ELECTROMAGNETIC COMPATIBILITY QUALIFICATION OF POWER ELECTRONICS FOR I&C POWER APPLICATIONS

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ABSTRACT

Electromagnetic Compatibility (EMC) is a growing field in nuclear equipment qualification. Previously confined to I&C equipment residing in control and cable spreading rooms, EMC qualification has expanded to include the inverters and battery chargers which often power safety-related I&C equipment, as well as adjustable speed drives and material handling equipment which could potentially affect sensitive safety-related I&C systems.

Because much of the data collected to form the current EMC limits and guidance was collected from low-power equipment in relatively low EMI environments, the same guidance, applied to power electronic equipment, produces overly conservative estimations of the performance needed for EMC. Excessive modification in an attempt to bring the equipment into compliance with EMC limits may not be necessary.

This paper provides a brief summary of current applicable EMC guidance and demonstrates a roadmap for the qualification of larger, more powerful devices which takes into account the entire EMC process, including design, testing, mapping of the installed location, and justification of EMC failures with the end goal being successful, timely, and cost-effective implementation of upgrades and compatibility with existing plant infrastructure (in the intended installation environment), even if equipment exceeds traditional operating envelopes.

Key Words: Electromagnetic Compatibility, Equipment Qualification, Inverters, Variable Frequency Drives,

1 INTRODUCTION

One area of plant modernization which has seen significant growth in recent years is power electronic-based devices for power and material handling applications. Advances in semiconductor technology have facilitated increases in efficiency, and increasing automation has produced a host of newer, more efficient designs for mission critical devices such as inverters, jib and polar cranes, and fuel transfer systems, creating better control, higher efficiency, and safety margins in areas of I&C power, material handling, and fuel movement[1]. During the same timeframe, Electromagnetic Compatibility (EMC) requirements have expanded to cover significantly more plant equipment including these power electronic devices, without corresponding research or evaluation of what the requirements imposed on power electronic devices should be.

EMC guidance has historically focused on low power, safety-related I&C equipment. The guidance available for qualifying equipment for EMC in nuclear facilities was developed by measuring low-power digital and analog I&C devices in relatively well-protected environments. Because of the inherently lower voltage and power nature of I&C equipment compared to power electronics, as well as the more stringent EMI control surrounding this equipment, when existing EMC guidance is applied to these higher power devices, the devices fail qualification testing by significant margins, requiring modification, additional engineering time, and often extensive justification for installation. In order to correct this issue, both short-term and long-term solutions are required. In the short term, the best approach is to follow a holistic design process with regards to EMC which includes the following elements:

- Understanding the EMC guidance and limits used for qualifying nuclear power plant (NPP) equipment
- Designing new power electronics upgrades adhering to EMC best practices
- Gathering and interpreting quality EMC qualification data
- Justifying equipment which exceeds qualification limits
  - Using representative plant emissions data
  - Mapping pre and post-installation to determine the impact of the new equipment
  - Using alternative limits based on guidance specific to power electronics

In the long term, guidance for EMC qualification of these larger devices needs to be developed or integrated from other sources so that realistic limits exist for this larger, more powerful equipment. Additionally, installers and manufacturers need to be trained on best installation and design practices for these devices to ensure EMC at the point of installation, as these devices do have a history of creating EMC issues if they are installed improperly. This paper is designed to support the designer and the manufacturer seeking to qualify new power electronic designs by:

1) Providing a brief history of existing EMC guidance, as well as its shortfalls with regards to power electronics.
2) Highlighting best EMC practices for the design of power electronic systems
3) Discussing how to gather and interpret data from EMC qualification, and
4) Determining how to assemble a justification for any failures encountered.

By following this process, necessary upgrades can be successfully implemented, even in the event that traditional qualification envelopes cannot be met with reasonable effort.

2 EMC LIMITS AND GUIDANCE

The guidance used for the EMC qualification of I&C equipment of all kinds comes from EPRI TR-102323[2]. In order to form the limits and guidance used for EMC qualification, EPRI conducted surveys of electromagnetic ambient environments in several operating NPPs in the 1990's. Specifically, the EPRI data was collected from the following plants and locations:

- Haddam Neck installed a digital feedwater control system in the control room. Survey data was collected for this modification in June 1993.
- Browns Ferry installed a NUMAC system in the control room. Survey data was collected for this modification in April-May 1993.
- Brunswick installed a NUMAC system. Survey data was collected in May 1993.
- Perry installed a NUMAC system. Survey data was obtained in November 1993 from several locations including the RPS and turbine deck.
- Vogtle installed a new digital controller on a diesel generator. The data was collected in October 1993.

