



SMART GRID INTEROPERABILITY PANEL

Electromagnetic Compatibility and Smart Grid Interoperability Issues

SGIP Electromagnetic Interoperability Issues Working Group

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Contents

1 Introduction 1

2 Electromagnetic Compatibility and the Smart Grid 3

3 Recommendations for EMC Standards and Testing..... 4

4 Recommended follow-on action by SGIP, SDOs and EMII WG..... 7

5 Strategy to maintain EMC as the Smart Grid evolves 8

6 Interaction with other SGIP Committees and Working Groups 9

7 Conclusions..... 10

8 References..... 10

9 Revision History..... 13

 9.1 Contributors 14

10 APPENDIX A – Review of Smart Grid EMC Issues and Standards 15

 10.1 Introduction to Appendix A 15

 10.2 Electric Power Delivery System Electromagnetic Environments 17

 10.2.1 Bulk Generation 17

 10.2.2 Transmission System..... 18

 10.2.3 Distribution System..... 18

 10.2.4 Substations 19

 10.2.5 Control Centers 20

 10.2.6 Distributed Energy Resources (or Distributed Generation) 21

 10.2.7 Communications Systems 21

 10.2.8 Smart Meters and Advanced Metering Infrastructure..... 25

 10.3 Customer Electromagnetic Environments 26

 10.3.1 Residential Environment..... 26

 10.3.2 Commercial/Public Environment..... 28

 10.3.3 Industrial Environment 29

 10.4 Setting EMC Requirements..... 32

 10.4.1 Approach for Power Customer Environments 32

 10.4.2 Electromagnetic Phenomena in Power Customer Environments and the Application of IEC 61000-2-5..... 34

 10.4.3 Recommended EMC test approach and performance criteria for both Power Delivery and Power Customers 41

 10.4.4 Performance criteria - evaluation of test results 41

 10.4.5 Power Delivery EMC Aspects..... 42

 10.4.6 Power Delivery EMC Recommendations 45

 10.4.7 Standards Gaps for Power Delivery (utility) Equipment..... 60

 10.4.8 Power Customer EMC Aspects..... 61

 10.4.9 Power Customer EMC Recommendations..... 65

Electromagnetic Compatibility and Smart Grid Interoperability Issues

10.4.10	Standards Gaps for Power Customer Equipment	72
10.5	Definitions and Acronyms	73
10.5.1	Definitions.....	73
10.5.2	Acronyms.....	75
10.6	Appendix A References	75
11	APPENDIX B – HEMP, IEMI and Extreme Geomagnetic Storm Events	81
11.1	Introduction to Appendix B.....	81
11.2	What is the Smart Grid?	81
11.3	HPEM Threats.....	83
11.3.1	IEMI Background.....	83
11.3.2	HEMP Background.....	84
11.3.3	Extreme Geomagnetic Storm Background	85
11.4	Potential Impacts of HPEM with the Power Grid.....	86
11.4.1	Early-time (E1) HEMP Impacts.....	86
11.4.2	Intentional Electromagnetic Interference (IEMI) Impacts	89
11.4.3	Late-time (E3) HEMP Impacts.....	90
11.4.4	Extreme Geomagnetic Storms	91
11.5	HPEM Protection Approach	91
11.5.1	High-frequency HPEM Protection Approach.....	92
11.5.2	Low-frequency HPEM Protection Approach.....	92
11.6	Organizations Dealing with the Threats of HEMP and IEMI	93
11.6.1	IEC SC 77C (EMC: High Power Transient Phenomena)	93
11.6.2	ITU-T Study Group 5	93
11.6.3	IEEE P1642	94
11.6.4	Cigré C4 Brochure on IEMI	94
11.7	HPEM Summary.....	94
11.8	Appendix B References	95
12	APPENDIX C: Evolution of Smart Meters and the Advanced Metering Infrastructure	98
12.1	Smart Meter Historical Evolution	98
12.2	Automatic Meter Reading Infrastructure Background.....	99
12.2.1	WAN.....	100
12.2.2	LAN	100
12.2.3	RF AMI Networks	101
12.2.4	PLC AMI Networks.....	101
12.2.5	Hybrid AMI Networks.....	102
12.2.6	Other AMI Networks	102
12.2.7	Additional Uses of LAN AMI Networks	102

Electromagnetic Compatibility and Smart Grid Interoperability Issues

12.2.8	HAN.....	103
13	ANNEX – Electromagnetic Compatibility (EMC) Issues for Home-to-Grid Devices	104

1 Introduction

This report introduces electromagnetic compatibility (EMC) as an integral process needed for the design of devices that are used in the operation of the Smart Grid, and is an output of the SGIP Electromagnetic Interoperability Issues Working Group (EMII WG). The report examines EMC issues for Smart Grid equipment on both the electric power system delivery and the power customer sides of the Smart Grid meter and summarizes recommendations for EMC standards. It is intended as a guide to apply documented EMC principles to better ensure the operation and interoperability¹ of the Smart Grid in its intended electromagnetic (EM) environments. The general recommendations that follow come from the analysis contained in Appendix A (*Review of Smart Grid EMC issues and standards*) and Appendix B (*HEMP, IEMI and Extreme Geomagnetic Storm Events*). Consult these Appendices for more details.

The reliable delivery of electric power to customers is the most obvious measure of how well a power grid is performing. The Smart Grid has the potential to improve the reliability of power delivery in many ways. But due to its increased complexity and reliance on technologies not previously incorporated into the grid, the Smart Grid also may be susceptible to factors that can negatively impact the reliability of power delivery. Some of these factors result from electromagnetic interference (EMI).

As defined in ANSI/IEEE Standard C63.14-2009 [1], EMC is “*the capability of electrical and electronic systems, equipment, and devices to operate in their intended electromagnetic environment within a defined margin of safety, and at design levels of performance without suffering or causing unacceptable degradation as a result of electromagnetic interference.*” So for a device, equipment, or system to be compatible it must be immune (or at least tolerant) to the EM disturbances that exist in its environment and not introduce additional disturbances. This implies that it will coexist and interoperate as designed with other systems in its environment.

¹ Interoperability, in the context of this report, is the ability of a device to continue to operate and communicate reliably in its anticipated EM environment and to not cause undue electromagnetic

EMC may also be a factor in functional safety² depending on the consequences of a failure due to electromagnetic interference (EMI). A high degree of EMC minimizes possible safety and performance failures due to EMI.

EMC is also related to electric power quality in terms of the level of certain EM disturbances that may exist in the environment. Many of the interference phenomena or disturbances discussed in Appendix A can be related to power quality (i.e. power line harmonics, voltage surge, etc.). However, other than to recommend good installation and suppression practices, the EMII WG did not address the cause or control of these power quality issues, concentrating instead on the immunity requirements needed to be compatible with a given level of EM disturbances.

Smart Grid devices (e.g. microprocessor-based systems, communications devices, plug-in electric vehicle chargers, etc.) may also generate incidental electromagnetic emissions that could cause harmful interference to nearby electronic devices. The allowable emissions are limited by various national authorities (e.g. FCC in the U.S.) at sufficiently low levels to minimize possible interference to other systems. Many of these regulations are based on consensus standards developed by Standards Development Organizations (SDOs) like ANSI [2], IEEE [3] and IEC/CISPR [4]. Hence, with the assumption that all electronic equipment will meet regulatory emissions limits, the scope of this report includes only the immunity of Smart Grid systems and devices to the possible external electromagnetic interference impinging on this equipment.

In addition, the electromagnetic environments resulting from communications devices, and from typical transmitters in common use and not a part of Smart Grid devices and power customers, are assumed to generate EM fields well below human exposure limits that protect against adverse effects in humans. These limits, in terms of electric and magnetic field strength and power density, ensure that the exposure does not exceed the basic restrictions on which contemporary radio frequency safety standards (e.g. ANSI/IEEE C95.1-2005 [5], ANSI/IEEE C95.6-2002[6], and ICNIRP³ Guidelines [7, 8]) and regulations (e.g. FCC Code of Federal Regulations 47 CFR 2.1093, 47 CFR 1.1310) are based. These standards are stated

² The basic approach to achieving this functional safety is to evaluate the margins between the expected levels of emissions that create the EM environment and the levels of immunity that equipment possesses. In many cases the most appropriate approach is to raise the immunity level of the equipment to ensure that unsafe conditions do not result during normal operation.

³ ICNIRP is the International Commission on Non-Ionizing Radiation Protection.

in terms of specific absorption rate (SAR), the rate of energy absorbed into human tissue per unit mass (for measurement example see EN 62209-1:2006 [9]). Hence possible electromagnetic hazards to humans are not within the scope of this report. The focus remains on the electromagnetic immunity of Smart Grid devices and the Smart Grid infrastructure.

2 Electromagnetic Compatibility and the Smart Grid

EMC must be considered to ensure continuous reliable real time operation in the many locations where the Smart Grid equipment will operate. Components and devices in the Smart Grid system are subjected to a wide range of conducted and radiated noise sources that are disruptive to all electronic systems (Smart Grid systems included). These sources can be categorized as follows:

- Conducted noise from such sources as power line harmonics, surge (from lightning and power system switching transients), and fast transients/bursts (interruption of inductive dc circuits)
- Radiated noise or signals from known transmitters (AM, FM, and TV broadcast transmitters, communications radios, wireless devices, etc.).
- High power events such as geomagnetic storms, intentional EM interference (IEMI) from portable transmitters, and EM pulses associated with high altitude nuclear detonation (HEMP).
- Electrostatic discharge events when a statically charged body (human or inert) comes in contact with a Smart Grid device.

The above EM interference phenomena are described in more detail in Appendix A and Appendix B, as indicated in the first paragraph of the introduction.

Presently, for most equipment sold in the United States there is no regulatory mandate that a manufacturer's product meet any immunity specification as immunity is considered a quality issue. Hence immunity considerations are left to the manufacturer and the purchaser to determine how much immunity is needed to work properly and to avoid recalls or in-field repairs. Thus many electric utilities include specific requirements in their purchase specifications for equipment such as protective relays, power station and substation apparatus, and kilowatt-hour meters (including Smart Meters). This is done by requiring compliance with specific

IEEE, ANSI, or IEC standards. As a result, most manufacturers of products for the electric utility industry design them to meet specific standards – such as the IEEE C37.90 series for protective relays [10, 11, 12, 13], IEEE 1613 for communications networking devices [14], and ANSI C12.1 for kilowatt-hour meters, including Smart Meters [15] (see Tables 10.3 and 10.4). The situation is different in other countries, for example, the countries within the European Union (EU) require products to meet the EMC Directive 2004/108/EC [16]. This directive requires both emissions and immunity conformance. Meeting harmonized standards [17] presumes compliance to the EMC Directive although other means of demonstrating such conformity are permitted. In general, manufacturers address specific EMC requirements for each country or region in their intended market.

3 Recommendations for EMC Standards and Testing

A prerequisite for achieving electromagnetic compatibility between an electronic device and the electromagnetic environment and events that may cause interference is to quantify the environment. A clear understanding of the possible interference phenomena is necessary to design the most cost-effective device that is immune to the interference. However, it is difficult to determine the actual environment in every location the device may be installed so a “typical” or in some critical situations a “worst case” picture of the interference potential may have to guide the design.

The starting point, therefore, for the EMII WG to determine if current EMC standards are adequate for the Smart Grid was to define the electromagnetic environments where Smart Grid devices may be installed. Appendix A details a list of distinct environments that span the electric power grid from bulk generation to residential use. These environments each have particular characteristics that may warrant specific equipment design features in order to meet EMC requirements. Sources of possible interference in each of these environments are identified and several applicable EMC standards that may address the interference to Smart Grid devices are presented.

The EM environments at customer locations (residential, commercial, and industrial), as identified in Appendix A, are highly variable and, in many instances, unpredictable. These environments may contain any number of interference sources in various densities and intensities ranging from very low in a remote single family home (for example) to extremely noisy in a dense industrial location (similar to a power substation). One method to characterize these locations is to assemble an inventory of known interference sources and map the expected intensity at a

“typical” residential, commercial, or industrial location. The IEC Technical Committee 77 [18] has developed such a mapping in Technical Report IEC/TR 61000-2-5 ed.2 published in 2011 [19]. This report is the most comprehensive source of information for the power customer environments available to the EMII WG and is used as a basis for evaluating which immunity tests should be performed and the test levels for equipment placed in these locations.

The electromagnetic environments within the electric utility system (generation, distribution, substations, etc.), while more severe than the customer locations, are generally more predictable and better quantified. However, the information in IEC/TR 61000-2-5 ed.2 [19] does not generally apply to electric utility environments (except possibly some of the industrial environments wherein utility control facilities may be located) so applicable product EMC standards intended for these locations were examined directly. Several of these are listed in Table 10.3, Appendix A.

If a Smart Grid device is to be installed at more than one of these environments, a decision has to be made as to which environment is the most likely. Investigation of the noise source levels in the industrial environment generally indicate the highest level of potential interference to Smart Grid devices and require a corresponding high level of immunity and test levels. If however, the likelihood is far greater that the device will be located in the residential and/or commercial environment, then the highest immunity level may not be appropriate. It is also noted that expected level of interference in IEC/TR 61000-2-5 [19] may be the same for two of the three environments. This, of course, reduces the number of possible immunity test levels to select and thus implies that the two environments are similar for those particular RF phenomena. If on the other hand, the Smart Grid device or system is installed in all locations, then it must be designed to withstand the most severe environments (e.g. power substation).

Lightning is a common event that effects local sections of the grid but can strike anywhere. The installation of proper grounding, surge protection, and equipment designed to tolerate moderate levels of electrical surges are all necessary to protect equipment against lightning events. Appendix A (e.g. Table 10.3) gives some guidance on immunity test levels for lightning surge events. These values assume that proper installation and surge suppression exist.

Some events plague large areas of the power grid simultaneously such as geomagnetic storms or high power pulses. The high power electromagnetic (HPEM) events mentioned in the previous section (HEMP, and severe geomagnetic storms) are discussed in detail in Appendix B. While these events have a low probability of

occurrence, if one does occur, the effects on the Smart Grid could be serious. IEMI is a more localized (and more likely) threat that can also cause serious problems to unprotected facilities. The technical basis for providing a level of immunity to these events is discussed in Appendix B along with standards development organizations currently addressing these high power events.

The EMII WG firmly believes that the first level of HPEM protection begins with a solid EMC program and robust Smart Grid immunity to the typical EM interference events. The application of protective measures for high power events then builds on the immunity at the equipment level. The EMII WG recommends that the standards cited in Appendix B be considered when selecting equipment for critical Smart Grid applications. Ultimately, protecting the electric grid from these high power events requires a coordinated effort between the utilities, regulators, and policy makers. That discussion is beyond the scope of this report.

The EMII WG did not attempt to indicate that there be immunity margin designed into products such that the product meets test levels higher than those in this document. That decision is up to the manufacturer and those that specify requirements such as electric power utilities or regulators. Once the immunity requirements are set, the manufacturer can then design and test to those levels. These requirements and associated performance criteria may also form the basis for a possible immunity compliance testing program performed by certified manufacturers or third party test/compliance laboratories.

Based on the above arguments, the Working Group (WG) recommends that all Smart Grid equipment should be designed to ensure electromagnetic compatibility to its intended operational environment and, in particular, immunity to electromagnetic interference. This can be accomplished by the following:

- 1) Manufacturers should design Smart Grid products for EM immunity to at least the disturbance levels in IEC 61000-2-5 [19] for customer environments (see Table 10.1). Two product standards CISPR 24 (very similar to EN 55024) [20] and IEC 61326 (EN 61326) [21] are detailed in Table 10.7. Additional EMC standards may be necessary depending on the product class and the intended market.
- 2) Manufacturers should design equipment for electric power utility environments to levels specified by the IEEE C37.90 [10 – 13] series for protective relays, ANSI C12.1 [15] for kilowatt-hour meters and IEEE 1613 for communications networking devices. Immunity tests in IEC 61850-3

- [22], the IEC-60255 (EN 60255) series [23] and IEC-61000-6-5 [24] are necessary to address disturbances not covered by the above IEEE and ANSI standards (see Table 10.3). Additional EMC standards may be necessary depending on the product, utility requirements, and the intended market.
- 3) Devices must be designed to meet emissions requirements as per national regulations (e.g. FCC or EU).
 - 4) Adequate EMC should be verified by testing using established IEEE, IEC, or other standard test methods. The testing may be accomplished by the manufacturer or, if appropriate, by an accredited third-party test laboratory.
 - 5) For installations on the customer side of the Smart Meter, reduce adverse EM exposure by appropriate installation practices and suppression of disturbance levels.

4 Recommended follow-on action by SGIP, SDOs and EMII WG

The EMII WG has identified several important tests that are not currently specified in IEEE EMC standards for distribution and substation relays and equipment for the U.S. market. The WG will continue to track and encourage the revision of IEEE 1613 to address this lack of coverage for the disturbances identified in Section 10.4.7. These tests are defined in IEC standards (e.g. IEC 61850-3 [19], IEC 61000-6-5 [24] and basic test standards IEC 61000-4-x [25]).

The EMII WG has also identified a gap in all existing IEC and IEEE RF immunity standards, as the frequencies used by present in-service 3G and 4G cellular phones and digital tablets are not addressed in any of these existing standards. These frequencies are from 1.0 to 3.8 GHz AM modulated and from 1.7 to 5.8 GHz pulse modulated. We urge the relevant SDOs to close these gaps as soon as possible.

All IEC and IEEE RF immunity tests, whether performed by the manufacturer or by an accredited external laboratory, are explicit in requiring that all service panels and other cabinet openings be closed during the RF immunity tests. The shielding provided by the cabinet or enclosure may be a significant factor in the RF immunity design for these devices. However, maintenance and other field personnel are rarely aware of the substantial loss of RF immunity when these doors are not closed or cover plates are not in place. Manufacturers of these devices are strongly urged to place warning labels on these doors and covers on all new devices. In addition, that

they supply additional labels to existing users of in-service devices (for field installation) that have been certified by the manufacturer as meeting an IEC or IEEE RF immunity test.

The WG notes that there may be challenges in the uniform application of existing EM immunity standards due to variations in test level requirements and voluntary, regulatory, or market-driven compliance paradigms.

There are likely to be EM interference and compatibility issues to be addressed as new technology and systems are introduced into the Smart Grid. Many of these EMC issues may be addressed through an update of established IEEE, IEC, or other standards while others may require new standards specifically tailored to the technology and the application. This is, of course, the primary task of SDOs. The IEEE and IEC have both organized working groups to provide guidance to their various EMC committees with regards to Smart Grid standards. The SGIP and the EMII WG are in a unique position to track the development of Smart Grid technology and progression of EMC standards, and to provide a forum for all the stakeholders to address possible EMC issues and recommend further standards development.

5 Strategy to maintain EMC as the Smart Grid evolves

The steady growth and changes to Smart Grid technology will necessitate a dynamic strategy to maintain EMC and reliable operation. All players in the Smart Grid (manufacturers, utilities, standards development organizations, government, and customers) have a role in maintaining a robust and reliable grid control system. The following identifies actions in these entities:

- **Manufacturers:** design and test products to demonstrate EM immunity per specific standards.
- **Utilities:** Continue to specify that components for the smart grid meet the EMC requirements in specific standards. Utilities may require additional compliance testing.
- **Electric power customers (especially commercial and industrial):** Practice good installation procedures and specify products that have good EMC design.

Electromagnetic Compatibility and Smart Grid Interoperability Issues

- SDOs: Continue to develop and update EMC standards where found necessary to reflect the progress in technology and the Smart Grid electromagnetic environments.
- Government: Evaluate national policies and priorities for protection of the electric power infrastructure from electromagnetic interference, especially high-power events like HEMP, IEMI, and geomagnetic storms.

The only way to know how well a device will perform in the presence of electromagnetic interference is to expose the device to similar phenomena in a controlled test. Conformity to any particular EMC standard should be verified through testing by the manufacturer at the design and development stage and/or later using production samples. These tests should be performed in accredited laboratories (either in-house by the manufacturer/utilities or by third-party test laboratories). In addition a quality program should be applied based on the competency of laboratories to determine if Smart Grid devices are compliant. Adherence to ISO/IEC 17025 [26] (with specific additional requirements for Smart Grid application) is a well-recognized method to show test laboratory competency. However this does not preclude the use of test labs, including those of the manufacturer/utility, that are not compliant with ISO/IEC 17025.

6 Interaction with other SGIP Committees and Working Groups

Electromagnetic compatibility and electromagnetic immunity are topics that affect the entire operation of the grid and as such the work described in this document is complementary to many other efforts within the SGIP. For example, the Home-to-Grid (H2G) Domain Expert Working Group (DEWG) has clearly identified the need for electromagnetic compatibility in SG devices used in the home environment as described in the H2G DEWG report (Electromagnetic Compatibility (EMC) Issues for Home-to-Grid Devices), attached as an Annex (Section 13). Many of the issues pointed out by this DEWG are covered in Appendix A. It should be noted that an installation guidance document is also part of H2G activity in cooperation with the Consumer Electronics Association [27]. Their document provides information on electrical installation techniques that will reduce the exposure of consumer electronic equipment to power line surge and other sources of interference. This work is also discussed and referenced in Appendix A.

