "smarter" grid will require more strict EMC guidelines due to the co-existence of power lines, sensors, data communication, and processing. Another justification for a dedicated EMC approach is that, in a complex environment, EMC "fixes" are generally more costly and less effective than preventive design and testing.

3.1 Definition for the Smart Grid

The International Electrotechnical Vocabulary [IEC, 2011] defines the smart grid as follows:

> *Electric power system that utilizes information exchange and control technologies, distributed computing and associated sensors and actuators, for purposes such as:*
>
> *– to integrate the behaviour and actions of the network users and other stakeholders*
>
> *– to efficiently deliver sustainable, economic and secure electricity supplies.*

The IEC further elaborates on the meaning of smart grid as "the concept of modernizing the electric grid. The Smart Grid comprises everything related to the electric system in between any point of Generation and any point of Consumption. It also includes the coupling effects with other forms of energy (thermal storage, etc.)".

In a recent roadmap publication [IEC, 2010], the IEC also observes that the smart grid has become more a marketing term, rather than a technical definition. The current technical consensus and de facto trends indicate that the present evolution of power grid monitoring is leading toward a widespread integration of digital communication (both wired and wireless) and processing technology.

In principle, this would allow a highly localized monitoring of the grid status and the ability to perform real-time or as-needed optimization of generation, power delivery paths, and characteristics of overall end-user electrical load. This technology upgrade tying together generation, distribution, and utilization is indeed commonly referred to as "smart grid."

The common trend towards the development of a "smart grid" infrastructure calls for an enhanced interaction among different components of the electric power system: on one end, at the generation level, the proper response to load variations must be in place; on the other end, the utilization level, the customer must be provided with a nominal level of power quality (within a set variance range), a high level of dependable service, and a fast recovery from power outages. The intermediate level, i.e. the transmission and distribution infrastructure, represents the means of ensuring this functionality.

The communication to and from the consumer level is going to play a critical role in the overall planning and managing of grid operations. The ability to collect timely data on end-usage levels and their patterns—supported by an adequate information technology infrastructure comprised of telecommunication, data storage/processing, and data analytics—would allow for the "intelligent" management of grid resources. Overall improvement of reliability, energy efficiency, and customer satisfaction (both in terms of quality of service and economy) would result. Within this large-scale picture, the smart meters—the upgraded version of the revenue meters—represent the natural interface with large numbers of customer installations.

Such infrastructures have already been designed, tested, and in many areas, implemented, allowing a large number of smart meters to operate and communicate in a mesh-network environment. In the United States, the typical implementation of this network relies on wireless communication — organized in a similar fashion to the cellular telephone network. The smart meters designed for this application utilize radios operating in the high-frequency region of the EM spectrum, near the frequencies allocated for cellular telephones.

The smart meters can communicate directly with a receiving concentrator node, or with another smart meter nearby depending on the radio wave propagation condition that may favor one connection versus another. This design allows for maximum flexibility in the deployment and installation of the network, providing high reliability for communication in both high-density urban environments, and rural, sparsely populated areas.

3.2 Near-term developments and the need of EMC guidelines and standards

Following the smart-grid evolution perspective, the near-future power utility new "look" features ubiquitous spreading of control electronics, sensors, and data communication channels (see Figure 3.1, introducing also the Internet of Things as a natural follow-up to the smart grid). While this vision opens the door to many enhancements in terms of efficiency, resilience, improved power quality and outage prevention, it also creates a new level of electromagnetic vulnerability (EMV, see also Figure 2.2).

As with the evolution of the EMC role in other engineering sectors, such as aerospace and defense, the main goal of EMC integration in the electric power industry shall be the creation of a specifically-tailored standard, including all the relevant aspects of *Smart Grid* technology and the proper strategies for counteracting EMV issues.

Besides some testing recommendations from IEC (publication 61000-4-30:2008), no existing standard may be used directly as a reference for the purpose of designing and implementing smart grid technologies. Without ensuring its proper EMC functionality, a fully-developed, smart grid-based power system may represent an additional burden for the power utility industry, rather than an improvement.