- Peach Bottom mapped emissions for HPCI, RCIC, and CAD upgrades at several locations including the alternate shutdown panel and cable spreading room in October 1993 through December 1993.
- Palo Verde installed an 850 MHz trunked radio system. Emissions data was collected in the control room in April 1994 through May 1994.

In the case of safety-related equipment, the NRC has published Regulatory Guide 1.180 Revision 1[3], whose technical basis is derived from NUREG/CR-6431, NUREG/CR-5609, and NUREG/CR-6782 as well as EPRI TR-102323 Revision 0, which the NRC evaluated and determined to be an acceptable method of addressing EMC for safety-related equipment.

All of the NRC and EPRI guidance includes the limits for the test levels for emissions and immunity limits. Emissions limits dictate how much electrical noise a device can generate and release into the plant environment, both along its interfacing cables (conducted emissions) and through the air (radiated emissions). These limits are expressed as amplitude vs frequency for both conducted and radiated tests and are tied to specific test methods, such as MIL-STD-461 and IEC 61000-6-4. An example for the MIL-STD-461 RE102 radiated emissions test is shown below in Figure 1.

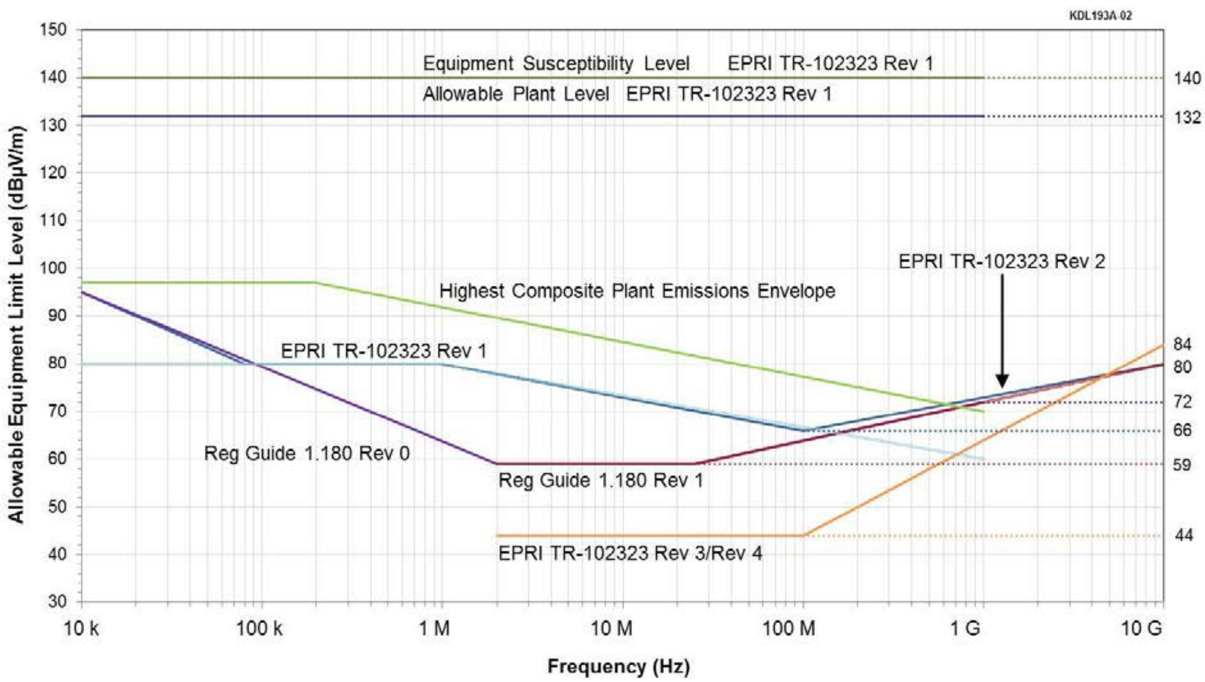

Figure 1. Comparison of EPRI and NRC limits for high frequency radiated emissions

While this guidance is often applied to systems such as inverters and battery chargers in EMI-harsh environments such as switchgear rooms and containment, much of the data that forms its technical basis was collected from areas of the plant which are less severe with respect to EMI. Coupled with the fact that power electronic devices typically operate at 480 VAC and above, and draw more current than most analog and digital I&C systems, these limits represent a large burden on engineers and designers in order to make higher power equipment comply. In order to demonstrate where and how these devices typically fail the emissions limits, typical qualification data from a high power device is presented in the next section.