The work of the EMII WG also complements the activity of the SGIP SG Testing and Certification Committee (SGTCC). The SGTCC is preparing documentation on end-

to-end testing as well as requirements for Interoperability Testing and Certification Authorities (ITCAs) in implementing the Interoperability Process Reference Manual (IPRM). This activity clearly indicates the need for verification of Smart Grid devices meeting usage requirements. An EMC component should be included in any testing and certification program for Smart Grid interoperability under consideration by the SGTCC.

7 Conclusions

This EMII WG report provides recommendations to improve the ability of Smart Grid devices to interoperate as intended and survive the electromagnetic environment that exists in such locations as those associated with residential, commercial and industrial environments. It is important that EMC be designed into all components/devices that comprise the Smart Grid control system so that reliability is better assured. There is no guarantee that all Smart Grid devices will tolerate all such EMC environments, but without taking into consideration EMC the probability of the system failing to operate as intended increases significantly. Good EMC practices combined with the EMC design test levels indicated in this report and the referenced standards should be used to significantly increase the probability that the Smart Grid system will work and withstand the disturbances caused by the EM environment.

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9 Revision History

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1.0	10/15/2012	Galen Koepke	Version 1.0 draft.
1.0	12/05/2012	Galen Koepke	Update gap analysis and cite IEC copyright release. Version 1.0 complete

9.1 Contributors

This document has been prepared by the members of the Electromagnetic Interoperability Issues Working Group within the Smart Grid Interoperability Panel. The following individuals are noted as having contributed time, expertise, and content to the development of this white paper.

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10 APPENDIX A – Review of Smart Grid EMC Issues and Standards

10.1 Introduction to Appendix A

All existing power grid devices are immersed in an electromagnetic (EM) environment of natural and man-made EM sources that are either directly radiated into devices or are conducted via the power, signal and ground connections. The Smart Grid will introduce a great number of data flows in support of applications with widely divergent functions that can all be degraded by electromagnetic interference. These functions will have different reliability requirements, correlating with different levels of data flow reliability, and may require different radiated and conducted immunity levels.

This Appendix is intended to provide an overview of the electromagnetic compatibility (EMC) immunity performance and testing needed in order to produce the desired reliability of Smart Grid devices at the lowest practical cost.

The scope of this Appendix is to identify specific locations and typical EM environments for both the electric power delivery system and power customer locations including particular threats that warrant attention. High impact/low probability events including geomagnetic storms, HEMP or IEMI are considered in Appendix B. A power delivery system location example is a transmission substation. The power customer locations include residential, commercial and industrial buildings where electricity is used. Some of these customer locations may also include Distributed Generation. The approach taken in this report for determining the EMC requirements includes:

1. Analysis of EM environments with respect to electronic equipment and transactions exposed to possible interference and/or damage to electronic equipment that would prevent reliable operation.
2. Determining the availability of existing EMC standards and recommended practices.

Electromagnetic Compatibility and Smart Grid Interoperability Issues

3. Identify gaps and formulate recommendations for new EMC standards or recommended practices or the possible need to revise or amend existing standards.

The mandate that Congress has given NIST is to determine what deficiencies exist in standards for the Smart Grid, and to coordinate the process of filling those gaps. The SGIP Electromagnetic Interoperability Issues Working Group (EMII WG) is performing that task as it relates to the impact of electromagnetic interference on Smart Grid functions (immunity) and the potential for electromagnetic interference to non-SG devices due to emissions from Smart Grid devices.

The major concern addressed in this Appendix deals with the immunity of Smart Grid devices and equipment to a variety of EM sources that can affect communications and operation. The other aspect of EMC that must be taken into account is controlling emissions from these devices and equipment that might adversely affect nearby electronics, either by radiated emission or those conducted over a common power supply system. Fortunately there is mandatory control of emissions. Such devices and equipment must meet regulatory requirements for incidental radiated and power line conducted emissions as specified in the United States in Part 15B of the Federal Communications Commission Rules (47 CFR Part 15) [1] using measurement methods in ANSI C63.4 [2]. In other parts of the world, emission limits are generally specified and are based on IEC/CISPR Publication 22 [3] which sets limits and measurement methods for information technology equipment which includes almost any device or equipment that contains microprocessors. (Note: CISPR 22 will soon be replaced by the new CISPR 32. The date of this crossover depends on the national regulatory authority and will be different in each country.) There is also another safeguard in the U.S. in that if these devices and equipment cause what is referred to as “harmful interference”, the user and/or the manufacturer must take steps to reduce the interference. It should be noted that in this context, “harmful interference” to the FCC means that licensed radio services are harmed if emissions adversely affect the use of these radio services.

There are a variety of electromagnetic disturbances that could potentially interfere with the performance of Smart Grid equipment and systems. This Appendix provides a basic introduction to these possible phenomena and environments that may be relevant to the function and reliable operation of the Smart Grid. The remainder of this report will then focus on the electromagnetic immunity aspects of protecting Smart Grid devices and equipment.

10.2 Electric Power Delivery System Electromagnetic Environments

Electricity delivery is the process and infrastructure that begins with generation of electricity in the power station and ends with the use of the electricity by the customer. The main components in the power delivery process are: bulk generation, substations, transmission, distribution, distributed energy resources, and retailing. This holistic electricity delivery “system” can be known as power delivery, though some viewpoints consider power delivery as “the wires portion of the system” which is transmission, substation, distribution, and possibly distributed energy resources and retailing. This report and its recommendations are targeted to Smart Grid interoperability and thus the holistic definition of power delivery.

Hence, for the purpose of this EMC discussion, the power delivery system consists of Bulk Generation, Transmission, Distribution, Substations, Control Centers, Distributed Energy Resources (DER) or Distributed Generation (DG), Smart Meters, and Advanced Metering Infrastructure. These are discussed briefly below. Communications systems are a common feature in most Smart Grid devices and their EMC implications are discussed in sections 10.2.7.

10.2.1 Bulk Generation

Bulk Generation tends to include large capacity facilities (nuclear, hydro-electric, steam and gas turbine generators), dedicated to the function of generating electric power, and their co-located substations. Extensive high speed communication links connect them to other substations and control centers. In many respects, the concept of Smart Grid already exists in these facilities, and changes from the advent of the Smart Grid are not expected to change the electromagnetic interference (EMI) environment, which is very harsh and essentially the same as substations.

Bulk generation is also generally considered to be dispatchable. This typically means that the utility is capable of, and is authorized to, increase or decrease the output of the facilities. The frequency of dispatch communications varies widely throughout the industry.

Modern power plants all utilize complex protection and control systems to maximize efficiency and provide safety. Electronics have largely replaced some of the electromechanical devices in older plants and are used exclusively in plants

constructed in the past one or two decades. Even generator exciters now have microprocessors and analog-to-digital converters.

10.2.2 Transmission System

Electrical energy from the various power plants travels over a system of lines and substations to regions and locales where it is consumed. The electric transmission system consists of the substations at generating plants, the transmission substations and the conductors/cables between towers/manholes at these substations. Within this power transmission network, there are many control, monitoring and protection functions already embedded, with a number of different communications networks/technologies used to support these functions. For the Smart Grid, a significant increase in the number of synchrophasors measurement units (PMUs) is expected to be installed in transmission substations for enhanced wide area situational awareness, and new live-line sensors are expected to be installed on transmission line conductors to facilitate dynamic ratings on these lines.

10.2.3 Distribution System

Power distribution system designers are expected to significantly add to or enhance automation and control functions as the Smart Grid evolves. Distribution automation functions include monitoring and control of the distribution equipment, local automation of equipment on feeders, managing distributed energy resources and communication with smart meters. Advanced line protection schemes will increasingly be applied at the distribution feeder level. The sensors, communications and control interfaces must be compatible with the EM environment. This is especially true as electronic devices replace mechanical devices that were not affected by EM fields or conducted disturbances.

Communication links to a limited number of applications exist today within many distribution systems. A variety of sensor and control functions using various communication technologies are used with devices such as sectionalizing switches/reclosers, line voltage regulators, switched capacitor banks, and voltage and fault sensors as elements of distribution automation programs. Existing point-to-point communication technologies used include power line communications, narrow-band radio, spread spectrum radio, and fiber optics.

The future may include more widespread use of applications such as fault location and isolation, self-healing networks, meter disconnects, load curtailment/demand response, distributed generation/storage control, electric vehicle (EV) control, and islanding. Communications will include options available today as well as an increase in the types and occurrences of wireless networks.

10.2.4 Substations

The term “substation” describes the physical location in the power grid that contains transformers, circuit breakers, capacitor banks, voltage regulators, sensors, protective relays, control, and other equipment as necessary for controlling and distributing electric power. Substations are essentially critical interconnections in the electric power grid and are located throughout the grid for generation (as part of a power plant), for the transmission and distribution systems, and for distributed generation (DG) projects. The primary voltages at these substations will vary depending on the location in the power grid. Transmission substations, for example, have primary voltages of 100 kV – 800 kV while a distribution substation may operate with primary voltages up to 100 kV and distribute to feeders at medium voltages of 35 kV or less. These substations can be as simple as a few circuit breakers or include complex systems covering several acres.

For the purpose of this EMI discussion, the substation EM environment is defined as an area of high EM fields, including transients from switching that are higher than those found in other portions of the distribution system. The physical substation environment is generally the area bounded by a grounded fence around the substation yard and/or building and the area extending a few meters outside the fence. This is the most severe EM environment in the Smart Grid.

Substations have become complex in their protection and control schemes. Microprocessor-based protective relays are rapidly replacing electromechanical relays, especially at major transmission substations. These devices not only perform protective functions but also act as intelligent electronic devices (IEDs) that perform control functions, metering, substation automation, etc. Communication among all these devices is currently serial based over copper wire; however, a trend is underway to replace the wires between devices with Station Bus technology using Ethernet IP connectivity over fiber-optic cable and to network communication protocols (away from serial/DNP3 to IEC 61850) for new or expanded installations. The power line carrier (PLC) transmitter/receivers, microwave and optical fiber communication multiplexers used in conjunction with protective relays to provide

pilot protection schemes are now IEDs. Traditional remote terminal units (RTU) used for supervisory control and data acquisition (SCADA) are being replaced by substation integration and automation (SIA) packages. The SIA packages contain communications equipment such as Ethernet switches and routers, GPS time syncing clocks, discrete programmable automation controllers, computers and HMIs (Human Machine Interfaces – such as video displays, alarm screens, active one-line diagrams, operator alerts) at control centers to control and monitor substation equipment. In addition to the above devices, larger transmission stations usually include digital fault recorders (DFR), sequence of events (SOE) recorders and phasor measurement units (PMU). IEEE and IEC standards exist for the EMC testing of these devices (see Section 10.4.6).

10.2.5 Control Centers

Overlaid on the three primary elements – generation, transmission and distribution – is a control system that directs the power where it is needed, maintains the frequency, and protects the system. Control is also necessary for the business aspects. The controls must protect the system from transients such as lightning, correct synchronization errors by activating reactive sources or loads, isolate malfunctioning elements of the grid, and prevent self-damage from improper compensation or human error. The control systems also enable the deregulated energy marketplace by tracking the origin, route, and destination of the energy commodity. Central to the monitoring and coordination of the power grid is a broad class of devices called supervisory control and data acquisition (SCADA) systems. These conform to an agreed set of standards that make it possible to network many such systems over a generic communication system, regardless of modality.

Control Centers consist of PCs/terminals, display boards, computer and communications rooms. While the control center may look similar to a commercial facility in terms of its EM environment, in many cases it is adjacent to substations, so the same EMC requirements apply.

Also while some power control centers are isolated from their surroundings (below ground and/or in rural areas), some are located in the middle of urban areas and also co-located within the footprint of a large substation. Poor wall shielding and the use of copper (unshielded twisted pair) cabling may create a serious EMC immunity issue. IEEE and IEC standards exist for the EMC testing of the devices installed in control centers (see Section 10.4.6).

10.2.6 Distributed Energy Resources (or Distributed Generation)

Distributed Energy Resources (DER) or Distributed Generation (DG) refer to sources of electric power, usually directly connected at the Distribution level, either behind (customer side of) the meter or at the individual feeder level. DERs include small scale generators such as micro-turbines, modular reactors, and fuel cells, and renewable sources like solar, wind, and geothermal. These generators are located in many diverse environments ranging from residential (rooftop solar panels) to industrial or regional wind and solar farms. DER can also include stored energy from batteries or other systems. Utilities currently consider these sources (excluding storage) as being non-dispatchable, referring to the ability to call for changes to power flow rate or schedules. There are two reasons for this: 1) a wind or solar farm cannot increase output when the resource (sun or wind) is not available; and 2) these facilities tend to be small, independently owned and operated, and even where it made sense to the utility, they may still refuse such requests. As these systems become more coupled to centralized control through Smart Grid communication resources, they will become an important part of the mix of available generation, and therefore will have increased sensitivity to EM disruption.

More information needs to be collected to evaluate special EMC problems associated with these newer types of generators and their locations. For example there is a concern expressed by the wind turbine manufacturers that they have no EMC immunity standard to cite for the electronics involved with the rotating blades, which may be vulnerable to the near-by magnetic fields produced by current flow in the structure during a lightning strike. In addition, rooftop inverters that convert DC to AC power do not yet have comprehensive EMC immunity standards. Multiple inverters will likely be coupled to controllers by various communications systems and these systems will have to be considered when investigating immunity levels. The EMII WG recommends using EMC standards intended for the line voltages serving the DER system. This approach is described in more detail in Table 10.2, Section 10.4.6.

10.2.7 Communications Systems

The application of communication technology (wired and wireless) within the power grid has existed for decades. However, the anticipated growth of data

communications networks and advanced applications sending control data in both directions throughout the power grid is the mechanism by which the power grid will become “smarter”. Also, “interoperability”, as defined with respect to the Smart Grid, is essentially the ability of two or more systems, networks, devices, applications, or components to communicate and operate reliably in real time. Hence, the reliable operation of the myriad communication systems proposed for Smart Grid applications is an essential prerequisite for interoperability no matter where the hardware is physically located.

There are many variables that comprise “reliable” communications for a particular application. The same degree of reliability is not required for all applications so the designer has to weigh cost, security, traffic loads, level of performance, quality of service, and the operating physical environment, along with management requirements in choosing the appropriate technology for the application. The possible candidates include dedicated wire or optical fiber systems, conducted power line communications, and/or one or more of the wireless technologies (e.g. narrow band radios, wireless mesh technologies (900 MHz, ZigBee® [4], etc.), Wi-Fi® [5] and even 4G (WiMAX® [6] or LTE® [7]) as well as microwave and satellite options). Each of the technologies has the ability to deal with different requirements within the Smart Grid, and each selection must be governed by the specific needs of the application. The Smart Grid Testing and Certification Committee is examining how end-to-end testing for communications interoperability can be confirmed. EMC issues should also be addressed based on specific applications of communication technology.

The parameters that we are focused on in this report are the potential sources and levels of interference resulting from interaction with the electromagnetic environment where the communication systems are deployed. While this interaction may be measured by coexistence criteria in some situations, the view taken in this report is compatibility with all sources and receptors in the environment.

The intentional (from wireless or radio systems) or unintentional (from wired systems) radiation from Smart Grid devices may also couple into and interfere with other nearby electronics or receivers. As stated earlier, the level of radiated and conducted emissions is regulated by the FCC or other regulatory body. These levels are based on assumed separations between the RF sources and nearby electronics. If the separation is less than anticipated by these assumptions, the probability of disturbances increases. This consideration is also complicated by the possibility of a system being placed in a wide range of environments.

A robust communication system that is compatible with the most severe environments may not be the most cost-effective solution for more benign environments. Conversely, a system designed with lower interference protection while perhaps less expensive initially would be much more problematic in severe environments.

10.2.7.1 Wireless Communications

Advanced Metering Infrastructure (AMI) and Distribution Automation (DA) communications are two examples of applications that may span widely diverse geographic areas and operating environments. An initial set of requirements for these applications have been evaluated with regards to wireless communication systems by the *SGIP Priority Action Plan (PAP) 2* authors. . The PAP2 report "[Guidelines for Assessing Wireless Standards for Smart Grid Applications](#)" (NISTIR 7761) contains a framework and tools to help the network designer identify an appropriate technology for an application. A companion inventory of wireless technologies and protocols currently being considered for Smart Grid applications can be found in spreadsheet form in "[Consolidated NIST Wireless Characteristics Matrix-V5.xls](#)". There are many performance and environmental parameters (i.e. channel propagation, coexistence, interference, etc.) to consider. Smart Grid network designers are encouraged to study the PAP2 report for guidance, especially with regard to co-existence issues, but it is important that EMC aspects also be considered as part of any trade studies to select the best communications solutions.

Since wireless (i.e. radio) systems by definition use the surrounding environment as the communication path for operation, these technologies contribute to and are vulnerable to the electromagnetic phenomena in that environment. Published interference criteria and assumptions addressed by the individual protocol standards may be qualitative and hence difficult to map to a particular environment. Additionally the models used may not adequately take into account the harsher EM environments in some Smart Grid locations.

Therefore, when choosing a wireless technology for a particular application, the Smart Grid designer must be aware of the immunity characteristics of the wireless system and relate those to the actual environment. The environment in question can be estimated from IEC/TR 61000-2-5 [8] using typical values for known sources or, if the application is critical, specific on-site measurements. These on-site measurements may have to be performed over time to gain a real sense of the variability. The immunity of the wireless system can be estimated from the

specifications published by the relevant standard if quantitative values are available or again, if the application is critical, the realized performance can be measured in the actual or simulated electromagnetic environment. When the communication modules are installed in the smart grid device (i.e. smart meters) these modules should be included in the EMC testing and evaluation. However, at present, the kilowatt-hour meter standard (ANSI C12.1 [9]) is silent on the testing of meters incorporating such communication modules.

10.2.7.2 Dedicated-wire or optical fiber Communications

Wireless systems are receiving much attention as solutions to many of the communications needs in the Smart Grid. The lack of wires and ability to take advantage of a variety of propagation methods are the most obvious advantage. However these systems are dependent on the characteristics of the surrounding environment as described above and may not be appropriate for all situations. Dedicated shielded wire or optical fiber (not encased in metal protective covers) systems can offer increased isolation from harsh electromagnetic environments.

Wired systems may couple interfering signals onto the connecting wires if not properly shielded and routed away from strong sources. Optical fiber systems eliminate this problem but may experience failure due to dielectric break down of the fiber in especially severe electromagnetic fields. Some installations encase the optical fiber in protective metal jackets or use fiber with internal metallic strengthening materials, which in turn provides EM coupling similar to a metallic wired system. These coupled currents can then enter the electronics connected to the fiber cable. Proper grounding techniques and installation practices can reduce or eliminate these concerns. Generally, the optical fiber system may be the best solution for many point-to-point higher data rate applications. The wire and optical fiber systems will both need adequate EMC immunity for the electronics at the endpoints or interfaces.

10.2.7.3 Power Line Communications

Power line communications or power line carrier (PLC) has an advantage over other wired solutions because it uses an existing wire, the electric power distribution system. Low frequency (<150 kHz in EU and <490 kHz in US) and low data rate power line carrier or power line communications (PLC) systems have been

effectively employed by utilities in power grids for many years, and are now widely used for remote meter reading and energy management. These systems have not generated significant interference complaints.

Another consideration is the increase in broadband PLC or broadband over power lines (BPL) technologies proposed for Smart Grid applications and home networking (e.g.: IEEE P1901 [10], ITU G.hn [11]). These technologies promise much higher data rates (up to 1 Gbit/s), using higher carrier and modulation frequencies. Coexistence between these technologies is being addressed in SGIP PAP15. Interference to sensitive receivers by unintended radiation from the signals impressed on the power lines, primarily in the high frequency (HF and VHF) part of the spectrum is possible if not managed properly. Proper EMC techniques and frequency management must be used in these networks. The FCC rules [12] require BPL systems mask their frequency usage and signal amplitude to avoid “harmful interference” to licensed radio operations such as radio navigation, military communications, public safety, and amateur radio. This simply means that such services must be given preference for use and not be subjected to interference by unlicensed sources.

New Smart Grid electronics that are connected to the power lines should be designed to be immune from the conducted environment created by these signals, at the same time BPL should not interfere with existing Smart Grid equipment.

10.2.8 Smart Meters and Advanced Metering Infrastructure

An objective of the Smart Grid is to improve the monitoring and control of the power grid which in turn will improve its reliability and efficiency. A critical component of a properly functioning Smart Grid system is the Smart Meter and its associated Advanced Metering Infrastructure (AMI).