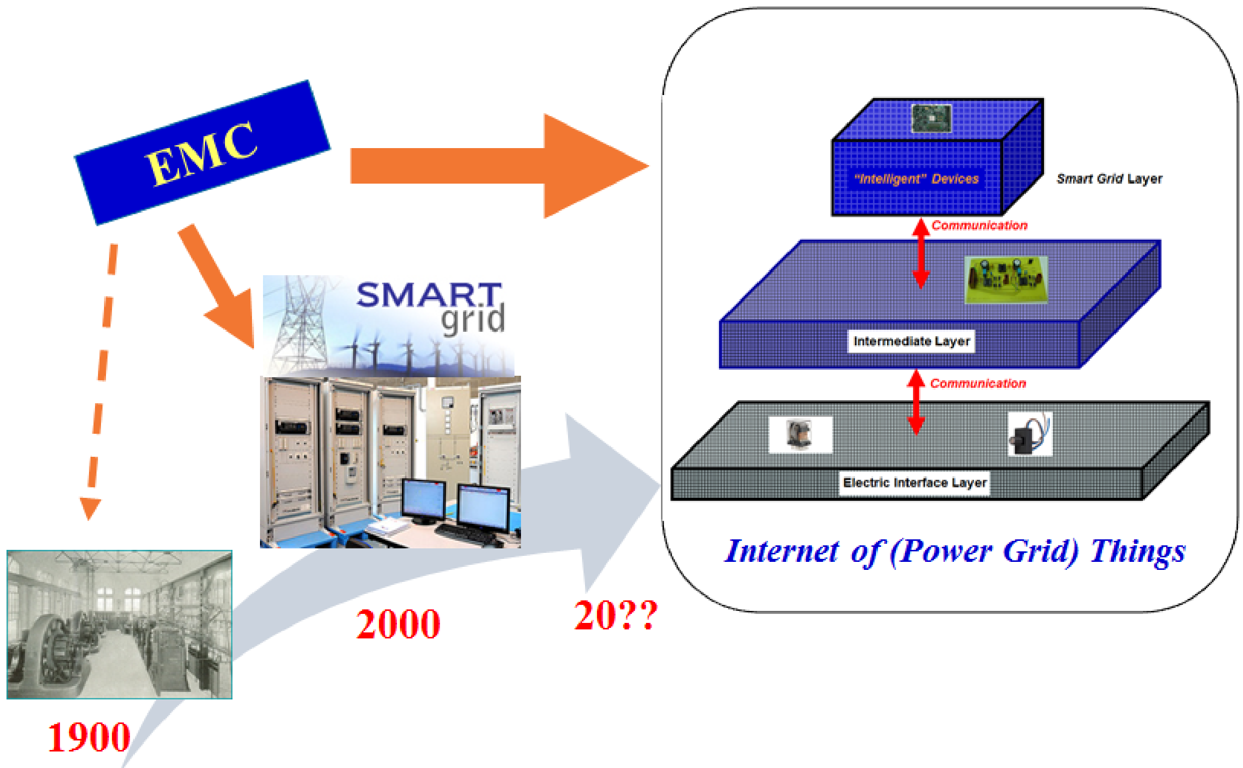

Figure 3-1
EMC Impact in the Evolution of the Power Grid

In the development of smart grid design standards, power quality provides a critical figure of merit in determining what levels of susceptibility (precisely in the EMC sense) can be acceptable before any particular grid component may be declared compliant and acceptable for deployment on the grid. Thus, it would be appropriate to develop smart grid EMC regulatory efforts that include power quality verification techniques as part of the test methods.

3.3 The Equipment Manufacturing Perspective: EMC-Aware Design and Installation of New Smart Grid Technologies

Due to the lack of regulatory standards regarding the smart grid, manufacturers have a wide range of options and they can drive the market toward specific technology choices. In this environment, manufacturers should be made aware that an EMC-compliant design would most likely lead to a product development that is not only ahead of the competition, but would most likely withstand, if not set the reference for, near-future regulatory efforts.