3 TYPICAL QUALIFICATION DATA FROM LARGE EQUIPMENT

Because most modern inverters and VFDs are switched-mode devices, the most challenging qualification tests to pass are those emissions tests which encompass the following

1) The primary switching frequency of the equipment in question.
2) The harmonics associated with the rising edges of the pulse-width modulated (PWM) waveform.
3) Any ring or overshoot frequencies produced when the inductive primary winding of the output transformer or motor winding is excited by the square waves of the PWM waveform.

These results appear in conducted and radiated emissions tests, typically in the frequency range of 10 kHz to 200 MHz as shown in Figure 2. These results were obtained from a 250 VDC – 120 VAC 60 Hz, 7.5 kVA inverter being qualified for a safety-related service. The primary switching frequency of the inverter is 18 kHz. The harmonics of the primary switching frequency cause conducted emissions failures beginning at 180 kHz, and the peak at 2.5 MHz is caused by overshoot and ringing of the output transformer primary winding, where a total of 175 VAC of overshoot was measured. Approximately 0.3% of this overshoot was parasitically coupled to the power input, where it appeared in the conducted emissions test.

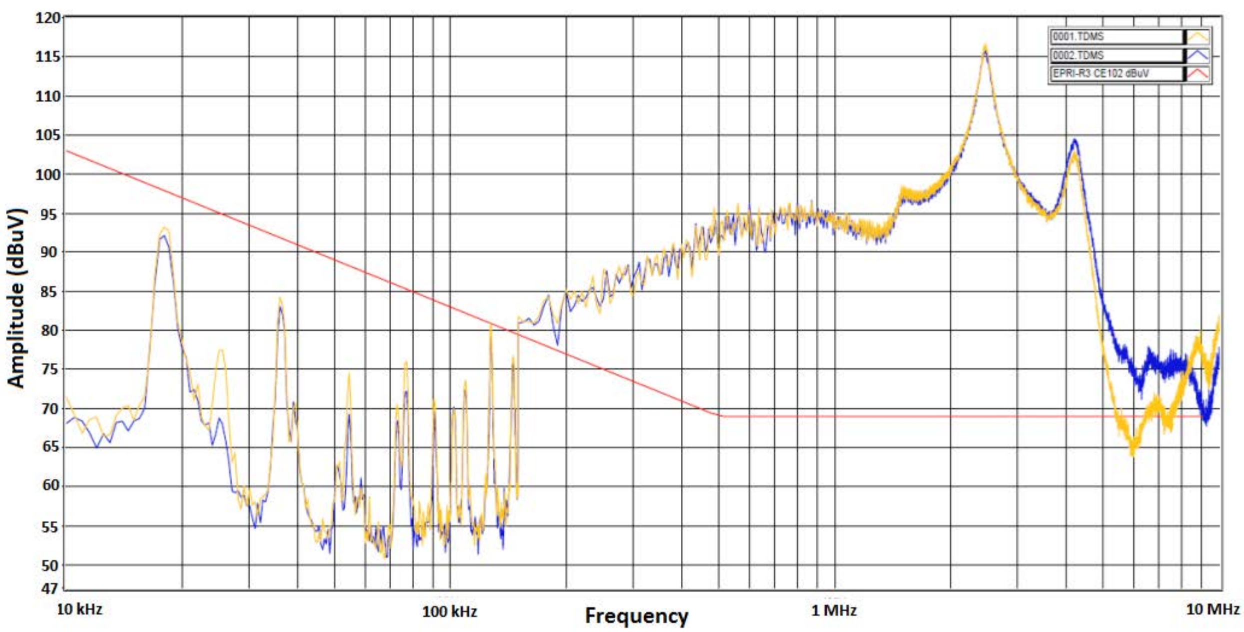

Figure 2. Conducted emissions from a 7.5 kVA inverter

In order to correct the excessive emissions, modifications were made to the enclosure and power line filters had to be added to each section of the inverter. This effort caused weeks of delay in the delivery schedule and increased cost, both in materials and engineering time. Even in a modified configuration, the plant that ordered the inverter ultimately accepted the inverter based on the NRC Regulatory Guide 1.180 Revision 1 limit for RE102, which represented a 15 dB relaxation from the original specification. While this project and others like it have been ultimately successful, they consistently require limit tailoring and design changes, which raise two critical questions:

1) What are realistic qualification limits for power electronic devices?

2) How can the design phase of a project leverage best EMC practices?

4 DESIGNING FOR EMC

The best time to solve EMC issues is in the design phase, when the greatest amount of design flexibility exists. By employing some best practices for EMC design, the number of modifications necessary during EMC qualification can be minimized, the qualification process can be significantly shortened, and costs controlled. As part of the preparation process for EMC qualification, ensure that best practices for design with respect to EMC are followed.

4.1 Include Properly Installed Power Line Filters on All Power Inputs and Outputs.

Regardless of whether the input to the system is AC or DC operated, high frequency EMI can appear at the input *and* output terminals of the device. Many designs include an output filter, but neglect to consider an equivalent filter for the input. Conducted emissions testing, which is applicable to the input power to the device, is one of the most commonly failed tests during qualification. In Figure 3, the impact of input power filtering on the CE102 test for a 7.5 HP VFD hoist is shown. The selected filter improved the emissions at problem frequencies by a factor of 1000. Choosing the correct EMI filter for a given application is extremely important, and several excellent resources address this concern in great detail[4].

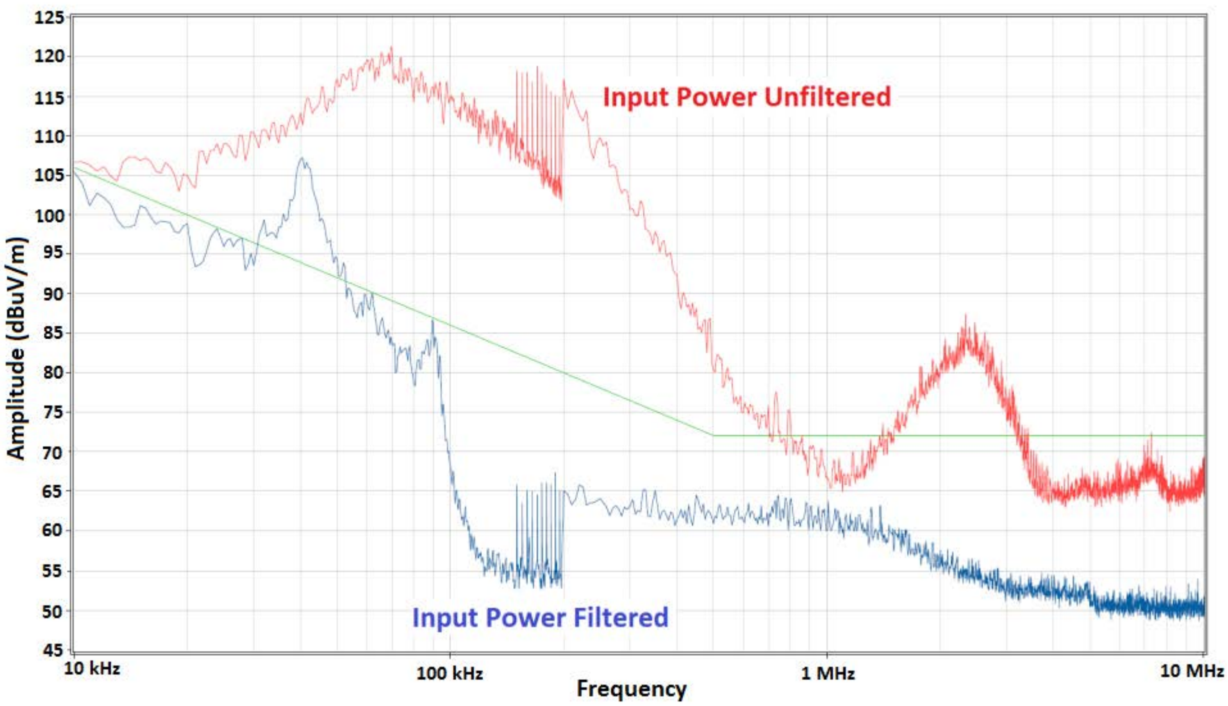

Figure 3. Impact of input power filtering of a 7.5 HP hoist VFD

4.2 Utilize Best Practices in Cable Routing and Component Layout

Oftentimes, proper EMI control devices are in place, but their placement and interconnection produce undesirable effects. In Figure 4, results from a 2 kVA inverter are shown before and after evaluating cable routing internal to the enclosure. In the as-received condition, the AC output filter leads were intermixed, allowing noise to couple around the filter. By segregating “clean” and “dirty” power to the output filter, the radiated emissions from the inverter were reduced by a factor of almost 100 and brought into compliance with the equipment limits.

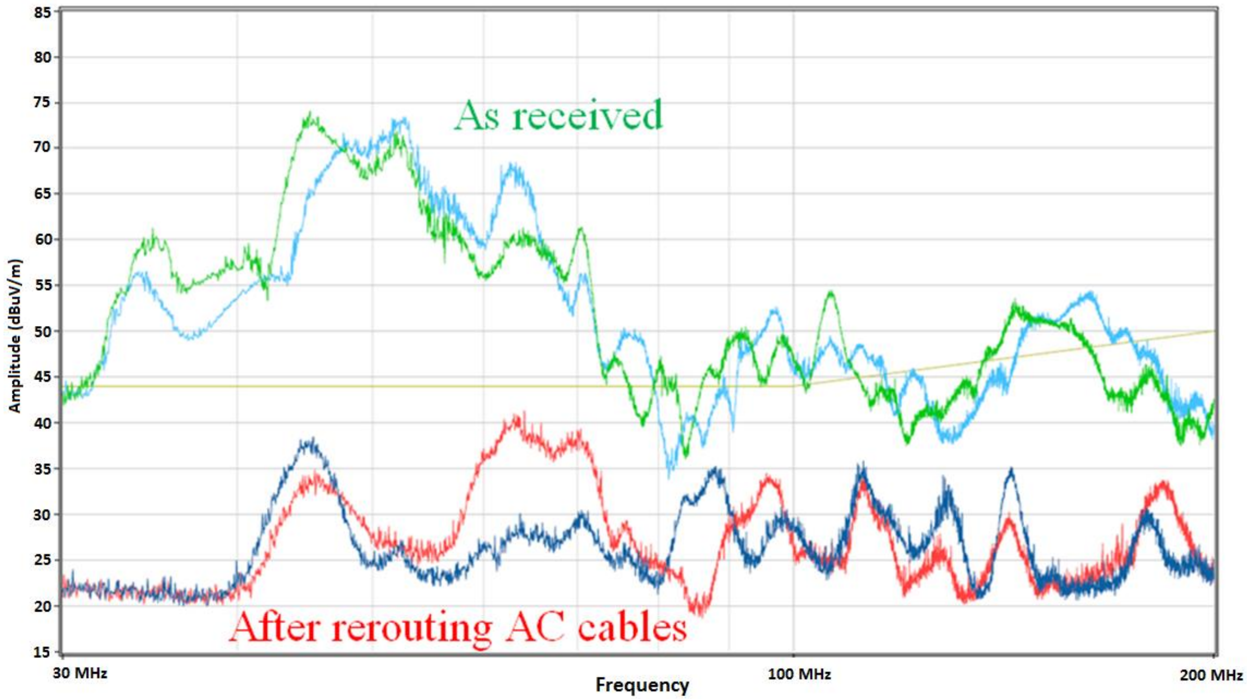

Figure 4. Effect of rerouting cables in a 2 kVA inverter

Relatively simple design considerations such as cable routing and panel layout can offer large gains in terms of EMI reduction, and they are easily implementable and cost very little if they are identified in the early design phase when panel layouts, conduit penetrations, and cable routes are still flexible.