Smart Meters have advanced from the initial analog electromechanical models to the latest and most advanced AMI devices enabling two-way communication. There may be two (or more) separate communication channels within Smart Meters: the communications link from the utility to the meter and the link from the meter to the local energy management system in the building or residence. These links span the entire communications gamut from fiber optic to wired and wireless using both proprietary and standard protocols for the AMI infrastructure.

More detailed information on the evolution and the development Smart Meters and communication links is contained in Section 12 (Appendix C).

Smart Meters:

- May provide two-way digital communications between the utility and the customer, thereby enabling:
 - customer empowerment – providing customers with more information and the capability to facilitate energy management and
 - demand response via both information and rate programs.
- Give utilities operational advantages such as outage detection and management, remote meter reading, and remote customer connection and disconnection;
- May help accommodate smart charging of plug-in electric vehicles; and
- May help facilitate the integration of distributed generation resources.

Smart Meters, including all the functionality not found in electromechanical meters, must work properly in the electromagnetic environment where they are installed. The meters are deployed in all three of the operating environments (industrial, commercial, residential) described in section 10.3.

10.3 Customer Electromagnetic Environments

The power customer electromagnetic environment is segmented using the general classifications of IEC/TR 61000-2-5 ed2.0 [8], which are Residential, Commercial / Public and Industrial environments. The next clauses go into more detail of what is covered by each of the three environments.

10.3.1 Residential Environment

In accordance with IEC/TR 61000-2-5 ed2.0 [8], the Residential environment is an area of land designated for the location of domestic dwellings. These dwellings can be a single, separate building (as in a detached house) or a section of a larger building (as in an apartment in an apartment block/complex). The function of a domestic dwelling is to provide a place for one or more people to live.

The electromagnetic environment in a residential area varies widely but, in general, is a complex mix of EM signals that originate external (to the residence) and inside the residence. External EM sources (and nominal separation distances) that may contribute to the environment in a residence include (taken from table 40 of IEC 61000-2-5 [8] and used by permission⁴):

- Amateur radio further than 100 m (unless the resident owns the Amateur station)
- CB Radio further than 20 m
- Broadcast transmitter operating below 1.6 MHz further than 5 km
- FM and TV transmitters further than 1 km
- Cellular communication systems with remote base station further than 200 m (hand-held transceivers, e.g. GSM, WiMAX etc.)
- Paging systems, base stations, further than 1 km
- Aviation RADAR further than 5 km
- AC Power Feeding MV- or HV-line further than 20 m
- Telecommunication line
- Cable TV
- Proximity to MV/LV substations further than 20 m
- Proximity to arc welders (mobile) further than 20 m
- Proximity to HV sub-stations further than 100 m
- Lightning exposure
- Smart Meter

Sources that may exist inside a typical residence include:

- Cellular communication systems with external base station (hand-held transceivers, e.g. GSM, etc.)
- Portable communication systems with internal base station (hand-held transceivers, mobile phones i.e. CT, CT2, DECT, Bluetooth, Wi-Fi etc.)
- High concentration of multimedia and household equipment
- Presence of microwave oven up to 1,5 kW

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- Presence of medical equipment (Group 2 according to CISPR 11 [13]) further than 20 m
- AC Power, AC cabling LV
- High concentration of switched mode power supplies
- Existence of PLT equipment
- Signal Lines < 30 m

10.3.2 Commercial/Public Environment

A Commercial / Public location is defined as the environment in areas of the center of city, offices, public transport systems (road/train/underground), and modern business centers containing a concentration of office automation equipment (PCs, fax machines, photocopiers, telephones, etc.).

The following areas correspond to this environment:

- retail outlets, e.g. shops, supermarkets;
- business premises, e.g. offices, banks; data centers (server farms);
- area of public entertainment, e.g. cinemas (movies), public bars, dance halls;
- places of worship, e.g. temples, churches, mosques, synagogues;
- outdoor locations, e.g. petrol (gas) stations, car parks, amusement and sports centers.

Commercial/public locations are characterized by a high density of varying equipment installed or brought in (purchased) by the public. Generally, the equipment provides a service for many users and can be operated simultaneously. Some or all of these might act as an adverse interference source.

The electromagnetic environment in commercial/public locations are not constant but varies as a function of time depending on the functional use of the installation and of course whether they are powered on or in a shutdown mode. A non-exhaustive list of equipment typically operated in a commercial/public location is given as follows:

- Information Technology (IT) Equipment: A variety of fixed and mobile IT equipment including but not limited to: mobile communication devices, video information display systems, public address systems, audio frequency inductive loops (e.g. hearing assistance devices), general IT equipment, POS

(point of sale) terminals, audio frequency information systems (public address systems);

- Transportation Equipment: trams, buses, cars;
- Lifts (elevators) and Escalators;
- Area and signage lighting;
- Power equipment: low and medium voltage power equipment, power generators, UPS (uninterrupted power supplies).

The external EM environment of a commercial/public area is similar to that noted in the residential description with essentially the same possible radiated and conducted sources. The EM environment within a typical commercial/ public area may include signals or disturbances generated by the equipment noted above and may also include (taken from Table 41 of IEC 61000-2-5 [8] and used by permission⁵):

- Paging systems
- Portable communication systems (hand-held transmitters, mobile phones)
- Proximity to low-power ISM equipment (Group 2 according to CISPR 11 [13]), typically less than 1 kW
- Proximity of medium-voltage and high-voltage lines closer than 20 m
- AC Power AC cabling LV

10.3.3 Industrial Environment

Industrial locations can generally be described by the existence of an installation with one or more of the following characteristics:

- operation of industrial and scientific equipment;
- many items of equipment connected together that may operate simultaneously;
- significant amount of electrical power is generated, transmitted and/or consumed;

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Electromagnetic Compatibility and Smart Grid Interoperability Issues

- power is supplied from one or more dedicated high or medium voltage transformer(s);
- follows specific guidelines for equipment installation, maintenance, and operations;
- external influences are less dominant (because the disturbances are mostly produced by equipment at the industrial location itself).

The last characteristic stresses the fact that the electromagnetic environment at an industrial location is predominantly produced by the equipment and installation present at the location rather than by influences external to the industrial installation. Some examples of installations include those used for metalworking, pulp and paper production, chemical plants, car production, etc. In this instance, there is a potential overlap of the environments for industrial locations where power is consumed and in sub-station where power is produced or routed.

The above characteristics do not apply to all industrial installations to the same extent. There are types of industrial installations where some of the electromagnetic phenomena appear in a more severe degree, for example high levels of radiated electromagnetic disturbances are more likely in industrial installations where ISM (industrial, scientific, and medical) equipment is operated that uses radio frequency for treatment of material, like RF welding for example. On the other hand there are also types of industrial installations where some of the electromagnetic phenomena appear in a less severe degree, for example when installation conditions are maintained preventing an electromagnetic phenomenon to appear, or if it appears then only with a reduced amplitude, e.g. installations inside an RF shielded room.

The electromagnetic sources that can be expected to impact an industrial environment can be located external to the industrial installation and include the following examples (taken from Table 42 of IEC 61000-2-5 [8] and used by permission⁶):

- Amateur radio further than 20 m
- Broadcast transmitter operating below 1,6 MHz further than 5 km
- FM and TV transmitters further than 1 km

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Electromagnetic Compatibility and Smart Grid Interoperability Issues

- Industrial area with limited access
- HV / MV sub-station close to sensitive area
- Cellular communication systems with remote base station further than 200 m (hand-held transceivers, e.g. GSM, WiMAX etc.)
- Paging systems, base stations, further than 100 m
- Aviation RADAR further than 5 km
- AC Power Feeding MV- or HV-line
- Signal Telecommunication line
- Smart Meter

As noted above, these external signals are expected to have less of a contribution to the electromagnetic environment than the stronger sources located within the industrial installation. Examples of significant sources located in this environment may include (taken from Table 42 of IEC 61000-2-5 [8]⁶):

- Paging systems
- Portable communication systems (hand-held transmitters, mobile phones)
- High concentration of ISM equipment (Group 1 according to CISPR 11 [13])
- Proximity to low-power ISM equipment (Group 2 according to CISPR 11 [13]), typically less than 1 kW
- Proximity to high-power ISM equipment (Group 2 according to CISPR 11 [13]), typically more than 1 kW
- Proximity to LV/MV sub-stations closer than 20 m
- Proximity to arc welders (mobile)
- Proximity to arc welders
- Proximity to HV sub-stations
- Proximity of medium voltage and high-voltage lines closer than 20 m
- Pipe heating systems
- AC Power AC cabling LV
- AC cabling MV
- AC bus bar systems
- Large power drive systems (> 16 A per phase)
- Power factor correction
- Possibility of high fault currents
- Arc furnaces
- Switching of inductive or capacitive loads
- High-inrush loads
- DC Power DC distribution systems

- DC Rectifier
- DC Switching of inductive or capacitive loads
- DC High inrush loads
- Signal Outdoor exposure Long lines (> 30 m)
- Conduit runs likely
- Separation of different cable categories by distance
- Lightning exposure
- Large ground loops
- Possibility of large ground fault currents
- Smart Meters

10.4 Setting EMC Requirements

10.4.1 Approach for Power Customer Environments

IEC/TR 61000-2-5 ed2.0 [8] gives guidance for those who are in charge of considering and developing immunity requirements for Smart Grid equipment placed in the residential, commercial/public, and industrial locations. The Technical Report (TR) provides typical ambient signal levels in these environments from nearby sources that either radiate interference signals and/or conduct them over the power and ground conductors that connect devices to the Smart Grid. The technical report also gives general test level guidance but does not prescribe test levels for these environments.

Based on these ambient levels it is recommended that, in general, test levels should be at least equal to or higher than those stated in the technical report. Higher test levels provide margin for Smart Grid products if it is expected that a given environment will exceed the levels in 61000-2-5.

The data are applicable to any item of electrical or electronic equipment, sub-system or system that operates in one of the locations as considered in the report.

The descriptions of electromagnetic environments given in IEC/TR 61000-2-5 ed2.0 [8] and referenced in this report are predominantly generic ones, taking into account the characteristics of the location classes under consideration. Hence, it should be kept in mind that there might be locations for which a more specific description is required in order to determine the immunity requirements applicable for those specific locations. An example would be the demarcation point between

power delivery and those that use power. The EMII WG considers this the point at which smart meters are installed. This environment may be different on either side of these meters. While the meter is an area where homes are located which would be seen generally as a residential environment, it may also be close to the main source of power delivery such as that at a power load switching station (at least an industrial area). In these instances, the more severe environment test levels are recommended.

Classification of the electromagnetic environment is based on the description of the electromagnetic phenomena prevailing at typical locations, not on existing test specifications. The IEC definition of electromagnetic environment makes reference to “electromagnetic phenomena”. The term “disturbance degree” is used in this report to quantify the magnitude of the phenomena contributing to the electromagnetic environment and is independent of any consideration of test levels.

Thus, the concept and term of electromagnetic phenomenon is the starting point for defining the environment and selecting disturbance degrees in a classification document. Three basic categories of phenomena are considered: low-frequency phenomena, high-frequency phenomena and electrostatic discharge. In the first stage of classification, attributes of the phenomena (amplitudes, waveforms, source impedance, frequency of occurrence, etc.) are defined generically, and the expected range of disturbance degrees established.

Then, in the second stage of classification, ONE SINGLE value from that range has been identified as most representative for each phenomenon at a specific class of location and set forth as the compatibility level for that location class. Normally the setting of immunity levels for equipment exceeds the compatibility level to provide margin. The decision to select test levels that do or do not have a margin is up to the specifier, manufacturer, and others responsible for system interoperability, as indicated earlier in this report.

Given the above, it is clear from an EMC perspective that immunity of Smart Grid devices is critical for proper operation. There is a balance between designing for worst case immunity levels or designing devices with limited immunity and relying on appliquéés or other after-market “fixes” to mitigate problems when needed. Classically these after-market devices are RF filters, RF absorption devices clamped onto cables, focused shielding, etc. This may be a compromise cost-effective approach if the devices are designed to reject or suppress the effects of the RF environment that is most likely to occur where the devices are typically used but have to account for a more severe RF environment at certain installations.

10.4.2 Electromagnetic Phenomena in Power Customer Environments and the Application of IEC 61000-2-5

The electromagnetic environment in which electrical and electronic items are expected to operate without interference is very complex. For the purpose of this classification, three categories of electromagnetic environment phenomena have been defined to describe all disturbances:

- electrostatic discharge (ESD) phenomena (conducted and radiated);
- low-frequency phenomena (conducted and radiated, from any source except ESD);
- high-frequency phenomena (conducted and radiated, from any source except ESD).

In the context of the present report and in accordance with the IEC EMC approach, the term low frequency applies to frequencies up to and including 9 kHz; the term high frequency applies to frequencies above 9 kHz. The main reason is that by international acceptance, radio services start at 9 kHz and hence the potential for radiated signals accommodating such services is assigned at 9 kHz up to well over 300 GHz.

Electromagnetic fields can be radiated from distant or close sources; hence the propagation and coupling can be governed by far-field or by near-field characteristics. The resulting field strength at a location is typically controlled by the radiated power, the distance from the radiator and coupling effectiveness. The frequency is also an important factor in order to describe electromagnetic fields at a location.

Radiated disturbances occur in the medium surrounding the equipment, while conducted disturbances occur in various metallic media. The concept of ports, through which disturbances have an impact on the device or equipment used in Smart Grid systems, allows a distinction among these various media:

- enclosure;
- AC power mains;
- DC power mains;
- signal lines;
- the interface between first 4 items and earth or electrical reference.

The source, coupling and propagation characteristics depend on the type of medium. The final tables in this report show the compatibility levels for various location classes, and are structured along this concept of corresponding ports.

Table 10.1 summarizes the typical environment levels for residential, commercial and industrial locations that may result from the listed electromagnetic sources. These data are drawn from Table 43 in IEC/TR 61000-2-5, Ed. 2 [8] and used by permission⁷. Note that the entries in columns 3 and 4 refer to other clauses and tables in IEC/TR 61000-2-5, Ed. 2 and the reader is encouraged to consult that document for more details. While these levels are typical, other references such as specific product immunity standards from the IEC, IEEE and ANSI standards must be examined to ensure that the most appropriate levels are considered for Smart Grid applications.

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Table 10.1. Typical or expected disturbance levels for specific phenomenon in residential, commercial/public, and industrial locations.

Phenomenon	For details concerning phenomenon see subclause ⁸	For details regarding disturbance, see Table ³	Standard for testing or for additional information	Disturbance Level for Location			
				Residential	Commercial / Public	Industrial	
LF – conducted	Harmonics	5.1.1	2	61000-4-13	THD = 8%	THD = 10%	THD = 10%
	Power supply voltage amplitude variations	5.1.2.1	3	61000-4-14	±10%	-15 to +10%	-15 to +10%
	Power supply voltage unbalance	5.1.2.1	4	61000-4-27	2%	2%	2%
	Voltage dips Short interruptions	5.1.2.1		61000-4-11	See Standard	See Standard	See Standard
	Power Supply Voltage frequency variations	5.1.2.2	5	61000-4-28	±1 Hz	±1 Hz	±1 Hz
	Power Supply network common-mode voltages	5.1.3	6	61000-4-16	1 V	3 V	10 V
	Signaling	5.1.4	7	61000-4-13	5% of U _n (1)	5% of U _n (1)	5% of U _n (1)

⁸ Reference to clause or table in IEC/TR 61000-2-5.

Electromagnetic Compatibility and Smart Grid Interoperability Issues

Phenomenon		For details concerning phenomenon see subclause ⁸	For details regarding disturbance, see Table ³	Standard for testing or for additional information	Disturbance Level for Location		
					Residential	Commercial / Public	Industrial
LF – conducted	Induced low-frequency voltages	5.1.6	8	61000-4-16	1 V (signal)	3 V (signal)	10 V (signal)
	DC voltage in AC networks	5.1.7		--	Under consideration	Under consideration	Under consideration
LF - radiated	Magnetic fields	5.2.1	9	61000-4-8	10 A/m	10 A/m	30 A/m
	Electric fields	5.2.2	10	--	0.1 kV/m	0.1 kV/m	1 kV/m
HF - conducted	Direct conducted CW	6.1.1		61000-4-6	Under consideration	Under consideration	Under consideration
	Induced CW	6.1.2	11	61000-4-6	3 V	3 V	3 V
	Transients - Unidirectional Nanoseconds	6.1.3	12	61000-4-4	1 kV	1 kV	4 kV
	Microseconds			61000-4-5	2 kV	2 kV	4 kV
	Milliseconds			61000-4-5	0.5 kV	0.5 kV	0.5 U _{pk} (2)
	Transients – oscillatory Low frequency	6.1.3	13	61000-4-12	2 kV	2 kV	2 kV
	Medium frequency			61000-4-12	2 kV	2kV	2kV
High frequency	61000-4-18			0.5 kV	1 kV	1 kV	
HF – radiated CW	ISM equipment	6.2.2	15	61000-4-3	1 V/m	1 V/m	10 V/m

Electromagnetic Compatibility and Smart Grid Interoperability Issues

Phenomenon		For details concerning phenomenon see subclause ⁸	For details regarding disturbance, see Table ³	Standard for testing or for additional information	Disturbance Level for Location		
					Residential	Commercial / Public	Industrial
HF - radiated modulated below 30 MHz	Amateur radio	6.2.3.1	16	61000-4-3	3 V/m	3 V/m	3 V/m
	CB radio		17		1 V/m	1 V/m	1 V/m
	AM broadcast		18		1 V/m	1 V/m	1 V/m
RF - radiated modulated 30 – 1000 MHz	Analogue services	6.2.3.2	19	61000-4-3	3 V/m	3 V/m	3 V/m
	Mobile phones	6.2.3.2	20		10 V/m	10 V/m	3 V/m
RF - radiated modulated 30 – 1000 MHz	Base stations of phones	Outside	21	61000-4-3	3 V/m	3 V/m	3 V/m
		Inside	21		30 V/m	30 V/m	30 V/m
	Medical/bio telemetry	6.2.3.2	22		1 V/m	1 V/m	0.3 V/m
	Unlicensed radio services 1		23		3 V/m	3 V/m	1 V/m
	Unlicensed radio services 2		24		10 V/m	10 V/m	10 V/m
	Amateur radio >30 MHz		25		3 V/m	3 V/m	3 V/m
	Paging services/base		26		0.3 V/m	0.3 V/m	1 V/m
	TETRA		31		1 V/m	3 V/m	1 V/m

Electromagnetic Compatibility and Smart Grid Interoperability Issues

Phenomenon		For details concerning phenomenon see subclause ⁸	For details regarding disturbance, see Table ³	Standard for testing or for additional information	Disturbance Level for Location		
					Residential	Commercial / Public	Industrial
RF - radiated modulated 1 - 6 GHz	Mobile phones	6.2.3.2	20	61000-4-3	10 V/m	10 V/m	10 V/m
RF - radiated modulated 1 - 6 GHz	Base stations	Outside	21		3 V/m	3 V/m	3 V/m
		Inside	21		30 V/m	30 V/m	30 V/m
	Amateur Radio	6.2.3.2	25		3 V/m	3 V/m	3 V/m
	Other RF services - 1		27		30 V/m	30 V/m	10 V/m
	Other RF services - 2		28		10 V/m	10 V/m	3 V/m
UWB	31	0.3 V/m	0.3 V/m		0.3 V/m		
RF - radiated modulated > 6 GHz	Amateur Radio	6.2.3.2	25	61000-4-3	3 V/m	3 V/m	3 V/m
	Other RF items - 3		29		10 V/m	10 V/m	10 V/m
	Other RF items - 4		30		0.3 V/m	0.3 V/m	0.3 V/m
	UWB		31		0.3 V/m	0.3 V/m	0.3 V/m
	Other RF items - 6		32		Under consideration	Under consideration	Under consideration
RF - radiated	RFID	6.2.3.3	33	61000-4-3	1 V/m	3 V/m	10 V/m
			34		10 µA/m	30 µA/m	100 µA/m
	Radiated pulsed disturbances	6.2.4	35	61000-4-9	300 V/m/ns	300 V/m/ns	1000 V/m/ns
			36	61000-4-10	0.3 V/m	0.3 V/m	0.3 V/m

Electromagnetic Compatibility and Smart Grid Interoperability Issues

Phenomenon		For details concerning phenomenon see subclause ⁸	For details regarding disturbance, see Table ³	Standard for testing or for additional information	Disturbance Level for Location		
					Residential	Commercial / Public	Industrial
ESD	Slow	7.2	37	61000-4-2	40 A/ns	40 A/ns	40 A/ns
	Fast	7.2	37		40 A/ns	40 A/ns	40 A/ns
	Fields	7.3	38		8 kV/m/ns	8 kV/m/ns	8 kV/m/ns
1) U_n is the RMS amplitude of the power line voltage involved in the signaling 2) U_{pk} is the Peak (not RMS) power line voltage							

10.4.3 Recommended EMC test approach and performance criteria for both Power Delivery and Power Customers

There are a variety of electromagnetic threats that could potentially interfere with the performance of Smart Grid equipment and systems. This section provides a basic introduction to these possible issues and how they may, or may not, be relevant to any specific Smart Grid function. This relevance will be based on the criticality of the function with regard to continued safe delivery of electrical power, as well as any specific customer requirements.