In this situation, a regulatory vacuum may actually favor the development of products that eventually become the model for a de facto standard. Utilities can play an important role in driving choices and manufacturers' designs for products that are specifically geared toward the deployment of smart grid technology.

A set of case studies showing examples of potential problems, or actual malfunctions of smart grid systems related to EMC issues, should be made available among stakeholders in the power grid community to facilitate an effective development of smart grid products that are also robust from the EMC point of view.

Current effective EMC standards in other engineering sectors have been developed based on many years of experience in the field. Manufacturers (and electric utilities) should develop an internal EMC culture that allows the identification and understanding of EMC problems as they occur during product development testing and deployment in the field—an important approach , especially considering that EMC issues are often hard to recognize without the proper technical background.

4

EMC NEEDS FOR THE ELECTRIC UTILITY LAB: HARDWARE TOOLS

This chapter provides a top-level description of the basic hardware tools required for EMC testing in a typical electric utility environment.

4.1 EMC Laboratory Tools for the Power Utility

From an electric utility perspective, the purpose of an EMC laboratory is to provide the capability of conducting basic tests that are recommended for the implementation of new technologies, maintenance, or troubleshooting.

The lack of specific EMC standards related to power grid applications makes the task of providing a consistent set of recommendations for hardware acquisitions and development of test methods difficult. In this case, the proper methodology can be devised on case-by-case basis.

For example, the installation of a new sensor can be considered a typical or representative scenario. The first step is to define the specific electromagnetic environment where the sensor is intended to operate (for example open-air, substation, high-voltage line proximity). Based on that information, an assessment of the peak level of the expected electromagnetic field and its frequency spectrum can be made. A spectrum analyzer represents a basic tool for EMC testing. One or two spectrum analyzers may be required to cover the entire frequency range of interest—possibly from low-frequencies to few GHz. Portable spectrum analyzers are currently available in the market as well.

A spectrum analyzer can be utilized to verify the electromagnetic field levels present in the region where the sensor is going to be installed. A wideband signal generator and a compatible antenna may then be used to generate field levels consistent with the estimated maximum values, and in the given frequency range.

This test provides the opportunity to expose the sensor to radiated emissions having the potential of causing interference. During the test, the sensor should be wired and connected to the monitoring equipment per design specifications. It is critical to be able to determine the proper functionality of the sensor while it is being irradiated in order to detect potential interfering effects.

If the sensor requires a connected power supply, a conducted emissions test can be performed (typically these tests are conducted at a lower frequency level compared to the radiated emissions). For this purpose, coils specifically designed to inject a signal that simulates a conducted emission condition are utilized. These coils (Rogowski-type) are clamped around the power supply wiring and are available from specialized EMC product vendors for different frequency ranges.

In summary, a basic experimental setup consisting of wideband frequency generators, antennas, injection coils, and spectrum analyzers allows a variety of customized EMC tests to be performed both in open-air environments as well as in the laboratory.

4.2 Laboratory vs. in-the-Field Testing

The previous example was developed in reference to the placement of a sensor; however, several other devices may be considered in a similar fashion. For example, a wireless remote terminal unit (RTU) part of a SCADA system can be tested both for radiated emissions at the same transmission frequency utilized for RTU data communication, as well as for low-frequency conducted disturbances on the power wires that could disrupt the operation of the digital electronics.

At this early stage of development of EMC applications to the power utility sector, the definition of the particular tests to be conducted is not prescribed by a standard. Instead, this effort is left to the operator, typically driven by the technical specifications of the device under test and by the assessed characteristics of the EM environment.

The definition of the type of test will lead also to the choice for the location of the test setup; in some cases, the choice is obvious, since the device under test is not portable, or no laboratory can reasonably accommodate its size.