Accredited testing labs (to ISO/IEC 17025 [14]) require a test plan to be agreed upon between the test laboratory and the client requesting the Type test so that it is clear what is to be tested, what are the requirements to be met, what test(s) are to be performed and what to look for in performance degradation during immunity testing, i.e. what is the “pass” or acceptable performance degradation criteria. Any performance degradation has to be instrumented to be quantified, and the instrumentation must not be affected by the test signal. Acceptance Criteria should be agreed to by both parties before testing. A typical generic criteria list is shown in the following section. NOTE: Many product standards (e.g. ANSI C12.1 [9], IEEE 1613 [15], IEC 61850-3 [16], and the IEEE C37.90 series [17, 18, 19, 20]) have more specific Acceptance Criteria for their particular product scope. Those criteria would take precedence over the following generic list.

10.4.4 Performance criteria - evaluation of test results

The test results should be classified in terms of the loss of function or degradation of performance of the equipment under test, relative to a performance level defined by its manufacturer or the requestor of the test or by agreement between the manufacturer and the purchaser of the product.

The following general criteria may be used as a starting point and may be modified as necessary based on the application, measurement, instrumentation, and what is contained in the test plan.

- *Performance criteria A:* Device continues to perform during the application of the interference test signal with no loss of data or function

Example of criteria A:

Operate without loss of function or interoperability continuously

No noticeable degradation

- *Performance criteria B:* Device returns to its normal operation without loss of data or function after the interference test signal is removed

Example of criteria B:

LCD display distortion during test

Error rate below manufacturer's specifications

- *Performance criteria C:* Device requires operator intervention to return it to operation without loss of data or function after the interference test signal is removed

Example of criteria C:

SG status monitoring needing operator to reset or restart

Runaway operation until stopped

Failure of error correction/retransmission

- *Performance criteria D:* Device is irrevocably damaged or destroyed during application of interference test signal

Example of criteria D:

Circuit board or power supply damaged beyond repair.

Other physical damage

These classifications may be used as a guide in formulating performance criteria, by committees responsible for generic, product and product-family standards, or as a framework for the agreement on performance criteria between the manufacturer and the purchaser, for example where no suitable generic, product or product-family standard exists. These criteria are then defined in the laboratory test plan which is agreed to by the client and the test lab technical staff.

10.4.5 Power Delivery EMC Aspects

The environment descriptions and nominal interference levels are described in IEC/TR 61000-2-5 ed2.0 [8] and Table 10.1 for the customer locations (residential, commercial/public, and industrial). However, the power delivery environments need further attention. The Working Group believed that there is a need for explicitly describing the power delivery EMC environment above that of 61000-2-5.

Electromagnetic Compatibility and Smart Grid Interoperability Issues

While there may be situations where the utility equipment is located in a residential, commercial or industrial environment that can be characterized by IEC 61000-2-5, typical power delivery environments are more severe and require higher immunity levels.

In this section we take a slightly different approach to determining immunity test level. The immunity levels noted in the customer environments above represent estimates of the actual environments that may be encountered. Those values do not include any safety or reliability margins. Here we will note actual test levels specified in various product standards which already include a margin agreed to by the standards body.

The various EMC immunity standards developed specifically for electric power utility equipment contain definitions and immunity test levels for phenomena likely to be encountered in the power delivery environments described in section A.2. Tables 3, 4, and 5 contain listings of several IEEE and IEC standards that identified EMC requirements for electric power utility equipment like relays, switches, controllers, meters, etc.

The fundamental aspect of Smart Grid devices is that they all have communications capability. Smart Grid devices currently in place or being installed include synchrophasors in substations and on transmission lines, smart sensors on transmission and distribution lines, distributed generation systems, and smart meters at the customer interface and within the power grid. Since many, if not all, of these devices may be installed in electric power substations, it is the harsh EM environment in those substations that dictates the EMC requirements. The potential failure of Smart Grid devices in substation environments may have serious and perhaps widespread consequences to the electric power grid.

Examples of electromagnetic phenomena that a Smart Grid device in substation or other utility environments may be exposed to include:

- EM transients are generated (high frequency oscillations) on a primary bus in the high voltage yard with normal switching operation of a capacitor bank or coupling capacitor coupling device (CCVT). These EM transients couple to the voltage transformer (VT), current transformer (CT), and control cables in duct banks below the busses and then arrive at the terminals of IEDs in the substation's control room. The effects of these transients are replicated the "oscillatory surge withstand capability test" (defined in IEEE C37.90.1 [18] and 1613 [15], IEC 61000-6-5 [21] and 60870-2-1 [22]).

- The control of circuit breakers, disconnect switches, and the interlocking system for their control are all powered by a station battery (in most cases 125 V dc). When inductances - such as dc operating coils of auxiliary relays - are de-energized, a very fast rising dc transient is created on the dc supply circuit. Its effects are replicated in the “fast transient SWC test” (a second test defined in [18], [15], [21], and [22]). NOTE: This transient is created when the relay or switch controlling the dc current through a large (many Henry) inductance attempts to open. These are often slowly opening contacts, so there are repeated flash-overs of the contact until it opens wide enough to create a high enough dielectric strength to stop the current flow. Then the remaining energy in the inductance creates a very fast rising transient, and dumps that energy into the stray capacitance of the connected control wiring - and every IED connected to that dc bus is thus subjected to this “fast transient”. If there are no DC control circuits connected to the device, or capacitively coupled to its wiring, there is no “fast transient” exposure.
- Roving operators and maintenance personnel commonly use 5 watt portable transceivers (aka “walkie-talkie radios”) for point to point communication in substations, generating stations, and out on the transmission and distribution systems. IEEE C37.90.2 [19] and 1613 [15] test levels provide immunity when the radio’s antenna is a minimum of 15 cm (~ 6”) from an IED, similar to IEC 60870-2-1 level 4 [22]. However, IEC 61000-6-5 [21], 60255-26 [23], and 61326 [24] are much less stringent, as they provide for the radio to be at least 1 meter from the IED and CISPR 24 [25] would provide for the distance to be at least 2 meters. The 1 or 2 meter distances are not always practical for maintenance operations and the EMII WG recommends the higher immunity provided by IEEE C37.90.2 [19] and 1613 [15].
- Some substation control rooms have vinyl asbestos insulated flooring. With insulated shoes and low humidity, high electrostatic discharges can be created. IEEE C37.90.3 [20] and 1613 [15] provide immunity for environments with relative humidity as low as 15%. Relative humidity below 50% is common in many areas, hence the higher immunity levels in [20] and [15] (8 kV contact, 15 kV air) are appropriate.
- There are other possible disturbances that may be a concern in substations and control rooms. These include but are not limited to:
 - Conducted RF disturbances

- power-frequency magnetic fields
- impulse magnetic fields
- dips and interrupts

The standards listed Table 10.3 define and provide test methods to address these and other disturbances.

10.4.6 Power Delivery EMC Recommendations

Smart meters can be deployed in all three of the operating environments (industrial, commercial, residential) described in section A.3 and both the energy measurement (metrology) and communication meter functions are potentially susceptible to both manmade and natural electromagnetic radiation sources.

While there are existing standards that can be applied to cover many of the potential conducted and radiated EMC immunity needs, AMI is a relatively new technology and unanticipated measurement and communications issues have occurred. It is very likely that many smart meters will be located in close proximity to other newly deployed equipment such as distributed generation and electric vehicle chargers, in wired and/or wireless communication environments, where standards are still under development. It is projected that 50 million smart meters will be deployed by the end of 2012 and the rapid growth of wireless devices of all types presents potential RF coexistence challenges in locations where the smart grid needs reliable communications to achieve its goals. The widespread deployment of public cellular networks and high power RF transmitter towers increase concerns about susceptibility of digital revenue meters to RF intrusion and potential effects on revenue accuracy performance. New shielding and grounding techniques have been applied and a comprehensive focus on RF grounding/bonding vs. just AC grounding has been brought to light.⁹

Clearly understood performance characteristics of consumer products and utility products along with rigid standards and testing requirements can ultimately prevent most EMC interference occurrences. However, due to the level of complexity, high parts count, and relatively low cost of most of these consumer grade devices, there is still the potential that individual products could “degrade” or drift over time and pose an interference problem to the Smart Meter in the future.

⁹ Grounding of Electric Utility Metering, Michael R. Hajny

Electromagnetic Compatibility and Smart Grid Interoperability Issues

Most of these devices are considered to be disposable electronic items and the cost vs. reliability performance specs dictates this.

Of course, for high end grid applications and large industrial customer's redundant systems, higher performance meter equipment with enhanced specifications and parts should be applied in cases where there exists a compelling business case justification for these customers. This can result in a significant increase in cost per installation however, often times 5-10X (or more) the cost of a typical residential Smart Metering endpoint.

The ANSI C12 standards suite is utilized by the electric industry for design and specification of North American electricity revenue meter products. Of particular importance are ANSI C12.1-2008, *American National Standard for Electric Meters - Code for Electricity Metering* [9] and ANSI C12.20, *American National Standard for Electric Meters – 0.2 and 0.5 Accuracy Classes* [26]. ANSI C12 standards are updated as electric grid technology and automation evolves.

Today all Smart Meter communications modules must pass FCC Part 15 A&B [1] compliance for radio modules/modems. Cellular modems must also be certified by the carriers to operate on public carrier networks – whether CDMA, GSM, 1xRTT, 3G, 4G, etc. with carriers such as ATT, Verizon, Sprint, etc.

When a Smart Device is connected to a Distributed Energy Resource (DER) – on the Customer side of the meter but still at a distribution or transmission voltage level - then immunity recommendations for these locations should be identical to those for the Utility at the same voltage level (aka Class A – see below). (Note: these class designations are not to be confused with the class designations for FCC compliance.) The utility owned metering transformers will not significantly attenuate these transients. We include the following matrix (Table 10.2) to make these distinctions abundantly clear, where Class A is the EMI zone for Utility Transmission, Distribution and Substations and Class B is the EMI zone we now refer to as the “Customer Side of the Meter”.

Table 10.2. Recommended EMI Zones for Typical Smart Grid DER Generation

DER Type Immunity Levels	Metered at 1 kV or above EMI Zone - Class A	Metered at < 1 kV EMI Zone - Class B
Solar (residential, commercial, or industrial and large-scale installations)	X	X
Wind (residential, commercial, or industrial and large-scale installations)	X	X
EV Charging/ Peak Period Discharge		X
Merchant Generator / Co-Generator	X	
Biomass Generation	X (typical)	rare
Tidal/ Wave Action	X	
All other	If metered	If metered

Stated another way, it is the voltage at the metering point - not the entity that owns a specific DER - that is the determining factor for Class A vs. Class B EMI Zone selection. Class B locations are then related to the commercial and industrial environments on the Customer side of the meter.

The most commonly applied EMC standards for power stations, and medium voltage (MV) and high voltage (HV) substations are summarized in Table 10.3. Table 10.4 provides the most commonly applied EMC standards for electricity metering (includes smart meters). Tables A.3 and A4 summarize the immunity test levels specified in IEEE and IEC standards for a wide variety of electromagnetic phenomena that may exist in electric utility environments. As mentioned in the previous section, Smart Grid devices will be installed in electric transmission

systems, substations, and throughout distribution systems. The EMII WG recommends testing to the higher immunity levels quoted in Table 10.3 for these environments. (This would include, for instance, the 35 V/m radiated field test level of C37.90.2 [19].)

The reader should note that there are differences in the scope of application for the standards listed in Tables A3 and A4. Here is a brief paraphrase of the scope for each of these standards.

IEC 61850-3 [16]: This part of IEC 61850 applies to substation automation systems and more specifically defines the communication between intelligent electronic devices in the substation and the related system requirements. The specifications of this part pertain to the general requirements of the communication network, with emphasis on the quality requirements. It also deals with guidelines for environmental conditions and auxiliary services, with recommendations on the relevance of specific requirements from other standards and specifications. Note: This standard refers to IEC 61000-6-5 for EMC tests not specifically identified in IEC 61850-3.

IEC 61000-6-5 [21]: This technical specification sets immunity requirements for apparatus intended for use by Electricity Utilities in the generation, transmission and distribution of electricity and related telecommunication systems. The locations covered are the power stations and the substations where apparatus of Electricity Utilities are installed. Non-electronic high voltage and power equipment (primary system) are excluded from the scope of this technical specification.

IEEE C37.90 series [17-20]: This standard specifies standard service conditions, standard ratings, performance requirements, and testing requirements for relays and relay systems used to protect and control power apparatus. A relay system may include computer interface equipment and/or communications interface equipment, such as a carrier transmitter/receiver or audio tone equipment. It does not cover relays designed primarily for industrial control, for switching communication or other low-level signals, or any other equipment not intended for control of power apparatus.

IEEE 1613 [15]: This document specifies standard service conditions, standard ratings, environmental performance requirements, and testing requirements for communications networking devices and communications ports in controllers, sensors and protective relays installed in electric power facilities. It does not cover such equipment designed for operation in other environments, such as office locations. Other than their communications ports, it does not cover such equipment

used in protective relaying applications for which IEEE Std C37.90™ series shall apply.

IEC 60870-2-1 [22]: This section of IEC 60870-2 applies to telecontrol equipment and systems with coded bit serial data transmission for monitoring and control of geographically widespread processes. It is also a reference document for teleprotection equipment and systems and for equipment included in a distribution line carrier (DLC) system supporting a distribution automation system (DAS).

This standard specifies, with reference to the various components of the systems defined above: 1) the characteristics of the power supply to which these components are connected during the normal operation; and 2) the EMC minimum requirements, expressed in terms of immunity and emission test levels.

IEC 60255-26 [23]: This part of IEC 60255 is applicable to measuring relays and protection equipment for power system protection, including the control, monitoring and process interface equipment used with those systems. This standard specifies the basic requirements for electromagnetic compatibility for measuring relays and protection equipment used in open air HV substations and power plants and – for those locations - requires essentially the same immunity levels as those specified in the IEEE standards cited above. However, for measuring relays and protection equipment to be used at substation control rooms and industrial locations, the IEC required immunity levels are reduced by 50%. For this reason, we recommend that the IEEE standards be cited, as they are unchanged irrespective of location.

IEC 60439-1 [27]: This International Standard applies to low-voltage switchgear and control-gear assemblies (type-tested assemblies (TTA) and partially type-tested assemblies (PTTA)), the rated voltage of which does not exceed 1 000 V a.c. at frequencies not exceeding 1 000 Hz, or 1 500 V d.c. This standard also applies to assemblies incorporating control and/or power equipment, the frequencies of which are higher. In this case, appropriate additional requirements will apply. This standard applies to assemblies intended for use in connection with the generation, transmission, distribution and conversion of electric energy, and for the control of electric energy consuming equipment.

ANSI C12.1 [9]: This Code establishes acceptable performance criteria for types of ac watt-hour meters, demand meters, demand registers, pulse devices, and auxiliary devices. It describes acceptable in-service performance levels for meters and devices used in revenue metering. (Table 10.4)

IEC 62052-11/EN 62052-11 [28]: This part of IEC 62052 covers type tests for electricity metering equipment for indoor and outdoor application and applies to newly manufactured equipment designed to measure the electrical energy on 50 Hz or 60 Hz networks, with a voltage up to 600 V. (62052-11 sections 7.5.x address EMC, see Table 10.4)

International Organization of Legal Metrology (OIML) - OIML R 46-1 and -2: Active Electrical Energy Meters [29]: This Recommendation specifies the metrological and technical requirements applicable to electricity meters subject to legal metrological controls. The requirements are to be applied during type approval, verification, and re-verification. They also apply to modifications that may be made to existing approved devices.

The provisions set out here apply only to active electrical energy meters; other meter types may be addressed in future versions of this document. Meters can be direct connected for system voltages up to 690 V, or transformer operated. (Table 10.4)

Table 10.3: EMC Immunity Requirements for Equipment in Power Stations, medium-voltage and high-voltage Substations as quoted from respective product standards.

Phenomena	Immunity Levels and referenced Test Standards						
	IEC 61850-3	IEC 61000-6-5	IEEE C37.90.1, 2, 3	IEEE 1613	IEC 60870-2-1	IEC 60255-26	IEC 60439-1
Power frequency magnetic field (CRT monitors)		3 A/m continuous Note 1 61000-4-8					
Power frequency magnetic field	Amplitudes dictated by environment 61000-4-8 61000-4-10 61000-4-16	100 A/m continuous 1000 A/m for 1 s Note 2 61000-4-8			100 A/m continuous 1000 A/m for 1-3 s 30/300 A/m 10/- A/m 3/- A/m 61000-4-8		30 A/m Note 2 61000-4-8
Radiated, RF EM field, 80-3000 MHz	10 V/m per 61000-4-3 class 3 or 35 V/m per C37.90.2	10 V/m Note 3 61000-4-3	35 V/m 1 kHz AM 80 - 1000 MHz Note 15 C37.90.2	35 V/m 1 kHz AM 80 - 1000 MHz Note 15 C37.90.2	30 V/m 10 V/m 3 V/m 1 V/m Note 7 61000-4-3	10 V/m 1 kHz AM 80 - 1000 MHz Note 3 60255-22-3	10 V/m 80 - 2000 MHz Note 3 61000-4-3
Electrostatic discharge		6 kV contact 8 kV air Note 4 61000-4-2	8 kV contact 15 kV air Note 16 C37.90.3	8 kV contact 15 kV air Note 16 C37.90.3	2 kV – 8 kV, depends on ESD controls Note 14 61000-4-2	6 kV contact 8 kV air Note 14 60255-22-2	4 kV contact 8 kV air Note 14 61000-4-2

Phenomena	Immunity Levels and referenced Test Standards						
	IEC 61850-3	IEC 61000-6-5	IEEE C37.90.1, 2, 3	IEEE 1613	IEC 60870-2-1	IEC 60255-26	IEC 60439-1
Signal port-mains frequency voltage	Varies according to Table-1 in 61850-3 61000-4-16	30 V continuous 300 V for 1 s 61000-4-16				100 V 150 V 300 V Note 13 60255-22-7	
Signal port - surge 1.2/50 μ s common mode/ differential mode	4 kV 1.2/50 and 10/700 μ S 61000-4-5	4 kV/2 kV Note 5 61000-4-5	5 kV line to ground, line to line C37.90	5 kV line to ground, line to line C37.90	4.0 kV 2.0 kV 1.0 kV 0.5 kV 61000-4-5	1 kV, 0.5 kV Line to earth 60255-22-5	2 kV, line to earth 1 kV, line to line 61000-4-5
Signal port - damped oscillatory wave common mode/differential mode	2.5 kV/1 kV 61000-4-12	2.5 kV/1 kV Note 6 61000-4-12 61000-4-18	2.5 kV 5/50 ns 2.5 kHz repetition Note 16 C37.90.1	2.5 kV 5/50 ns 5 kHz repetition.	2.5 kV 1.0 kV 0.5 kV 61000-4-1		
Damped oscillatory magnetic field					100 A/m 30 A/m 61000-4-10		

Phenomena	Immunity Levels and referenced Test Standards						
	IEC 61850-3	IEC 61000-6-5	IEEE C37.90.1, 2, 3	IEEE 1613	IEC 60870-2-1	IEC 60255-26	IEC 60439-1
Signal port - fast transient/burst	4 kV 5 or 100 kHz repetition 61000-4-4	4 kV Note 8 61000-4-4	4 kV 5/50 ns 2.5 kHz repetition C37.90.1	4 kV 5/50 ns 5 kHz rep. Common Mode	4.0 kV 2.0 kV 1.0 kV 0.5 kV Note 8 61000-4-4	2 kV 1 kV 5/50 ns 5 kHz rep. Common Mode 60255-22-4 60255-22-1	1 kV 61000-4-4
Signal port - conducted disturbances induced by RF fields	10 V 61000-4-6	10 V 61000-4-6				10 V 1 kHz AM .15-80 MHz 60255-22-6	10 V .15 - 80 MHz 61000-4-6
LV ac port - voltage dips		30% for 1 period 60% for 50 periods Note 9 61000-4-11		Operate at 80% - 110% rated voltage	60% - 0.5 s 30% - 0.5 s 61000-4-11		30%, 0.5 cycle 60% 5-50 cycles 61000-4-11
LV ac port - voltage interruptions		100% for 5 periods Note 9 61000-4-11			100% - 0.5 s 100% - 10 ms 61000-4-11	100% for 5 to 200 ms 60255-22-11	>95% for 250 cycles 61000-4-11

Phenomena	Immunity Levels and referenced Test Standards						
	IEC 61850-3	IEC 61000-6-5	IEEE C37.90.1, 2, 3	IEEE 1613	IEC 60870-2-1	IEC 60255-26	IEC 60439-1
LV ac port - surge 1.2/50 μ s common mode/ differential mode	4 kV 1.2/50 and 10/700 μ S 61000-4-5	4 kV/2 kV 61000-4-5	5 kV line to ground, line to line C37.90	5 kV line to ground, line to line C37.90	4.0 kV 2.0 kV 1.0 kV 0.5 kV 61000-4-5	2 kV 1 kV 0.5 kV 60255-22-5	2 kV, line to earth 1 kV, line to line 61000-4-5
Power supply port 1 MHz burst Differential / Common mode						1 kV /2.5 kV 60255-22-1	
LV ac port - fast transient/burst	4 kV 5 or 100 kHz repetition 61000-4-4	4 kV 61000-4-4	4 kV 5/50 ns 2.5 kHz repetition C37.90.1	4 kV 5/50 ns 5 kHz rep. Common Mode	4.0 kV 2.0 kV 1.0 kV 0.5 kV 61000-4-4	4 kV 2 kV 5/50 ns 1 MHz Note 8 60255-22-4 60255-22-1	2 kV 61000-4-4
LV ac port - damped oscillatory wave common mode/differential mode	2.5 kV/1 kV 61000-4-12	2.5 kV/1 kV Note 10 61000-4-12 61000-4-18	2.5 kV 5/50 ns 2.5 kHz repetition C37.90.1	2.5 kV 5/50 ns 5 kHz rep.	2.5 kV 1.0 kV 0.5 kV 61000-4-1		
LV ac port - conducted disturbances induced by RF fields	10 V 61000-4-6	10 V 61000-4-6				10 V 1 kHz AM .15-80 MHz 60255-22-6	10 V .15 - 80 MHz 61000-4-6

Phenomena	Immunity Levels and referenced Test Standards						
	IEC 61850-3	IEC 61000-6-5	IEEE C37.90.1, 2, 3	IEEE 1613	IEC 60870-2-1	IEC 60255-26	IEC 60439-1
LV dc port - voltage dips		30% for 0.1 s 60% for 0.1 s Note 11 61000-4-29					30%, 0.5 cycle 60% 5-50 cycles 61000-4-11
LV dc port - voltage interruptions		100% for 5 periods 100% for 50 periods Note 11 61000-4-29					>95% for 250 cycles 61000-4-11
LV dc port - ripple on dc power supply		10% variation Note 11 61000-4-17		5% peak ripple C37.90			
LV dc port - mains frequency voltage		30 V continuous 300 V - 1 s 61000-4-16				100 V 150 V 300 V Note 13 60255-22-7	
LV dc port - surge 1.2/50 μ s common mode/ differential mode	4 kV 1.2/50 and 10/700 μ S 61000-4-5	2 kV/1 kV 61000-4-5	5 kV line to ground, line to line C37.90	5 kV line to ground, line to line C37.90	4.0 kV 2.0 kV 1.0 kV 0.5 kV 61000-4-5	2 kV 1 kV 0.5 kV 60255-22-5	2 kV, line to earth 1 kV, line to line 61000-4-5

Phenomena	Immunity Levels and referenced Test Standards						
	IEC 61850-3	IEC 61000-6-5	IEEE C37.90.1, 2, 3	IEEE 1613	IEC 60870-2-1	IEC 60255-26	IEC 60439-1
LV dc port - fast transient/burst	4 kV 5 or 100 kHz repetition 61000-4-4	4 kV 2.5 kHz repetition 61000-4-4	4 kV 5/50 ns 2.5 kHz repetition C37.90.1	4 kV 5/50 ns 5 kHz rep. Common Mode	4.0 kV 2.0 kV 1.0 kV 0.5 kV 61000-4-4	4 kV 2 kV 5/50 ns 1 MHz Note 8 60255-22-4 60255-22-1	2 kV 61000-4-4
LV dc port - damped oscillatory wave common mode/differential mode	2.5 kV/1 kV 61000-4-12	2.5 kV/1 kV Note 10 61000-4-12 61000-4-18	2.5 kV 5/50 ns 2.5 kHz repetition C37.90.1	2.5 kV 5/50 ns 5 kHz rep.	2.5 kV 1.0 kV 0.5 kV 61000-4-1		
LV dc port - conducted disturbances induced by RF fields	10 V 61000-4-6	10 V 61000-4-6				10 V 1 kHz AM .15-80 MHz 60255-22-6	10 V .15 - 80 MHz 61000-4-6
Functional earth port - fast transient/burst	4 kV 5 or 100 kHz repetition 61000-4-4	4 kV Note 12 61000-4-4	4 kV 5/50 ns 2.5 kHz repetition C37.90.1	4 kV 5/50 ns 5 kHz rep. Common Mode ????		4 kV 2 kV 5/50 ns Note 8 60255-22-4	2 kV 61000-4-4

Phenomena	Immunity Levels and referenced Test Standards						
	IEC 61850-3	IEC 61000-6-5	IEEE C37.90.1, 2, 3	IEEE 1613	IEC 60870-2-1	IEC 60255-26	IEC 60439-1
Functional earth port - conducted disturbances induced by RF fields	10 V 61000-4-6	10 V Note 12 61000-4-6				10 V 1 kHz AM .15-80 MHz 60255-22-6	10 V .15 - 80 MHz 61000-4-6
Lightning discharge 10/700 μs					1 kV-protected, 2 kV- not protected 61000-4-5		
	<p>NOTES:</p> <ol style="list-style-type: none"> 1. Applicable to CRT monitors 2. Applicable only to apparatus containing devices susceptible to magnetic fields, e.g. Hall sensors 3. This level normally allows the use of portable 5 watt transceivers at 1-2 meters distance 4. Higher test values shall be adopted for equipment installed in a severe electrostatic environment, or at outdoor locations 5. Surge waveform - 10/700 μs is recommended for signal ports connected to a telecom network or remote equipment 6. Test is performed at 1 MHz for AIS using 61000-4-12. For GIS use 61000-4-12 up to 30 MHz 7. Different severity levels can be applied for installations where proper mitigation methods (Faraday cage, limits on use of portable radios, etc.) are adopted. 8. Repetition rate of 2.5 kHz used at 4 kV. 9. Not applicable to ac output ports 10. Test is performed at 1 MHz for AIS using 61000-4-12. For GIS use 61000-4-12 up to 30 MHz 11. Not applicable to dc output ports 12. Applicable to dedicated functional earth connections separated from the safety earth connection 13. Test voltage depends on Class A or B, differential or common mode arrangement. 14. The ESD test voltages (6 kV contact and 8 kV air) are for environments with relative humidity of 50% or higher. 15. This level normally allows the use of portable 5 watt transceivers at 15 centimeters distance. 16. C37.90.3 and 1613 also require ESD testing at 2, 4 kV (contact) and 4, 8 kV (air discharge) in addition to the levels noted. 						

Table 10.4: Electrical metering (including Smart Meters) EMC specifications

Phenomena	Immunity Levels and referenced Test Standards		
	ANSI C12.1	IEC 62052-11 EN 62052-11	OIML R 46-1 and -2
Voltage variation test	Test at 90% and 110% of rated voltage ANSI C12.1 Note 1.	50% for 1 minute	30% for 0.5 cycle 60% for 1.0 cycle 60% for 30 cycles (60 Hz) 25 cycles (50 Hz)
Frequency variation test	Test at 98% and 102% of rated frequency ANSI C12.1 Note 1		
Voltage interruptions test	0 volts for 100 ms. Perform 10 times within 10 s ANSI C12.1 Note 2.	100% (0 volts) for 1 second Perform 3 times, Restore time 50 ms. Also 100% for one cycle Single interruption	0 volts for 300 cycles (60 Hz) 250 cycles (50 Hz) 61000-4-11 61000-6-1 61000-6-2
ac port - surge 1.2/50 μ s combination wave	6 kV, 3 kA IEEE C62.41.2-2002 Note 3.	4 kV 61000-4-5 Note 10.	2.0 kV line to line 4.0 kV line to earth 61000-4-5
ac port - 100 kHz ring wave	6 kV, 0.5 kA IEEE C62.41.2-2002 Note 4.		
Current surge in ground conductor	20 kA in a conductor 1.5 inches from the metering device ANSI C12.1 Note 5.		
External power frequency magnetic field	100 ampere-turn ANSI C12.1 Note 6		1000 A/m, 3 second IEC 61000-4-8

Phenomena	Immunity Levels and referenced Test Standards		
	ANSI C12.1	IEC 62052-11 EN 62052-11	OIML R 46-1 and -2
Radiated RF EM field	200 kHz – 10 GHz 15 V/m (+-5 V/m) ANSI C12.1 Note 7.	80 – 2000 MHz 10 V/m, with current 30 V/m, no current 61000-4-3	80 – 6000 MHz 10 V/m, with current 30 V/m, no current 61000-4-3
Oscillatory SWC	2.5 kV IEEE 37.90.1-2002 Note 8.	2.5 kV, common 1.0 kV, differential 61000-4-12	
Electrostatic discharge	15 kV air 10 discharges 61000-4-2	8 kV contact 15 kV air 10 discharges 61000-4-2	8 kV contact 15 kV air >=10 discharges 61000-4-2
ac port - fast transient/burst	4 kV 61000-4-4 Note 9.	4 kV 61000-4-4 Note 11.	4 kV 61000-4-1 61000-4-4
signal ports - fast transient/burst	2 kV 61000-4-4 Note 9.		2 kV 61000-4-1 61000-4-4 Note 13
ac port - conducted cw 150 kHz to 80 MHz		10 V 61000-4-6	10 V 80% AM, 1 kHz sine 61000-4-6
ac port - damped oscillatory wave common mode/differential mode		2.5 kV common mode 1.0 kV differential 61000-4-12	2.5 kV common mode 1.0 kV differential 61000-4-12
ac port - harmonics, including mains signaling		See Note 12. 61000-4-13 to be amended	0.02 line Voltage 0.1 transitional current, frequency from 15 – 40 line frequency

10.4.7 Standards Gaps for Power Delivery (utility) Equipment

There are several concerns related to EMC requirements for power delivery (utility) Smart Grid equipment. These include

- While there are basic test standards for all identified EM disturbances (e.g. IEC 61000-4-x series, for all standards in this series see [30]) there is variability in the scope and test levels of the several product standards that call out these basic test standards. As new Smart Grid equipment is developed these product standards should be examined and updated to both address and test the new technology in a consistent manner.
- The differences in the scope and application of the standards listed in Tables 10.3 and 10.4, and differences in the requirements for the various markets (e.g. U.S. vs. EU for example) require manufacturers to either make multiple versions of a product or design/test to all the various standards. While this issue is beyond the scope of this committee, greater coordination between the various standards bodies and more harmonized standards and requirements would be beneficial.
- The differences in the IEC and the IEEE standards in Table 10.3 highlight the fact that IEEE does not address all the possible EM disturbances for utility substation environments (reference IEC 61850-3 [16] and IEC 61000-6-5 [21]). Since IEEE 1613 [15] is often specified for the U.S. market, the WG recommends that the IEEE include those EM disturbances relevant to the North American power system. This will both simplify compliance for the manufacturers and strengthen EMC in substation environments. The following EM immunity tests should be considered and added to IEEE 1613:
 - *Surge* (Basic test standard IEC 61000-4-5)
 - *Conducted RF immunity* (Basic test standard IEC 61000-4-6)
 - *Power-frequency magnetic field* (Basic test standard IEC 61000-4-8)
 - *Damped Oscillatory Magnetic fields* (Basic test standard IEC 61000-4-10)
 - *Conducted Common-mode disturbances* (Basic test standard IEC 61000-4-16)

The analysis did not consider all possible systems in each section of the grid, but rather focused on key environments and associated systems that may be impacted

by interoperability issues related to EM disturbances. This reduced the scope of the standards analysis to substation and control center environments (which are ubiquitous throughout the power grid) and smart meters. There may be additional EMC issues for the bulk power generation environments (gas and coal fired thermal, hydro, and in particular nuclear) that go beyond interoperability into safety or operational concerns. Since the charter for this Working Group was to examine Smart Grid interoperability issues the discussion of these environments was limited to the substation and control center parts of the bulk power facility.

The EMII WG has identified and addressed issues known to the members. However, we don't know what we don't know and input from the EMC experts in the industry may identify additional concerns. Also, the Smart Grid is dynamic and rapidly evolving so it is not possible to anticipate all the devices that may be developed in the future. While the majority of the standards mentioned in this report can be applied to a wide variety of electronic products there will likely be a need for updated or new EMC standards to continue to enable EMC as these devices are incorporated into the Smart Grid.

10.4.8 Power Customer EMC Aspects

The EM environments that are appropriate for each location where there are power customers are complex and changing with time of day and over time. In general the environment that will be exposed to highest levels of electromagnetic fields will be industrial areas, followed by commercial/public areas with the residential environment at the lowest level. However it is realized that certain phenomena such as lightning and geomagnetic storms cover a wide area and hence will provide a high level interference potential to all three environment classifications, even at the same time. None-the-less, the residential environment is the appropriate classification for most power customers that live in single family homes. The commercial /public environment, with some consideration of enhanced functional performance requirements, is probably most appropriate for other types of residences (apartments, mixed commercial/residential). This is due to the fact that residences tend to be surrounded by commercial businesses or alternately be next to a centralized business district surrounded by homes. That does not leave out consideration for the industrial structure locations, which may be a worse case consideration for the electromagnetic environment. In any case it is important to consider the critical nature of power customer services in this context.

While the day-to-day EM environments are identified in IEC 61000-2-5 [8], there are low probability events such as HEMP, Geomagnetic Storms and IEMI events that may also threaten both the power delivery and the power customer. The IEC has published a series of standards dealing with these threats including IEC 61000-2-9 [31], 61000-2-10 [32], 61000-2-13 [33], 61000-4-25 [34] and 61000-6-6 [35]. These events and the applicable standards are described in more detail in Appendix B.

For EMC applications the following immunity checks apply to power customer installations:

- Radiated fields, electrostatic discharge, fast transients/bursts, lightning surge, conducted cw (continuous wave) currents, power harmonics, etc.

As indicated above the low probability events are:

- High energy/power phenomena (HEMP, Geomagnetic Storms, Intentional EMI) See Appendix B for more detail.

Other nearby (within range of being affected) electronics must be protected from radiated and conducted emissions from the normal operation of the power grid and other SG components. For power customers this is usually handled by the power grid components meeting Part 15 of the FCC rules for unintended conducted and radiated interference.

10.4.8.1 Residential Environment Installation Issues

The reliability of Smart Grid equipment depends in part on its immunity to electromagnetic disturbances. Moreover, the importance of reliability for Smart Grid equipment increases with the number of customers that depend on that equipment. For example the failure of a piece of equipment in a substation has the potential to impact every customer connected to that substation. On the other hand, the failure of a single appliance in a home impacts only that one customer since the local nature of EMC disturbances (other than high power events) means that it is unlikely that more than a handful of devices will be affected by an EMC event at any given time.

For consumer electronics and appliances sold in the U.S., only electromagnetic emissions and safety issues are subject to mandatory regulations, leaving it to manufacturers to voluntarily test their products for EM immunity and for the

marketplace to provide the necessary feedback through returns, warranty repairs, complaints, etc. In many other countries regulations cover both emissions and immunity. The overwhelming evidence, based on manufacturers' returns and complaints data, is that consumer electronics and appliances do not pose a significant reliability issue to the Smart Grid, especially when installed and used as intended.

This report details the standards and test levels that consumer electronics and home appliance manufacturers should reference when designing and testing their products. Additionally, the SGIP Home-to-Grid Domain Expert Working Group has developed a report on "EMC Issues for Home-to-Grid Devices" that highlights the possible interference issues that should be considered in the design of smart devices for the home. This report is attached as Appendix E and is an integral part of this white paper. However, no matter which standards Smart Grid devices are designed to meet, their reliability will suffer if they are improperly installed.

The residential Smart Grid customer and their contractors can reduce the potential for electromagnetic compatibility issues by proper installation, wiring and grounding practices, and installation of lightning and surge protection. While this is true in all environments, it is especially important in the residential environment where it is more likely that only the minimum requirements necessary to meet building safety codes have been implemented.

All structures are built to meet the local building electrical codes that were in effect when they were built. However, these codes are focused on safety issues such as shock and fire, not EMC. To avoid EMC problems, special attention should be paid to wire routing and spacing, proper grounding, surge suppression and lightning protection beyond the minimums required by building codes. For example, while in most cases the National Electrical Code [36] requires 2 inches of separation between line voltage and low voltage wiring, most wiring standards such as TIA 570B [37] require a minimum of 6 inches to avoid electromagnetic interference. Proper installation practices will become even more important as more communicating devices are installed in homes to take advantage of the Smart Grid's communications capabilities. One reason is that a surge event such as a lightning strike can enter the home over any unprotected wires and propagate over and couple between line and low voltage wires causing damage to some or all connected devices. Additionally, if wires are run improperly electromagnetic noise from, for example a motor, dimmer or florescent light can couple into network wiring resulting in unreliable communications. The Consumer Electronics Association has developed an installation guide (CEA/CEDIA/CEB-29) [38] that, along with codes

and standards it references, can assist the consumer, builder or installer to improve the performance and reliability of Smart Grid and other connected electronics equipment by reducing electromagnetic interference, and potential damage from lightning and other surge events.

10.4.8.2 Commercial and Industrial Environment Installation Issues

Due to the higher density and power demand of devices in commercial and industrial locations, proper installation of both the wiring and the devices is even more critical than in the residential environment. Mitigating this is the fact that most wiring and device installations in commercial and industrial environments are performed and maintained by trained electricians and IT specialists who know and understand the regulations and requirements specific to their field and the environment they work in. While many of the requirements for the residential environment apply, these environments have a much more comprehensive set of requirements which are defined in many different standards and building, electrical, installation, and fire regulations. A few of these are listed below. Others may also apply.

Safety: The following are safety codes and standards. They specify the minimum requirements necessary for safety considerations and are not necessarily adequate to ensure interoperability between communicating devices or immunity from EMC.

- NFPA 70-2011 [36]: National Electrical Code provides information on the proper installation of electrical equipment and infrastructure with respect to safety – fire and shock hazard.
- NFPA 780 [39]: Standard for the Installation of Lightning Protection Systems, 2011
- UL 96A [40]: Standard for Safety Installation Requirements for Lightning Protection Systems, May 2007
- State and Local Building and Electrical Codes: Building and Electrical Codes may vary based on the location of your building. Consult with a professional knowledgeable in your local codes.

Wiring and Installation: The following standards provide, among other things, information on how to properly install wiring and devices to minimize EMC issues.

- ANSI/TIA 568-C [41]: Consists of 4 sections covering proper installation, performance, and testing of telecommunications cabling.
 - ANSI/TIA-568-C.0: Generic Telecommunications Cabling for Customer Premises
 - ANSI/TIA-568-C.1(2009): Commercial Building Telecommunications Cabling Standard
 - ANSI/TIA-568-C.2: Balanced Twisted-Pair Telecommunication Cabling and Components Standard
 - ANSI/TIA-568-C.3: Optical Fiber Cabling Components Standard
- ANSI/TIA-758-A: Customer-Owned Outside Plant Telecommunications Infrastructure Standard [42]
- ANSI/TIA-942: Telecommunications Infrastructure Standard for Data Centers [43]
- ANSI/TIA-1005: Telecommunications Infrastructure Standard for Industrial Premises [44]
- BICSI Telecommunications Distribution Methods Manual, 12th Edition [45]

The above lists are not exhaustive. There are numerous standards from Underwriters Laboratories (UL), National Electrical Manufacturers Association (NEMA), and other organizations that may be applicable to specific devices, materials, wiring, and installation in these environments.

10.4.9 Power Customer EMC Recommendations

All of the IEC 61000-4-x [30] series of standards in clause 10.4.2 above are candidates in being applicable to Smart Grid products used by power customers. When setting test levels, there needs to be a decision made as to which test level to use, i.e. that for a residential, commercial/public or industrial environment. That decision is left to the specifier and manufacturer as they are the ones that know where their Smart Grid devices will be installed. It may be appropriate to include some margin of immunity even if the installation is in a residential area where there is generally the lowest test level used. Margin might be obtained by testing then to

either the commercial/public or the industrial environment test levels as shown in various tables in IEC 61000-2-5 and which are repeated in part in Table 10.6 below.