The laboratory environment is typically the most expensive item for the development of an EMC test facility. In general, a shielded anechoic chamber is required to provide both an environment free of external disturbances and one without EM wave reflections when transmitting equipment is utilized inside the laboratory.

Open-air testing, or testing in the field where the devices are actually meant to operate, is often a viable and economical choice, especially with the increased availability of high-end, portable EMC diagnostic instrumentation.

The option of testing in the field is often preferable for power grid applications considering the current lack of applicable standards and the variety of conditions where the grid hardware is required to operate.

4.3 Testing of Critical Assets

EMC testing may pose a challenge because the levels of the fields required are hard to reproduce, for instance, or because the test location is not accessible. The lightning effect test is an example of the former, while the latter case could apply to the diagnostic of partial discharges occurring in the interior of a cable insulator or of a transformer.

Radiated fields at both high intensity and frequency can be produced by high-power military radar systems—these effects are hard to reproduce in an environment other that the actual one that is being examined.

Similarly, lightning strikes can produce both direct and indirect effects corresponding to very high currents, high voltages and waveforms characterized by steep, short pulses (military standards and the Federal Aviation Administration provide specifications for a realistic simulation of the lighting waveform, with a peak to 200 kA).

Lightning pulse simulators are available, typically reproducing either the high-current or the high-voltage aspect of the strike. Some are portable and can be utilized for simulating near-strike lightning conditions, a common occurrence for power grid assets with direct impact on power quality.

In other situations, as previously mentioned, physical constraints may limit the access to the desired diagnostic locations. In these conditions, non-destructive evaluation (NDE) techniques are possibly the only suitable choice.

In this regard, a relatively novel NDE diagnostic technique is available based on EM waves in the THz region of the spectrum. With wavelengths in the millimeter range or less, these diagnostics can provide imaging of the interior of dielectric structures, at selectable depth planes—with a much higher resolution than microwaves—and without posing safety concerns as is the case with x-rays.

5
EMC NEEDS FOR ELECTRIC UTILITY: SOFTWARE ANALYSIS TOOLS

5.1 Software Tools for EMC Applications to the Electric Power Grid

Two fundamental classes of software tools may be considered for EMC analysis: simulation software and instrumentation supporting software.

Simulation tools are typically used in the component device design and test phases (rather than for EMC purposes) to ensure that the design is technically sound and consistent with its basic physical description.

Simulation software, however, can be very useful also as a first-level EMC investigation tool. This should not be used as the primary tool mainly because EMC issues typically result from non-ideal effects, such as EM signal leaks through shielding structures, improper grounding or bonding, EM wave reflections, etc. All these effects, although theoretically well understood, are hard to quantify in practice, especially in relation to a specific device or system (in fact, they are often hard to quantify even from an experimental perspective).

However, for a "big-picture" estimate, design, or worst-case scenario analyses and parametric studies, EM simulation represents an invaluable approach, providing the ability to build a physically sound description of the problem and a framework for interpreting experimental measurements.

As a typical example, quasi-static field solvers, providing the ability to calculate and visualize both DC and low-frequency electric and magnetic fields, are often used for power-frequency simulation studies.

Another common tool, an antenna pattern simulation software (especially those providing both near- and far-field solutions), can be utilized for estimates of the impact of radiated emissions for both large antennas as well as an energized structure, or printed circuit boards.

More general EM field solvers are also available with a custom choice of modules to provide solutions from simple static fields to the full set of Maxwell equations with realistic boundary conditions and material specifications. There are also "multi-physics" packages that allow the specification of custom, complex problems—for example, coupling EM and thermal models.

Most simulation software is currently available in 3D and may run on high-end personal computer hardware for problems of medium-size complexity (i.e., more than just "demonstrations" with simple geometries limited to discretization meshes of few hundreds of nodes). Software for supporting EMC instrumentation provides a high return on the investment (in terms of time savings from an EMC test operator point of view) when the same tests are repeated consistently.