Drawing from the tables in IEC 61000-2-5 [8], the list of most applicable test methods for devices on the power customer side of the Smart Grid meters is shown in the following table.

Table 10.5. Typical test methods for power customer devices

61000-4-2	ESD immunity test
61000-4-3	Radiated immunity test
61000-4-4	Electrical fast transients/burst immunity test
61000-4-5	Surge (lightning) test
61000-4-6	Conducted cw immunity test
61000-4-8	Magnetic field immunity, power frequency test
61000-4-11	Voltage dips, interruptions immunity test
IEEE P1642 [46]	Intentional electromagnetic interference

Internationally, the most used product committee immunity standard is CISPR 24 [25] which applies to information technology equipment covering products that operate using a microprocessor. The European Union version of this standard is EN55024. Those devices in the power customer side of the Smart Grid meter will most likely fall into the products covered by CISPR 24. Note that at this time, no other applicable product standard has been found that could also be compared to the test methods and test levels contained in CISPR 24 and in IEC 61000-2-5. Even if there is found at a later time such a standard, the test methods would be the same but the test levels may be different—or the same. It is not envisioned however that the test levels would be outside of the extremes shown in Table 10.6 below.

The question then is which of the test methods in Table 10.5 were considered of most importance in CISPR 24? To make this comparison, Table 10.6 was generated. The first column is the RF immunity phenomena. Columns 2, 3 and 4 are taken from IEC 61000-2-5 and represents test levels that would be applied for the three RF environments shown. The test method is at the bottom of each row. On the far right are the test methods and test levels required to meet CISPR 24/EN55024 for the phenomena indicated in column 1.

By comparing test levels in any row you will find how these levels differ between those shown in IEC 61000-2-5 [8] and CISPR 24 [25] or IEC 61326 [24].

Table 10.6. EMC Immunity Requirements for Equipment in Residential, Commercial/Public, and Industrial locations

Phenomena	IEC 61000-2-5 environment levels			Product Standards	
	Residential	Commercial / Public	Industrial	CISPR 24 EN 55024	IEC 61326 ed2.0 EN 61326
Radiated, RF EM field 80-1000 MHz	O.3 to 30 V/m depending on device to be protected 61000-4-3	O.3 to 30 V/m depending on device to be protected 61000-4-3	O.3 to 30 V/m depending on device to be protected 61000-4-3	3 V/m 61000-4-3	1, 3 or 10 V/m 61000-4-3
Radiated, RF EM field 30-1000 MHz	O.3 to 30 V/m depending on device to be protected 61000-4-3	O.3 to 30 V/m depending on device to be protected 61000-4-3	O.3 to 30 V/m depending on device to be protected 61000-4-3	3 V/m Between 80 and 1000 MHz; no requirement in the range 30 MHz to 80 MHz 61000-4-3	1, 3 or 10 V/m Between 80 and 1000 MHz; no requirement in the range 30 MHz to 80 MHz 61000-4-3
Radiated RF EM field 1 to 6 GHz	O.3 to 30 V/m depending on device to be protected 61000-4-3	O.3 to 30 V/m depending on device to be protected 61000-4-3	O.3 to 30 V/m depending on device to be protected 61000-4-3	No requirement	No requirement
Radiated RF EM field Greater than 6 GHz	O.3 to 10 V/m depending on device to be protected 61000-4-3	O.3 to 10 V/m depending on device to be protected 61000-4-3	O.3 to 10 V/m depending on device to be protected 61000-4-3	No requirement	No requirement
Power frequency magnetic field	10 A/m 61000-4-8	10 A/m 61000-4-8	30 A/m 61000-4-8	1 A/m 61000-4-8	30 A/m 1 A/m on CRTs 61000-4-8

Phenomena	IEC 61000-2-5 environment levels			Product Standards	
	Residential	Commercial / Public	Industrial	CISPR 24 EN 55024	IEC 61326 ed2.0 EN 61326
Electrostatic discharge	Not covered	Not covered	Not covered	4 kV contact 8 kV air 61000-4-2 Note that the air discharge test is with ambient relative humidity between 30 and 60 percent; contact discharge is independent of relative humidity	4 kV contact 8 kV air 61000-4-2
Signal port - surge 1.2/50 μ s common mode/ differential mode	Not covered	Not covered	Not covered	1 and 4 kV, line to earth (for high speed data ports adversely affected by the 10/700 μ s coupling network) 61000-4-5	2 kV, line to earth 1 kV, line to line 61000-4-5
Signal port - surge 10/700 μ s common mode/ differential mode	Not covered	Not covered	Not covered	1 and 4 kV, line to earth 61000-4-5	No requirement
Signal port - fast transient/burst	Not covered	Not covered	Not covered	0.5 kV 61000-4-4	0.5 or 1 kV 61000-4-4
Signal port - conducted disturbances induced by RF fields	Not covered	Not covered	Not covered	3 V .15 – 80 MHz 61000-4-6	1 or 3 V .15 – 80 MHz 61000-4-6

Phenomena	IEC 61000-2-5 environment levels			Product Standards	
	Residential	Commercial / Public	Industrial	CISPR 24 EN 55024	IEC 61326 ed2.0 EN 61326
LV ac port - voltage dips	Not covered	Not covered	Not covered	30% for 25 periods 95% for 0.5 periods 61000-4-11	100 % for 1 period 61000-4-11
LV ac port - voltage interruptions	See standard 61000-4-11	See standard 61000-4-11	See standard 61000-4-11	>95% for 250 cycles 61000-4-11	100% for 0.5 period each polarity
LV ac port - surge 1.2/50 μ s common mode/ differential mode	Microsecond 2 kV Millisecond 0.5 kV 61000-4-5	Microsecond 2 kV Millisecond 0.5 kV 61000-4-5	Microsecond 4 kV Millisecond 0.5 Upk 61000-4-5	2 kV, line to earth 1 kV, line to line 61000-4-5	1 or 2 kV, line to earth 0.5 or 1 kV, line to line 61000-4-5
LV ac port - fast transient/burst	1 kV 61000-4-4	1 kV 61000-4-4	4kV 61000-4-4	1 kV 61000-4-4	1 or 2 kV 61000-4-4
LV ac port - conducted disturbances induced by RF fields (induced CW)	3 V .15 – 80 MHz 61000-4-6	3 V .15 – 80 MHz 61000-4-6	10 V .15 – 80 MHz 61000-4-6	3 V .15 – 80 MHz 61000-4-6	1 or 3 V .15 – 80 MHz 61000-4-6
LV dc port - surge 1.2/50 μ s common mode/ differential mode	No dc requirements	No dc requirements	No dc requirements	0.5 kV 61000-4-5	1 or 2 kV, line to earth 0.5 or 1 kV, line to line 61000-4-5

Phenomena	IEC 61000-2-5 environment levels			Product Standards	
	Residential	Commercial / Public	Industrial	CISPR 24 EN 55024	IEC 61326 ed2.0 EN 61326
LV dc port - fast transient/burst	No dc requirements	No dc requirements	No dc requirements	0.5 kV 61000-4-4	1 or 2 kV 61000-4-4
LV dc port - conducted disturbances induced by RF fields	No dc requirements	No dc requirements	No dc requirements	3 V .15 – 80 MHz 61000-4-6	1 or 3 V .15 – 80 MHz 61000-4-6
Ring Wave immunity Low Frequency	2 kV 61000-4-12	2 kV 61000-4-12	2 kV 61000-4-12	No requirement	No requirement
Ring Wave Immunity Medium Frequency	2 kV 61000-4-12	2 kV 61000-4-12	2 kV 61000-4-12	No requirement	No requirement
Damped Oscillatory Wave Immunity	0.5 kV 61000-4-18	1 kV 61000-4-18	1 kV 61000-4-18	No requirement	No requirement

The first thing that you will see is that CISPR 24 also includes testing for dc ports and dc power. That is not contained in IEC 61000-2-5 and hence those columns are populated with “no dc requirements”. The next observation is that, in general, CISPR 24 leans towards lower test levels for each phenomenon than that of the industrial RF environment levels in column 4. Another observation is that for radiated, RF EM field, 30MHz to 6 GHz, there is a wide range of test levels associated with sources of RF fields identified in IEC 61000-2-5. CISPR 24 has selected from that wide range of test levels, i.e. 3 V/m covering only the 80MHz to 1000 MHz range. Finally, IEEE 1642 (Recommended Practice for Protecting Public Accessible Computer Systems from Intentional EMI) [46] is not yet published and may be added to Table 10.6 at a later time. Test levels in this standard are proposed to be up to 30 V/m for radiated high frequency RF immunity.

In summary, Table 10.6 provides test levels for the test methods shown depending on the particular RF environment where devices are to be installed and/or to give adequate immunity performance.

10.4.10 Standards Gaps for Power Customer Equipment

At the present time, there are few major immunity test standards gaps; however it is envisioned that there may come a time when there is a need for more EMC product immunity standards that need to be developed and/or enhanced to cover new Smart Grid electronics/communication needs that are being introduced. The available electromagnetic immunity test methods as noted above, if applied appropriately, should presently provide adequate interference protection for Smart Grid equipment in typical customer environments (see IEC 61000-6-5 as an example). Manufacturers should develop their own immunity requirements and have the option of either testing for their own compliance using certified/accredited in-house test facilities or independent third party test laboratories. Hence the manufacturer can base sufficient immunity of their products by either route. Further, SG manufacturers might test to even higher levels of immunity from that recommended in this report to avoid costly field repairs or customer complaints stemming from inadequate immunity designs. For some categories of Smart Grid products, it would be advantageous for industry to develop specific product standards for their types of equipment taking into account the EMC immunity tests recommended above.

10.5 Definitions and Acronyms

10.5.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause. (*The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at [http://shop.ieee.org/.](http://shop.ieee.org/))

data flow: Application level communications from a producer of data to a consumer of the data.

data link: A physical communication connection (wire, fiber, wireless, etc) from a source to a destination.

distributed energy resources (DER): Sources of electric power that are not directly connected to a bulk power transmission system. DER includes both generators and energy storage technologies. (IEEE Std 1547-2003)

distributed generation and storage: A complex of entities which include PEVs and solar panels. Related to DER (above).

end-use application: The act or practice of employing a method or manner that serves the purpose of administering or controlling the consumption or production of electricity at a device (equipment or system) or facility.

energy management system (EMS): EMS is a system of computer-aided tools used by operators of electric utility grids to monitor, control, and optimize the performance of the generation and/or transmission system. The monitor and control functions are known as SCADA; the optimization packages are often referred to as "advanced applications".

geographic information system (GIS): Maintains exact geographic information on precise asset location.

information transfer time: The time from when the information is received from the source application to when the information is delivered to the receiving application (i.e. first byte sent by source application to last byte received by destination application).

interface: A logical connection from one entity to another that supports one or more data flows implemented with one or more data links.

interoperability: The capability of two or more networks, systems, devices, applications, or components to externally exchange and readily use information effectively, and with little or no inconvenience to the user.

latency: Channel access delay plus the propagation delay (first byte transmitted on the medium to first byte received at the destination).

load: The true or apparent power consumed by power utilization equipment.

persistence: A process of gathering state information for a working state machine and saving sufficient information about that machine to restore it to an identical state later.

reference model: A model of something that embodies the basic goal or idea of something and can then be used as a reference for various purposes.

reliability: Reliability is the ability of a component or system to perform required functions 1 under stated conditions for a stated period of time (IEEE Std 493-2007).

Smart Grid: The integration of power, communications, and information technologies for an improved electric power infrastructure serving loads while providing for an ongoing evolution of end-use applications.

The smart grid is a digital network that unites electrical providers, power-delivery systems and customers, and allows two-way communication between the utility and its customers.

Smart Grid equipment: Devices which communicate in two directions the control of power and interoperate with other SG equipment in the chain between power delivery and power customer use.

Smart Grid interoperability: The ability of organizations to effectively communicate and transfer meaningful data even though they may be using a variety of different information systems over widely different infrastructures, possibly across different geographic regions.

synchronicity: The requirement to take action at a specific time (e.g., using a timestamp to allow coordinated action at distant parts within a network).

user: The independent party that may be a purchaser of electric power or a producer of electric energy, or both. Synonym: customer

wide-area monitoring (WAM) system: Systems that provide a geographical view of generation and transmission conditions through GPS-synchronized PMUs.

10.5.2 Acronyms

EMC – Electromagnetic Compatibility

EMI – Electromagnetic Interference

EM-Electromagnetic

HEMP-High-altitude Electromagnetic Pulse

HV-High Voltage

IEMI-Intentional EMI

LV-Low Voltage

MV-Medium Voltage

RF-Radio Frequency

SCADA-Supervisory Control and Data Acquisition

SG-Smart Grid

UTP-Unshielded Twisted Pair

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11 APPENDIX B – HEMP, IEMI and Extreme Geomagnetic Storm Events

11.1 Introduction to Appendix B

This Appendix is focused on the threats and impacts of High Power Electromagnetic (HPEM) environments on the U.S. Power Grid and introduces the implications of making the power grid smarter through the introduction of additional electronics. These Smart Grid electronics may introduce additional vulnerabilities if the grid is exposed to the high power EM threats of High-altitude Electromagnetic Pulse (HEMP) from a nuclear detonation in space over the U.S., Intentional Electromagnetic Interference (IEMI) from terrorists or criminals who wish to attack and create regional blackouts using electromagnetic weapons, and finally from an extreme geomagnetic storm (initiated by solar activity) that could create damage to the high-voltage electric grid. An introduction to these threats can be found in [1].

This Appendix will briefly introduce the basic electricity delivery system, as it exists today with an explanation of the trends that are underway to make the grid “smarter”. Some discussion of the impacts of everyday electromagnetic interference on the existing grid will be mentioned, including the fact that EMC standards have been developed to protect existing power grid electronics from these “usual” electromagnetic threats. Next the relationship of the HPEM threats introduced here to the existing EM environments will be explained, including work initiated by the EMP Commission where tests were performed to determine vulnerability levels of the existing grid.

The next portion of this Appendix discusses an approach to be taken to protect both the current power grid and the future Smart Grid from these HPEM threats. This Appendix will then conclude with a summary of the activities of various national and international organizations working to develop HPEM procedures and standards to protect power grids and other critical infrastructures throughout the world.

11.2 What is the Smart Grid?

The electric power grid consists of basic elements of generation, transmission, distribution and users. Currently power generators are dispatched based on the projected power needs for each day, and in some states auctions are held to achieve the best price and reliability outcome for the consumer. Each large power company

has a control center that works to keep the power generated and used in balance, through diverse communications networks. In addition they use communications networks to keep track of the health of the control electronics within substations to react in case of faults or equipment failures. Fig. 1 illustrates a basic power grid example with three types of power generating plants illustrated and three types of users (residential, commercial and industrial). It should be noted that the terminology of transmission, subtransmission and distribution in the figure could vary with respect to particular voltage levels in different parts of the U.S. and the world. In addition the IEC [3] defines a.c. high-voltage as above 100 kV, low voltage as below 1 kV, and medium voltage as in between these two levels. Additionally the term EHV (extra high voltage) is usually defined above 345 kV, and a new term of UHV (ultra high voltage) is defined above 800 kV, both for a.c. power flow.

With regard to the trends for Smart Grid, there are several aspects to consider. Due to the emphasis put on renewable sources of energy (some of which are variable in their output), there are large numbers of wind turbines and solar farms being built by power companies. As these forms of generation become a larger portion of the power generation availability, sensors to track the actual flow of power over short periods of time become more important (as is the reliability of the communications networks to provide this information to the control centers). In addition forecasting of wind velocity over hours and even minutes will become important in the future. If the wind generation drops suddenly, the control center needs to have this information quickly in order to bring up alternate power generators (or drop load) to avoid a power blackout.

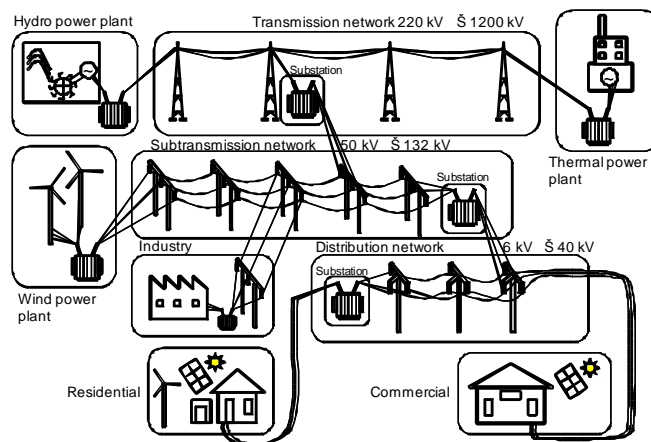


Fig. 1. Basic elements of a power grid [3]

Another area of Smart Grid activity is to upgrade the electronics in high voltage and medium voltage substations and to develop new rapid communications methods to relay status information and to take actions when necessary. Another area of power company activity is to increase the monitoring in the distribution network to determine the location of local outages if they occur and to command the opening of sectionalizing switches if needed.

A final area of Smart Grid activity involves the actual consumer of electricity through the rollout of Smart Meters. These electronic meters can communicate back to the control center through a communications network providing information regarding the use of electricity. In addition consumers may be given alerts regarding the use of power and even changes in the price of electricity during different times of the day. There is a plan to build in control chips for consumer appliances that would allow particular items to be turned off remotely by the power company (with the permission of the consumer, with a possible benefit of lower power rates). There is work ongoing now in the Smart Grid community to develop the communications protocols for this aspect of appliance control. It should be noted that this “demand response” aspect of Smart Grid is viewed as a way to avoid building too many power plants by shifting power usage from peak times to times where power demand is lower. Also with the development of the communications system, it is believed that power companies will be able to operate the grid with less margin between available power generation capacity and the load.

As indicated above, it is clear that one main aspect of Smart Grid is to introduce new electronics in large numbers with expanded ways to communicate to them. It is of some concern that with a smaller operating margin, if the ability to communicate is disturbed or if Smart Grid equipment is damaged, this would likely result in a lower reliability of operation of the power grid. As described below, it will be clear that severe (yet infrequent) electromagnetic threats have the capability to both damage and disrupt the current and future power grids.

11.3 HPEM Threats

11.3.1 IEMI Background

To inform the reader regarding the terminology employed here, the term Intentional Electromagnetic Interference (IEMI) refers to the deliberate attempt to produce electromagnetic radiated and/or conducted disturbances to interfere with the operation of commercial equipment or to create damage to that equipment [4-6]. This could be done for criminal or terrorist purposes, although the purpose of

the technical work underway is to determine the feasibility of such attacks and to determine ways to detect an attack and/or to protect against the types of disturbances that might be generated. As shown in Fig. 2, the IEMI environments (above 300 MHz) are split into two categories known as wideband and narrowband, with both normally produced at frequencies above 100 MHz. In the time domain, the peak electric fields exposing equipment are typically higher than 10 kV/m. Standardization work dealing with IEMI is moving forward in the IEEE EMC Society, IEC SC 77C, Cigré and ITU-T and will be discussed later in this Appendix.

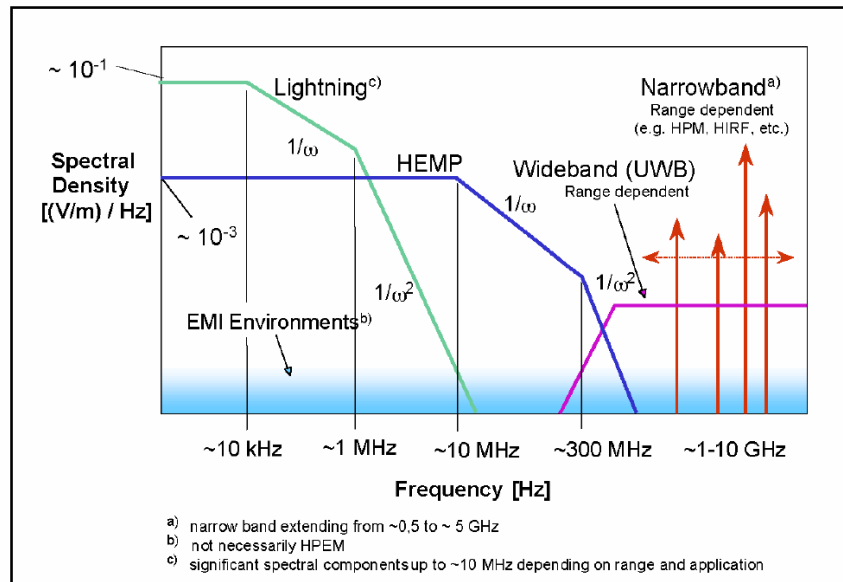


Fig. 2. Comparison of IEMI wideband and narrowband threats with the early-time HEMP and lightning electromagnetic fields [4].