These tools vary from a simple computer interface for a portable or laboratory bench instrument, to comprehensive EMC testing software that operates essentially in automatic mode, allowing for a “hands-off“ EMC compliance test for selected libraries of standards (the test operator is only performing initial setup and monitoring tasks).

Most EMC instrumentation vendors now provide software packages for their hardware, allowing straightforward operations from a laptop-based console. Another common option is to utilize a vendor-provided interface module written for use in general-purpose laboratory programmable data acquisition and instrumentation control packages, where a customized test involving different instruments and specified operation sequences can be programmed.

5.2 Integration of EMC Modules in Existing Grid Analysis/management Software

It is envisioned that present simulation software capable of modeling complex grid interconnects can be upgraded to include EMC capabilities. The development of such an integrated tool will allow a variety of scenarios to be tested—eventually leading to the definition of the proper test methods for EMC testing of the power grid at the system-level. For example, the simulation could model the localized effects of a lightning strike near a large transformer. The associated transient that propagates on the grid can then be evaluated leading to the definition of the proper lightning protection requirements for transformers connected on the grid.

Another example can illustrate how this approach may be utilized with a closer connection to smart grid technology. The grid interconnect simulation tool could be equipped with an additional model that represents the data flow in a typical SCADA system. By introducing a perturbation in the functionality of the SCADA controller, the response of the system can be observed, and, based on that, the proper EMC susceptibility requirements can be defined.

5.3 Data Analytics and Software/hardware Integration

Another important aspect of software development supporting EMC analysis of a system-wide grid level is the utilization of a database built through the introduction of a data analytics approach for grid management. This data collection and database design shall include EMC relevant information at different levels of the power grid infrastructure.

For example, the impact of a particular power quality event on a grid section equipped with electronic controls managed from a remote data center, or that provides data to a monitoring system utilizing a local array of sensors, can provide an EMC characterization that would be otherwise almost impossible to obtain. This data analytics-based process could eventually provide an automatic system that can continuously update an EMC model of the grid at the global level.

6 EMC ANALYSIS FOR THE POWER GRID AT SYSTEM LEVEL

6.1 An EMC Approach to the Analysis of the Power Grid at System Level

This section introduces a different perspective for using EMC tools applied to electric power grid problems. The typical EMC approach focuses on a particular piece of equipment that is being operated in a specified electromagnetic environment (where other devices are present). This approach can certainly be applied directly to a variety of grid components (actuators, sensors, SCADA systems, communication hardware).

However, the grid is extended on a much larger scale than the typical EMC environment of a vehicle, vessel, or building, where different EM devices are supposed to work together without interfering with one another. The EMC approach can then be readily extended to grid systems (or (sub-systems) considered essentially as large devices with a certain level of EM emissions and susceptibility limits within which the system is expected to work properly.

These systems can be substations, power generation stations, or transmission and distribution interconnects. Most of the EMC know-how can be directly applied, with the obvious difference that large-scale systems cannot be tested in shielded or anechoic chambers, although there is really no need for it, since real-life, in-the-field testing is all that is required.

The purpose of this analysis is to provide an overall picture of how the grid can operate as a complex system in the presence of perturbations, while still maintaining the desired range of nominal conditions.

Typical EMC problems involve measurements of emissions or susceptibility of equipment. For a system-level approach, the only difference is the size of the device. For example, connecting large capacitors could cause problems with sensitive loads on the grid, especially those connected in relatively close proximity. This should be regarded as a conducted susceptibility problem, more than radiated, as the perturbation on any load due to the capacitor “ringing” introduced on the mains will be typically much larger than any inductive coupling that can be picked up due to time-varying currents.

In summary, the application of an EMC perspective (with radiated and conducted emissions and susceptibilities) to a large segment of the power grid, considered as a complex system, provides the ability of performing

- Real-time analysis to determine how large grid components (e.g. transformers, substations, generators and large loads) can coexist within a given EM environment
- *Intra-system* EMC of the power grid interconnect, considered as a system itself
- Tests on specific components to verify that mutual interactions are not negatively impacting the ability of maintaining grid nominal parameters

6.2 EMC Transient Analysis at the Grid System Level

Another important aspect of EMC testing is related to transients. Using the IEC definition [IEC, 1990b], a transient is "pertaining to or designating a phenomenon or a quantity which varies between two consecutive steady states during a time interval short when compared with the time-scale of interest".

On a grid global scale, transients are relevant from a power quality perspective, and for this reason, the EMC analysis at the same system level becomes important: typical examples are phase faults that produce a wake of consequences felt across the grid, even over a significant distance.

In general, electrical transients can occur on all electrical systems and can alter their functionality as circuitry is exposed to voltages above design levels. From an EMC perspective, the concern is to ensure that a transient does not degrade equipment performance. However, testing based on injected signals or energized devices in steady-state operation cannot provide a meaningful response. Instead, tailored criteria must be devised for transient waveforms that are considered sufficiently representative of critical conditions for system performance evaluation. The intent of EMC methods that are specific to transients is to protect equipment from the effects of fast rise and fall times produced by switching operations or due to the external electromagnetic environment (including lightning and electromagnetic pulse).

Typically, transient emissions that follow from actuators triggered either by automatic control or manual operations pose a PQ concern: for example, a switching operation to connect a large load onto mains that produces a voltage regulation transient. Direct, manual, on-off switching of equipment is of less concern, as typically the equipment circuitry is designed to handle the effect of the mechanical switching action (e.g., the DoD MIL-STD-461 does not include manual switching transients).

Specific test methods that demonstrate the approach to transient testing are provided in the DoD MIL-STD-461standard. Examples quoted from this standard are as follows: CS106 (a test procedure for the transients coupled onto input power leads), CS116 (conducted susceptibility, damped sinusoidal transients, cables and power leads, 10 kHz to 100 MHz), and CS115 (conducted susceptibility, bulk cable injection, impulse excitation). These test methods are applicable to all connecting conductors from the EUT enclosure to the external environment.

6.3 Planning and Prevention: the Call for an EMC Power Utility Standard

The considerations that have been discussed both in Section 4 and in the present section highlight the necessity of developing an EMC standard that responds to the multifaceted needs of today's power grid technology and that provides the proper framework to support the development of the smart grid in the near future. It is expected that the definition of the standard will occur in several iterations, starting from basic test methods applicable to the most common situations and eventually including more complex and challenging testing conditions.

The primary objective of developing a new EMC standard for the power grid is to facilitate the deployment of electronics-based technologies mainly for smart grid oriented applications.

In this context, it is envisioned that a trial phase of the standard would be issued to cover a selected set of grid assets. In particular, the systemic approach to EMC power grid simulation, which has been outlined in Section 5, provides an ideal test bed that can utilize currently available information on the characteristic response of different grid nodes to specific perturbations on the power lines (mainly referring to power quality events).

7 CONCLUSIONS

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. The EMC classification of disturbances provides a practical and well-tested system for the monitoring and diagnostics of the complex grid environment.

A properly-tailored reference standard is needed to support implementation of the smart grid technology and related engineering practices that explicitly address the new control and communication infrastructure. This standard would flow naturally from an Electromagnetic Environmental Effects (E3) perspective applied to the power grid considered as a complex system.

In this context, power quality becomes the reference goal that provides a metric for the application of EMC standards and the definition of the related test methods. In general, the electromagnetic compatibility of the different systems that collectively constitute the power grid is a necessary—but not sufficient condition—to ensure acceptable power quality. Therefore, a complete definition of the requirements for ensuring satisfactory power quality would pertain to the analysis of the power grid from an E3 perspective.

It is important to eliminate the current knowledge gap between power grid engineering and the field of electromagnetic compatibility and electromagnetic environmental effects. Closing this gap will facilitate the development of properly-tailored EMC standards, the definition of the equipment set suitable for EMC testing performed by the electric utility, both in the field and in the laboratory, as well as the acquisition and development of proper software tools to support EMC analysis of power grid components and systems.

8
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