11.3.2 HEMP Background

The terminology of the electromagnetic pulse has evolved over the years, but today the generic term for all types of nuclear generated electromagnetic transients is EMP. Sometimes one will see the term NEMP, which clearly identifies the particular pulse of interest as being generated by a nuclear detonation. Of interest here is the EMP created by a high-altitude burst, generally defined as a burst height greater than 30 km. For this altitude regime, the radiation produced by the nuclear burst does not reach the Earth’s surface, but several types of intense electromagnetic fields will. Because the burst is at high altitudes (in space), this type of EMP is

usually referred to as HEMP. The HEMP has three time (and frequency) portions with the early-time (E1) HEMP reaching field levels of 50 kV/m within 10 ns, the intermediate-time (E2) HEMP reaching 100 V/m between 1 microsecond and 1 second, and the late-time (E3) HEMP reaching 40 V/km for times between 1 and several hundred seconds [1,7]. Based on research performed over the years, it has been concluded that the E1 and E3 HEMP are the biggest concerns to the power system due to their high peak field levels and their efficiency in coupling to power and control lines, respectively. They both have an area coverage that can exceed several thousand kilometers from a single burst.

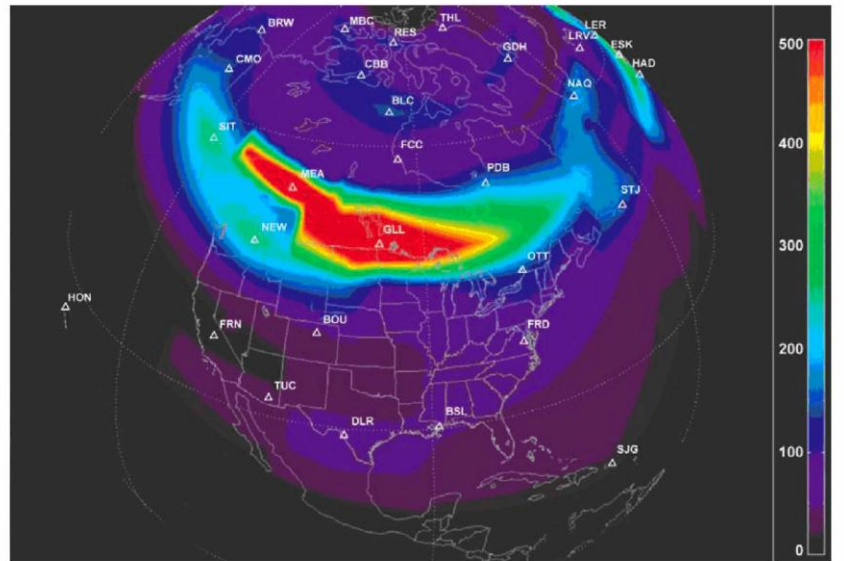
The concern is that these high-level electromagnetic fields and their area coverage will create simultaneous problems for computers and other electronic systems on the Earth's surface, including the critical infrastructures (power, telecommunications, transportation, finance, water, food, etc.). This was the focus of the U.S. Congressional EMP Commission studies [8, 9].

11.3.3 Extreme Geomagnetic Storm Background

The first two high-power electromagnetic environments discussed above are man-made. There is, however, a natural environment known as an extreme geomagnetic storm that has strong similarities (spatial distribution and time variation) to the late-time (E3) portion of the HEMP [10]. Because of this, the protection methods are also very similar, although the specification levels of protective devices may vary. It should be noted that the term extreme geomagnetic storm is used here to indicate that the level of the storm exceeds the usual description by NOAA of a severe geomagnetic storm, which may occur more than once during a solar cycle (11 years). The extreme geomagnetic storm is defined as a 1 in 100 year storm [8].

In brief, a large increase in charged particles ejected from the Sun and into the solar wind can interact with the Earth's magnetic field and produce a significant distortion of the geomagnetic field at the surface of the Earth. This rapid variation of the geomagnetic field (on the order of seconds to minutes) induces time varying electric fields in the Earth, which through the neutrals of transformers create time-varying (yet quasi-dc relative to 60 Hz) currents in the high-voltage power network. These currents induce severe harmonics, increased inductive load and produce heating in each exposed transformer. This can lead to voltage collapse of the network as experienced by the power grid in Quebec on March 13, 1989 and damage to highly exposed transformers. Fig. 3 illustrates the contours of the B-dot environment at the Earth's surface (in nT/min), minutes after the collapse of the

Quebec power network. The spatial extent of the severe fields is quite large, and the footprint can move (and has moved) further South during other storms. For additional information about geomagnetic storms and their impact on power grids, one should consult the literature [11, 12].



Geomagnetic field disturbance conditions, dB/dt (nT/min) over North America at time 7:45 UT on March 13, 1989
 Source: Metatech Corporation, Applied Power Solutions

Fig. 3. Level of B-dot disturbance (measured) from the severe geomagnetic storm that created the blackout in the Quebec power system a few minutes earlier [8]

11.4 Potential Impacts of HPEM with the Power Grid

11.4.1 Early-time (E1) HEMP Impacts

The early-time (E1) HEMP produces a fast rising and narrow electric field pulse (2.5/25 ns) that propagates at the speed of light from the burst point. Fig. 4 illustrates that the area coverage depends on the burst height. Due to the rapid rise of the E1 HEMP in the time domain, the frequency content is much higher in magnitude and frequency than lightning electromagnetic fields and normal substation electric fields produced by switching events in the high voltage yard. These electromagnetic fields can couple to low voltage control cables in a substation and propagate levels on the order of 20 kV to the control house electronics. This presents a severe disturbance to existing substation solid-state protective relays. In

addition the EM fields are high enough also to penetrate the walls of most substation control houses, as the walls are not designed to attenuate EM fields significantly (as shown in Table 1). As more Smart Grid electronics are placed in substations, these E1 HEMP fields become a significant concern to their performance. Also the placement of new Smart Grid communication antennas and electronics in substations should consider the threat of E1 HEMP. It is noted that microwave towers with their long cables extending to the ground are an ideal pickup geometry for E1 HEMP fields, and unless good high-frequency grounding practices (circumferential bonding) are employed at the entrance of the cables to communications buildings, the high-level induced E1 HEMP currents and voltages will propagate efficiently to the cable connections at the electronics, creating likely damage.

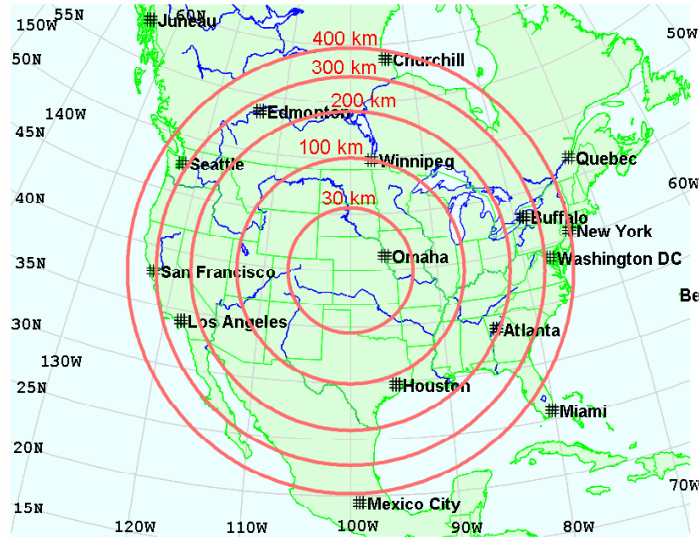


Fig. 4. Indication of the area exposed to E1 HEMP from a high-altitude burst over the central United States for various burst altitudes given in km.

Shielding Measurements		
Nominal Shielding, dB	Room	Shielding, dB
0	All wooden bldg	2
	Room under wood roof	4
5	Wood bldg-room 1	4
	Concrete Š no rebar	5
	Wood bldg-room 2	6
10	Conc.+rebar-room 1	7
	Conc.+rebar-room 2	11
	Conc.+rebar-room 3	11
20	Conc.+rebar-room 4	18
30	Metal bldg	26
	Conc.+rebar-well prot. room	29

Table 1. Shielding effectiveness measurements for various power system buildings and rooms.

E1 HEMP will also couple efficiently to aboveground medium and low voltage power lines that are typical for the distribution grid and also to the low voltage drop lines to homes or businesses. While burial of distribution lines is becoming more common in the U.S., there are still on the order of 70% of U.S. distribution lines at medium voltage that are above ground. The problem with this is that the E1 HEMP can couple voltages up to 1 MV common mode with a rise time of 10 ns and a pulse width of 100 ns [13]. These levels will create insulator flashover on many distribution lines (simultaneously) and can cause mechanical damage to some insulators [14]. For the shorter drop lines to homes, levels on the order of several hundred kV are possible that could seriously damage solid-state Smart Meters. As for distribution line sensors and electronic controls, these would also be fully

exposed to the E1 HEMP environment; without protection for the sensors, cables, electronics and communications, damage could be expected.

Another concern is the protection of the control center for each power company that consists of computers/terminals and displays to keep track of the status of the power system under control and the supporting computer and communications rooms to send and receive data to and from substations. Currently there is some variation in the building construction quality used at different power companies (Table 1), but the best approach to avoid problems is to place the control center in the middle of a large building on a low floor or in the basement. This is because soil and concrete provide some protection from high frequency EM fields. Locating the control center on the top floor with outside walls and windows increases the penetration of EM fields inside the building where they can interact directly with the computers and their ubiquitous Ethernet cables (which are extremely vulnerable to high levels of pulsed EM fields). In the context of Smart Grid, it is likely that more electronics and communications will be added to the control centers, increasing the likelihood of damage or upset to equipment that are required to operate at a higher data rate than today's equipment.

In terms of power generation, E1 HEMP is a threat to the low voltage controls of power plants, including those SCADA systems that control the flow of fuel to the generator. If additional communications are added to the generators to update the power control center periodically for Smart Grid, then these communication antennas, cables and electronics should be protected at least against damage (upset can be handled more easily as personnel are present). For the issue of distributed generation, the proliferation of variable generators such as wind turbines will require new communications for Smart Grid applications to keep track of the amount of power being generated on a shorter time basis. Both wind and solar power generators will be exposed to E1 HEMP fields, and additional test data are needed to determine whether the turbine electronics and power converters themselves will be able to survive the effects induced by E1 HEMP.

11.4.2 Intentional Electromagnetic Interference (IEMI) Impacts

As indicated in Fig. 2, IEMI environments tend to be present at somewhat higher frequencies than the E1 HEMP. The typical field levels are also on the order of 10s of kV/m (depending on the location of the attacker relative to the sensitive electronics), but because of the higher frequency content, most electronics appear to be slightly more vulnerable than when exposed to E1 HEMP. This is due to the fact that the penetration of EM fields into an equipment case is typically more efficient as the frequency increases. Also the ability to upset electronics is increased when the frequencies of the EM environment are close to the operational frequency of a microprocessor (typically in the GHz range). E1 HEMP has most of its field energy below 100 MHz.

While the IEMI threat field level is similar to E1 HEMP, it does not resemble a plane wave field that is propagating downward from space. Since the attacker for IEMI is likely within 100 meters, the EM field propagating away from the weapon tends to decrease as $1/r$. This variation in field level with distance (unlike E1 HEMP) does not allow significant coupling to lines with lengths on the order of 100 meters or more. Therefore IEMI is not a significant threat to insulators on medium voltage power lines. On the other hand, the IEMI threat to Smart Meters, distribution electronics, substation electronics, substation communications, control rooms and power generating facilities (including wind and solar facilities) is the same as for the E1 HEMP. Of course, only one facility at a time is exposed by IEMI, but a team of criminals or terrorists could expose a significant set of assets in a city or town by using a weapon mounted inside of a vehicle. It is likely that only a few seconds of exposure would be enough to cause an effect.

11.4.3 Late-time (E3) HEMP Impacts

The late-time (E3) HEMP produces a disturbed geomagnetic field beneath the burst that induces slow rising (rise time on the order of 1 second) electric fields in the Earth up to 40 V/km [7]. The area coverage beneath the nuclear burst is on the order of several thousand kilometers and long transmission lines (e.g., 100 km) can couple 4000 V between the grounded neutrals of their transformers at each end. With a typical line/transformer/grounding resistance of 5 ohms this results in a quasi-dc current flow of approximately 800 A (for this example). This is more than enough to create severe levels of transformer saturation, leading to the creation of high levels of even harmonics in the a.c. waveform and also heating and possible damage to the large transformer itself. As these transformers are very expensive (and for voltages of 500 kV and higher are manufactured offshore) the loss of a significant number of transformers could create a long-term power outage in the exposed area (months or more). Also a blackout situation is likely to result even where transformers were not damaged, and it would take significant time and effort to restart the grid where assets were not damaged.

A second aspect of the E3 HEMP is the fact that the severe harmonics would propagate throughout the grid and could create malfunctions and damage to building backup power systems. Harmonic immunity is built into most UPS and backup diesel generator systems; however, the harmonics generated by an E3 HEMP (and also an extreme geomagnetic storm) will greatly exceed those normal immunity levels. As for Smart Grid, there are already some concerns that the harmonics normally present in many power systems create accuracy problems for

Smart Meters. The IEC is working to add additional tests to the International Smart Meter standard [x] to address this matter. The IEC immunity tests do not cover the enhanced levels due to E3 HEMP or geomagnetic storms, so the impact to Smart Meters is not currently known.

Finally the low-frequency E3 HEMP environment occurs immediately after the early-time, high-frequency E1 HEMP. This raises the prospect that control electronics, including high voltage protection relays, may not operate properly due to the E1 HEMP, and this could result in additional damage that would occur due to the E3 HEMP. This is different than the case of the geomagnetic storm that only produces the low frequency environment similar to E3 HEMP.

11.4.4 Extreme Geomagnetic Storms

While geomagnetic storms are an act of nature (the Sun), they vary in intensity and location on the Earth. Through evaluations of the probability and magnitude of a worst-case geomagnetic storm, Kappenman (who studied the 1859 Carrington storm) [15] has estimated that an extreme geomagnetic storm could produce electric fields on the order of 20 V/km. . The particular types of impacts on the U.S. power grid would be similar to the E3 HEMP impacts discussed above, although the area coverage would likely be larger (by two to three times), depending on the latitude of the storm and its longitudinal coverage (see Fig. 3).

The major difference between the geomagnetic storm and the E3 HEMP is that there is no early-time, high-frequency electric field that precedes the geomagnetic storm. It is therefore likely that in the region of HEMP exposure, the total impacts would be more significant.

11.5 HPEM Protection Approach

Protection from electromagnetic fields is strongly dependent on the frequency range and magnitude of the environment. This is due to the fact that high frequency fields penetrate more easily through gaps in metal shields or through dielectrics such as windows; they also couple well to “floating” wires, which act as antennas. Also, high-frequency conducted transients usually have high power but modest energy, allowing the use of surge protection devices that do not require a high-energy handling capability.

In the case of low-frequency electromagnetic fields which couple to cables, grounding is very important as induced conducted transients with low voltages can be isolated by relatively small gaps.

For these reasons, we will discuss the protection concepts for the high-frequency HPEM threats (E1 HEMP and IEMI) together and the low-frequency HPEM threats (E3 HEMP and Extreme Geomagnetic Storms) together. While there are great similarities within the two groupings, care must be taken to ensure that protective devices are properly sized for both threats within each group.

11.5.1 High-frequency HPEM Protection Approach

The basic approach for protecting from high-frequency HPEM threats is to first take advantage of the EM shielding that is available in your installation. This is applicable to cases where the sensitive electronics are inside of a substation building, a power control center building, a generator control building, or a communications control building. Many building materials will attenuate high frequency fields from the outside to the inside. For cases in which the attenuation is insufficient (see examples in Table 1), then one can consider an augmentation of the shielding through external building additions, internal room wall shielding, or even moving equipment to a newly built shielded enclosure inside the building.

For electronics that are fully exposed to the E1 HEMP or IEMI (e.g. Smart Meters, distribution system sensors and communications, and antenna systems on substations, control center buildings and power plants), it will be necessary to evaluate, by analysis and test, the ability of connected electronics to withstand the E1 HEMP or IEMI environment after high-frequency grounding is improved and filters and surge arresters are added.

In both cases, it is necessary to perform detailed assessments that include evaluations of the electromagnetic shielding effectiveness, coupling to cables, consideration of fiber optic cabling, evaluation of existing filters and surge arresters and vulnerability of the equipment before protection is added. This approach is discussed in some detail for E1 HEMP and IEMI in a recent conference paper that provides additional details beyond those given here [16].

11.5.2 Low-frequency HPEM Protection Approach

The basic approach for protecting against the two low-frequency HPEM threats

described here is to prevent the electric fields induced in the Earth from coupling to the neutral connections of the high voltage transformers in substations. This can be done with neutral capacitors (to block) or resistors (to reduce), but the difficulty is that a fast bypass must be provided to allow for lightning surges and faults to flow safely to ground without damaging the neutral “blocking” device. While these types of devices have been successfully applied at lower transformer voltages than associated with the EHV power grid, some techniques have been developed that should work for EHV transformers. The next step is to develop and test prototypes, write standards and then field test and deploy the devices [17].

11.6 Organizations Dealing with the Threats of HEMP and IEMI

11.6.1 IEC SC 77C (EMC: High Power Transient Phenomena)

Since 1989, the International Electrotechnical Commission (IEC) headquartered in Geneva, Switzerland has been publishing standards and reports dealing with the HEMP and IEMI threats and methods to protect civilian systems from these threats under IEC SC 77C. As these are electromagnetic threats, it was decided from the beginning that this work would be closely integrated with the EMC work being performed by the IEC and other organizations throughout the world. In fact, IEC Technical Committee 77, the “parent committee” of SC 77C, has the title “EMC”. There are several recent papers that provide details on the 20 IEC SC 77C publications that can be applied to the definition of the threats, the coupling to systems and the protection of systems [6, 18]. It is noted that these are basic standards and as such do not describe the resultant recommended immunity levels for particular types of equipment; this means that the standards should be applied on a case-by-case basis.

11.6.2 ITU-T Study Group 5

The International Telecommunications Union – Telecommunications Standardization Sector (ITU-T) has been working since 2005 to protect telecommunications and data centers from disruption from HPEM threats, which include HEMP and IEMI. They have relied a great deal on the basic publications of IEC SC 77C to prepare their recommendations. As of 2011, they have completed two recommendations for protecting against the E1 HEMP and IEMI [19, 20].

11.6.3 IEEE P1642

The IEEE EMC Society, with the support of TC-5 (High Power EM), has been developing the “Recommended Practice for Protecting Public Accessible Computer Systems from Intentional EMI [21].” The purpose of this work is to provide guidance to businesses and government agencies that are operating computer systems in close proximity to public access. The concern is that criminals and terrorists could use electromagnetic weapons to disrupt or destroy important computer systems without any trace of an attack. The focus on this work is to establish appropriate threat levels, protection methods, monitoring techniques and to recommend test techniques to ensure that installed protection is adequate. This document is scheduled for publication in early 2012.

11.6.4 Cigré C4 Brochure on IEMI

The International Council on Large Electric Systems has formed a working group WG C4.206 entitled, “Protection of the high voltage power network control electronics against intentional electromagnetic interference (IEMI) [22].” This working group is preparing a brochure that will recommend IEMI protection methods for the control electronics found in high voltage substations.

11.7 HPEM Summary

In this Appendix, we have introduced three severe HPEM threats and discussed their likely impacts on the current and future U.S. power grid (Smart Grid). While we cannot be sure of all of the features of the eventual Smart Grid, there is enough information to evaluate the trends. In addition to pointing out the likely impacts on particular aspects of Smart Grid, assessment methods and protection measures have been described with references to more detailed studies. It is expected that efforts to assess and protect Smart Grid electronics and communications from electromagnetic interference (EMI) from “everyday” threats will continue as described in the main document; it is also recommended that assessments and protection be considered for these “low probability” HPEM threats.

In terms of standardization activities, the IEC 61000 series contains a significant set of basic immunity and protection standards that can be used to develop product immunity standards for the HPEM threats. The ITU-T has developed two applications of the IEC basic HPEM standards for HEMP and IEMI (K.78 and K.81)

for telecommunications facilities, which have some similarity to power system facilities; these might be extended to power system facilities. The IEEE EMC Society and Cigré are nearly finished with their efforts to describe IEMI protection methods for public accessible computers and power substation controls, respectively. Neither of these efforts will result in standards, but rather reports will be produced that will identify possible protection options.

While these efforts are important and considerable in nature, there is a need to assess the impacts of the HPEM threats on all aspects of the envisioned Smart Grid, including Smart Meters, Smart Meter communication systems (end to end), distribution sensors and communications (end to end), substation sensors and communications (end to end), power generator sensors and communications (end to end), and power system control center communications and computers. Once these assessments are complete, it will be possible to determine the specific needs for HPEM Smart Grid standards.

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12 APPENDIX C: Evolution of Smart Meters and the Advanced Metering Infrastructure

12.1 Smart Meter Historical Evolution

Electromechanical electricity meter technology stayed pretty much the same for nearly a century since the early day's electric power pioneered by the likes of George Westinghouse, Thomas Edison, and Nicola Tesla. In the early 1970's, new solid-state metering was initially developed in the form of a watt/watt-hour transducer used for energy interchange billing and special applications. Later, the register function evolved to electronics. In 1979 the first micro-processor based electronic register was seen as an addition to the traditional electromechanical revenue meter. This "hybrid" meter gained some acceptance because of expected benefits to reliably perform complex functions such as demand calculations, time-of-use, sliding demand and other functions and could provide these at a lower cost¹.

¹Handbook for Electricity Metering – Tenth Edition, Edison Electric Institute, Waldorf, MD.
http://www2.eei.org/products_and_services/descriptions_and_access/handbook_meterng.htm

However, some early vintage electronic registers deployed in the early 1980's were later found to be susceptible to power system disturbances, surges, and transients due to lightning, storms, and switching events in the field. In response to this, the utility Industry immediately developed enhanced test equipment and standards to help improve product performance and reliability. Handling of meters with electronic components also required additional requirements for electrostatic discharge immunity in these products.

The modern evolution of communications technologies eventually spilled over to revenue meter systems, eventually becoming integrated into the meter systems-- first by interconnecting pulse and serial data to outboard devices and then later to "under glass" modems and communications modules as costs and manufacturing techniques were refined.

In the early 1980's some interference was seen when 5 watt, 450 MHz walkie-talkie radios were keyed in the vicinity of electronic apparatus. Today, with widespread deployments of Advanced Metering Infrastructure (AMI) endpoints, AMI meters or Smart Meters, there are occasional reports of interference between household appliance and meters. This has manifested itself in reported interference events affecting GFCI circuit tripping, baby monitors, garage door openers, wireless ceiling fans, home computer networks, etc. In most of these cases, these were easily resolved and typically a "misbehaving" consumer grade product was found to be the

issue, as these devices are generally limited in the amount of immunity to such devices as transceivers.

This report focuses on increasing the immunity of Smart Grid devices with the application of immunity test standards at test levels appropriate to the electromagnetic environment where the devices are located. The report suggests that there will be a recognition that consumer devices may have to increase its radio frequency (RF) immunity to operate near the Smart Meter which by regulation will limit its emissions.

12.2 Automatic Meter Reading Infrastructure Background

Automated meter reading technology dawned primarily between the mid-1980s and early 1990s. In the beginning, there were three primary options:

- (1) walk-by/drive-by solutions,
- (2) one-way systems, and
- (3) two-way dial-up phone-based solutions.

Walk-by/drive-by solutions are used still for AMR data collection where RF modules chirp their readings periodically and a device, either handheld or a mobile fleet-mounted receiving unit, picks up the data when nearby.

One-way systems involve programming meters to send readings to the utility at periodic rates—typically daily—sometimes called bubble-up networks. These use consumer phone lines, radio technology or one-way, legacy power line carrier (PLC) signals transmitted over the utility's distribution lines.

Past and current two-way, dial-up phone systems are straightforward and use a computer to dial modems attached to electric meters, particularly at commercial accounts. A few of these solutions have evolved, allowing adequate data transfer with modern telephony technology, predominantly still used for small batches of meters rather than entire service territories.

Two-way communicating meters are the most advanced class of Smart Meters. Smart Meters are now part of the digital AMI, which now or in the future may have two-way communication between the utility and the user. The new ability of the utility to directly communicate to Smart Meters attached to buildings and

residences will further establish smart meters as the “face” of the Smart Grid to many consumers. At times AMI is even mistakenly thought to be the Smart Grid.

With this added digital AMR capability, the power utility may have the ability to communicate nearly real time energy pricing and demand response, or load control, signals directly to the location of use where energy management software could then be able to process those signals to help consumers make informed decisions on the financial implications of energy use.

Current AMI communications typically break into one of three main subsystems: wide area networks (WAN), local area networks (LAN), and the newest, home area networks (HAN), though these terms are not used universally. WAN communications refers to backhaul communications media that connect to the LAN. One can think of the WAN as an interstate highway: plenty of room for lots of traffic (bandwidth), and it links to cities (or gateways) where it connects to smaller thoroughfares (or LANs), such as state highways. The LAN, akin to the state highway network, handles the bulk of day-to-day regional traffic (or AMI messages) and ties to a single street entering a cul-de-sac. The street that connects to this small neighborhood represents the emerging concept of a HAN, which would serve only an endpoint such as a home.

12.2.1 WAN

People often call this “interstate highway” the bulk communications channel as it passes large payloads of data between LAN gateways and the master station usually located in a utility’s office. Media used for WAN communications typically use longer-range, high-power radios or Ethernet IP-based solutions. Common options include microwave and 900 MHz radio solutions, as well as T1 lines, digital subscriber lines (DSL), broadband connections, fiber networks, Ethernet radio, digital cellular and WiMAX.

12.2.2 LAN

The LAN is the core of AMI communications technologies and typically differentiates vendors. This subsystem can provide two-way communication paths directly to the utility’s meters or AMI endpoints. The two predominant technologies involved are, as they were in the beginning, PLC and RF. Because they are two-way networks with

significant speed and bandwidth, however, they differ substantially from some of the legacy technology mentioned previously.

12.2.3 RF AMI Networks

RF solutions include wireless technologies that use an assortment of frequencies, cover a range of distances and implement a variety of network topologies or methodologies. The two primary RF AMI network topologies include star networks, sometimes called point-to-multipoint systems, and mesh networks.

Bandwidth, or data capacity, of a radio system typically is inversely proportional to the distance the communication message can cover. Thus, designing communication systems typically involves selecting an optimum balance of distance and speed or bandwidth, which are interdependent on transmit power and frequency, as well as the cost of the transmitter. Typical frequencies include 900 MHz and 2.4 GHz, although others exist. It should be noted that these bands are also used for many wireless services and hence from an EMC perspective there may be co-existence issues with devices not interfering with each other's transmissions

As suggested, these radio systems can be used in two configurations. Star or point-to-multipoint typically involves a central gateway to a number of AMI endpoints (meters). This gateway could be a communications tower with a transmitter or a centrally located meter that talks to child or slave meters. For example, Gateway A may talk to meters 1, 2, 3 and 4. While redundant paths may exist to these slave meters, the relationships are typically pre-set and consistent.

A mesh system allows communication paths to weave together, often in a daisy-chain pattern. In this example, Gateway A may talk to meters 1 and 2, with meter 2 talking to meter 3, and meter 3 communicating with meter 4 to complete the link.

Typically, RF solutions are most cost-effective for urban, densely populated service areas.

12.2.4 PLC AMI Networks

PLC communications involve transmitting and receiving messages via a utility's distribution power lines that are already connected to every meter. The PLC

systems available use frequencies and modulation techniques that translate into a range of available speed and bandwidth options. These include using the 60 Hz power wave, as well as superimposing high-bandwidth carrier signals of other frequencies onto the power line.

PLC signals most commonly are coupled onto a utility's power lines at its distribution substations, where WAN back-haul communications equipment and LAN AMI injection equipment can be co-located to minimize expenses.

PLC solutions are utilized particularly in low-population-density areas such as rural and suburban service territories where feeders serving meters tend to be lengthy. North American PLC signals are routinely used to communicate with AMI endpoints that might be 10 to 100 miles from a substation.

12.2.5 Hybrid AMI Networks

As larger utilities serve diverse territories, including high- and low-density areas, hybrid solutions often are considered to meet utilities' needs. This is often a combination of RF and PLC systems, which may or may not be tied together into one head-end master station.

12.2.6 Other AMI Networks

Other technologies possible for AMI Networks include Internet Protocol (IP), Fiber-to-the Home (FTTH), and Hybrid Fiber Coax (HFC).

12.2.7 Additional Uses of LAN AMI Networks

LAN communications modules also can be used in devices other than meters to facilitate communications, maximizing a utility's return on its AMI investment. These include demand response (DR) devices, also called load management or load-control devices, and distribution automation (DA) equipment including smart sensor products.

While AMI LAN modules can be used for DR, non-AMI communications options exist, and sometimes non-AMI options are more cost-effective or offer minimal latency. This may be the case if the system was optimized such that all messages have equal priority or network latency was built in to accommodate meshing capabilities or system redundancies.

Distribution Automation (DA) is an ever-expanding suite of solutions, including tools providing monitoring and control capabilities for capacitor banks, voltage regulators, reclosers and sectionalizing equipment, intelligent electronic devices (IEDs) and sensors detecting everything from faulted circuits to energy theft. These solutions allow utilities to maximize system performance and efficiency. Again, some AMI networks lend themselves to facilitate real-time control messaging while others do not.

12.2.8 HAN

HAN was coined in the past few years and refers to communication to devices behind a meter inside a consumer's home. This includes messages to present information via in-home displays (IHDs), as well as messages DR devices can use to control key appliances to manage energy usage and capacity constraints. This network is being conceptualized in response to mandates across the nation to improve energy efficiency and educate and empower electrical consumers.

ZigBee is a common buzzword surrounding HAN communication conversations. Often confused for a communication technology, it's a network messaging protocol. ZigBee messages are transported via other RF messaging protocols in unlicensed RF spectrum shared by Bluetooth and Wi-Fi to communicate throughout a home.

A few RF and PLC communications technologies exist in this evolving arena. In this scenario, a meter would contain transmitters to communicate to the LAN and devices on the HAN, linking a utility to its customers by leveraging its AMI investment. Most HAN traffic is likely to be between only the meter and the IHD, displaying the meter's usage or demand information.

13 ANNEX – Electromagnetic Compatibility (EMC) Issues for Home-to-Grid Devices

Electromagnetic Compatibility (EMC) Issues for Home-to-Grid Devices

by the

Home-to-Grid Domain Expert Working Group (H2G DEWG)

(Contributors and editors are listed at the end of this paper.)

The primary goal of this paper is to ensure that Home-to-Grid devices address EMC adequately when deployed.

The Situation

The H2G DEWG believes that for the Smart Grid (SG) to deliver benefits it must be reliable, secure, and fault-tolerant. One of the key issues that must be addressed is electromagnetic compatibility (EMC). EMC is the ability to withstand the electromagnetic (EM) environment (sufficient immunity) without causing interference (disturbances) to others.

For Home-to-Grid devices to function properly and to coexist with other electrical and electronic systems in the home, they must be designed with due consideration for electromagnetic emissions from the grid or home and for immunity to various electromagnetic phenomena near the grid or in the home. They must also take into account the devices that are already present in the home to minimize interference to those products. Finally, EMC considerations must take the view that the home and a SG are a system since some issues such as surges caused by sources external to the home (e.g., lightning strikes) cannot be remedied at the end device. Potential approaches to mitigate these effects at the system level are suggested below.

The H2G DEWG asked the IEEE EMC Society for information about EMC. The EMC Society prepared a paper entitled *EMC Considerations in Home-to-Grid Devices*. The H2G DEWG appreciates this contribution; it was useful in developing the positions explained here. The EMC Society outlined four broad categories of EMC events that need to be considered:

1. Commonly-occurring EMC events like electrostatic discharges, fast transients and power line disturbances.
2. RF (radio frequency) interference from various kinds of wireless transmitters.
3. Coexistence with wireless transmitters so that wireless communications can be incorporated beneficially (reliably) into a SG.
4. High-level EMC disturbances, both intentional terrorist acts and naturally occurring events, such as lightning surges and geomagnetic storms.

A Smart Grid and associated components should be designed to be immune to interference from electromagnetic effects to the extent possible and economically feasible. If that immunity fails, they should be fault-tolerant so that failures due to such interference do not lead to systemic disruption. At the same time, the signals used to control the grid should not cause interference to other devices. The U.S. Federal Communications Commission (FCC) regulates emissions from devices in the home in FCC Part 15, which covers both conducted (over the power lines) and radiated (over-the-air) emissions. However, even if those limits have been met, the user must take action to mitigate or to eliminate harmful interference to licensed services such as broadcast TV and radio or amateur radio.

Each of the four broad categories of EMC events identified by the EMC Society is addressed in the following sections.

1. Commonly-occurring EMC events:

Manufacturers of Home-to-Grid equipment should consider a variety of electromagnetic phenomena to minimize operational failures or interruptions to Home-to-Grid equipment and systems. A variety of phenomena are known. They include for example, electrostatic discharge (ESD), electrical fast transient

(EFT), surge and radiated and conducted RF energy. Inadequate immunity to interference can cause communication or control failures of Home-to-Grid components. Such failures may lead to interruptions of communication to individual loads (e.g., appliances) or a home control system, rendering load devices unavailable for Demand Response events.

Phenomena that may upset a SG can originate from sources located both outside the home and within the home. One of the most important phenomena is lightning, as typical lightning strikes are measured in tens of thousands of amperes, creating large voltage potentials between equipment grounds and utility services (e.g., ground potential of a pool house to main house). Lightning effects on the power grid are well known, and mitigation measures are a normal part of any power grid topology mitigation. However, indirect lightning strikes on the grid, nearby structures, or from nearby ground strikes can cause failures in unprotected communications, control systems, and individual devices within the home.

A. Electrical surges:

Protection from electrical surges should be handled in a four layered approach.

- 1) The utility or service provider (cable/telephony) provides high-level surge protection “at the service pole.”
- 2) All wires, both line (AC wiring) and low voltage (cable/telephony, communications/control wiring to outdoor equipment such as pool and gate controls, security systems, etc.) entering or leaving the home should have surge protection, also called whole home surge protection. These first two levels of protection cover electromagnetic effects outside the home with the second also providing protection from high voltage spikes generated within the home.
- 3) High value devices such as computers, TVs, etc. should have local or outlet surge protection, which may be included in the outlet

itself or in an “outlet surge strip”¹⁰. This helps to eliminate surges from motors (vacuum cleaners, etc.), lighting controls (dimmers, switching), and other in-home sources.

- 4) The end device should include low-level surge protection, especially in higher value devices that are critical to proper SG operation. However, it should be noted that the primary element used for surge protection has a limited life expectancy based on the number and size of the surges it experiences. Thus, end-device surge protection is not considered a primary solution since the surge protection elements are not field-replaceable. Most entrance, receptacle, and higher quality surge strips include a visual indicator (light) that illuminates when the element needs replacement. These surge protective devices, when integrated with SG equipment, should show a level of robustness that has not been considered in the past by manufacturers.

Note that the first three levels of surge protection lie outside the control of the end-device manufacturer and therefore must be included in either a “best practices” or installation guideline. For high-value devices, testing to a standard such as CISPR 24 or the equivalent is recommended. The levels to test to are variable and depend on the surge environment, which differs from home to grid to power source. Any such recommendations would need to be in an installation guideline or best practices document.

B. Electrical Fast Transients:

Electrical fast transients may also propagate on a power line, having originated in switching operations on the lines. These bursts of low-energy, fast rise-time impulses can interrupt or latch-up communications or control signals on the lines, or interrupt equipment connected to the lines. They are very common and very disruptive. Outlet and end-device surge components are used to protect against this form of electromagnetic interference. It is recommended that outlet/strip

¹⁰ The surge strips should include ground reference equalization (additional communication ports that tie the service grounds together within the surge protective device).

surge protectors used in a SG installation include such fast transient protection. The rating however must be determined for adequacy. The installation guideline or best practices document may include recommendations on ratings.

C. Radiated and Conducted Emissions:

Unintended emissions (both conducted over the power lines and those emitted into the air) from Home-to-Grid systems have the potential to cause harmful interference to licensed broadcast and communications systems as well as other nearby electronic systems. Limits for these emissions are of critical importance in minimizing the potential for such interference. Limits are specified in the U.S. by the Federal Communications Commission. Methods of measurement to determine compliance with such limits exist and are also specified by the FCC. Note that even when meeting such limits, FCC Part 15 requires that if harmful interference is caused, the user must rectify the problem. This is often accomplished by moving or reorienting the device. However, if it cannot be otherwise rectified, the device must be taken out of service.

Harmful interference is any emission, radiation, or induction that endangers the functioning of a radio-navigation service or other safety services, or seriously degrades, obstructs, or repeatedly interrupts a radio-communication service operating according to the U.S. Code of Federal Regulations (47 CFR, §15.3(m)). Not all interference that may occur is “harmful interference” as defined by national and international regulations. The IEEE P1900.2 Recommended Practice, entitled *Recommended Practice for Interference and Coexistence Analysis* is a good source of additional information on this topic.¹¹

D. EMC immunity:

Immunity from EMC interference for most consumer electronic products sold in the U.S. is voluntary and driven by market forces. Devices that are found to be unreliable are either redesigned by the manufacturer to fix the problem or are rejected by the consumer or the distribution/retail channel. This is essentially the same as for other non-safety related reliability issues involving poor or inadequate design. If a store or manufacturer gets too many complaints, the product is

¹¹ Information about the scope and purpose of IEEE P1900.2 is available at <http://standards.ieee.org/findstds/standard/1900.2-2008.html>.

removed from the market. Warranty repairs, product returns to the retailer/manufacturer, and recall for safety related issues are paths by which defective products are removed from use. Note that consumer smart grid products (H2G) on the home side of a residential meter are non-critical infrastructure. Any immunity testing requirements or testing levels would be based on the criticality (size) of the load/source. These issues are being considered by the Building Subcommittee of the Smart Grid Interoperability Panel Electromagnetic Interoperability Issues Working Group (SGIP EMII WG). However, to help ensure reliability of the Demand Response and metering/billing systems installed, sold, or supplied by a utility for home use, immunity tests such as those defined in CISPR 24 with the proper test levels could be added to Request for Quotations (RFQs) when purchasing SG equipment.

2. Interference from wireless transmitters:

Radio-frequency currents on power, communications, and control lines can result from radio transmitters in the environment. These transmitters may be fixed in frequency, power, and location, as is the case for broadcast transmitters and cellular telephone base stations, or they may be flexible in terms of frequency, power, or location relative to the home, especially if they are moved about the home coming close to the SG electronics, e.g., meters. Such transmitters may be mobile police, fire, citizen's band, amateur radio, Wi-Fi transmitters, and various wireless devices in the home. Power levels of such transmitters range from milliwatts, to as much as 5 Watts or more. Fixed transmitters such as higher power amateur radios can radiate as much as 1,500 Watts although the antennas of high power transmitters are typically installed outside the home. TV, AM and FM broadcasters can be as much as 50,000 watts or more, but are required by the FCC to be installed far from user's premises. These transmitters may be modulated using a variety of techniques.

All of these aspects should be examined to determine the appropriate electromagnetic environment for critical Home-to-Grid equipment testing and the criteria and measurement techniques to be used for judging acceptance. In the U.S. consumer electronics devices are not mandated to be immune from interference from these devices. Instead, it is assumed the market will be self-policing as noted above, or the user will move the sensitive equipment to another location. However, for devices critical to the reliable operation of a SG, testing to voluntary immunity standards may be advisable. Again CISPR 24 contains the most used immunity standards for IT equipment. Further, as noted

above, utilities providing such devices may wish to include immunity testing and certification to determine compliance as a part of their RFQ process.

3. Co-existence with wireless transmitters:

A related issue arises from the intentional use of wireless SG devices in the home. The unlicensed frequency bands are not reserved for the exclusive use of these devices. Any device operating in these unlicensed frequency bands may be exposed to interference from other, unrelated, transmitters in those same frequency bands. Hence, unlicensed wireless transmitters have the potential to cause interference with other equipment.

It should be noted that in-band interference to existing products operating in unlicensed bands in the home (e.g., baby monitors), such as reported in some smart meter installations, is not an EMC issue. There is no way to guarantee non-interference in such cases. Instead, it is advisable that utilities, smart meter manufacturers, and manufacturers of other non-Critical Infrastructure (CI) SG devices choose wireless frequency bands and technologies that are proven to coexist with existing in-home devices. This will serve to minimize consumer backlash and safety issues with, for example, home medical devices by coexisting or not interfering with the use of spectrum already used for these purposes.

Effective planning, supported by appropriate analysis and research, will reduce conflicts among wireless devices (even in different bands when in close proximity) and between wireless and wired devices. Such conflicts could cause disruption of communications and possible failure of important Demand Response or metering/billing functions.

4. High level EM disturbances:

High Power Electromagnetic (HPEM) phenomena, which include high-altitude Electromagnetic Pulse (HEMP) created by a nuclear detonation in space, Intentional Electromagnetic Interference (IEMI) caused by electromagnetic weapons used by criminals and terrorists, and Severe Geomagnetic Storms created by solar activity all originate outside the home. While these disturbances may be rare, the damage they can cause to a Smart Grid and to

devices within the home is severe including damage to transformers and anything electronic whether it is connected to the grid or not. However, due to the nature of these disturbances, there is little that can be done at the device level or within the home, so we will not delve further into this issue here.

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