4.3 Ensure that Proper Shielding Practices are Followed, and that Shielding is Correctly Installed.

In the case of a VFD, shielded output cables are often specified by the manufacturer to obtain acceptable EMC performance. It is important to ensure that shields are correctly designed and installed. While many design guides for I&C cables call for cable shields to be grounded only at one end, this is primarily a concern for small signals which could be influenced by power frequency currents flowing on their cable shields. When dealing with large power electronics, this is less of a concern. Regardless of cable length, output cable shields should be bonded to the VFD or inverter enclosure as well as the motor casing[5] similar to conduit. If a special EMI connector is specified, ensure that personnel responsible for cable construction are familiar with the connectors and are trained and qualified in their construction. In Figure 5 an example of an incorrectly constructed EMI connector is shown below in the left side of Figure 5. The shield is cut back and not inserted into the EMI crimp ring, rendering it ineffective. After lengthening and dressing the shield, it is inserted into the crimp ring and properly dressed as shown in the right side of Figure 5. This modification alone allowed the VFD in question to comply with the applicable emissions limit.

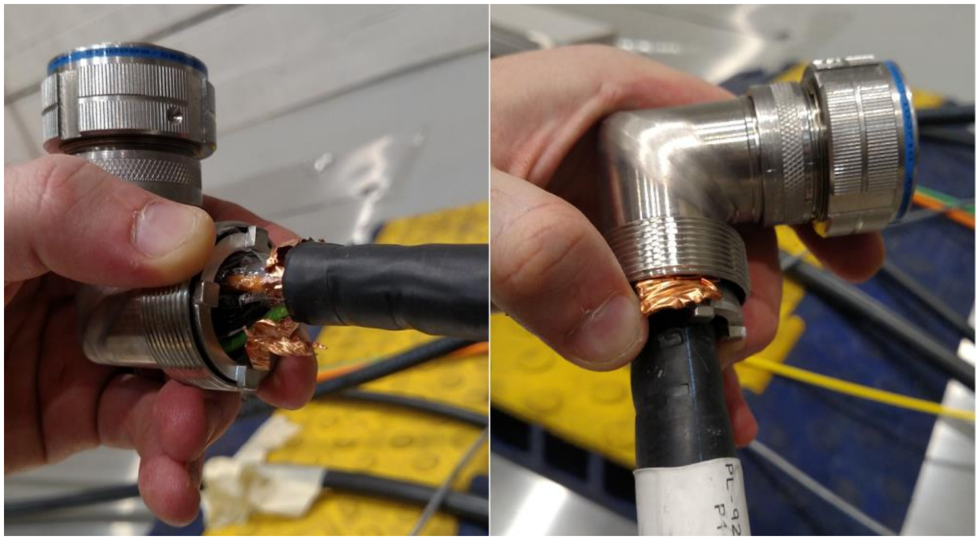

Figure 5. Improper and proper shield crimping in EMI twist lock connector

4.4 Contain Radiated Emissions Using Enclosure Sealing Techniques

Because significant radiated emissions can emanate directly from components in the enclosure, it is often necessary to create a faraday cage using the existing enclosure. One effective method of sealing enclosure seams is EMI gasket material as shown in Figure 6. Important considerations during application are to ensure that all surfaces to be joined are either bare metal or are treated with conductive material. A common issue encountered during equipment qualification is conductive EMI gaskets applied to painted or otherwise non-conductive surfaces, rendering them ineffective.

Figure 6. Application of EMI gasket to a 7.5 kVA inverter enclosure

5 JUSTIFICATION FOR EXCEEDING THE EQUIPMENT LIMITS

In the event that a device fails the traditional qualification envelopes despite best design practices and reasonable effort, a number of approaches are available to assist with justification of the exceeding emissions.

5.1 Ensure Compliance with EPRI TR-102323 Plant Composite Emissions Levels

As previously discussed, EPRI collected mapping data from several plants in the early 1990's, and while this data represents well-protected environments typically devoid of large power electronics, it still demonstrates that the level of EMI present in a typical plant environment is much higher than the limits imposed on new equipment. Using the EPRI plant composite emissions levels allows for significant relaxation of EMI limits while maintaining a valid technical basis for installation. Because the plant composite levels represent the environment of a typical plant, and EMI is a random process, any equipment emissions which are maintained below the current plant EMI levels should be lost in the existing environment. An example of the margin between the EPRI radiated emissions equipment limit and the plant composite level is shown in Figure 7.

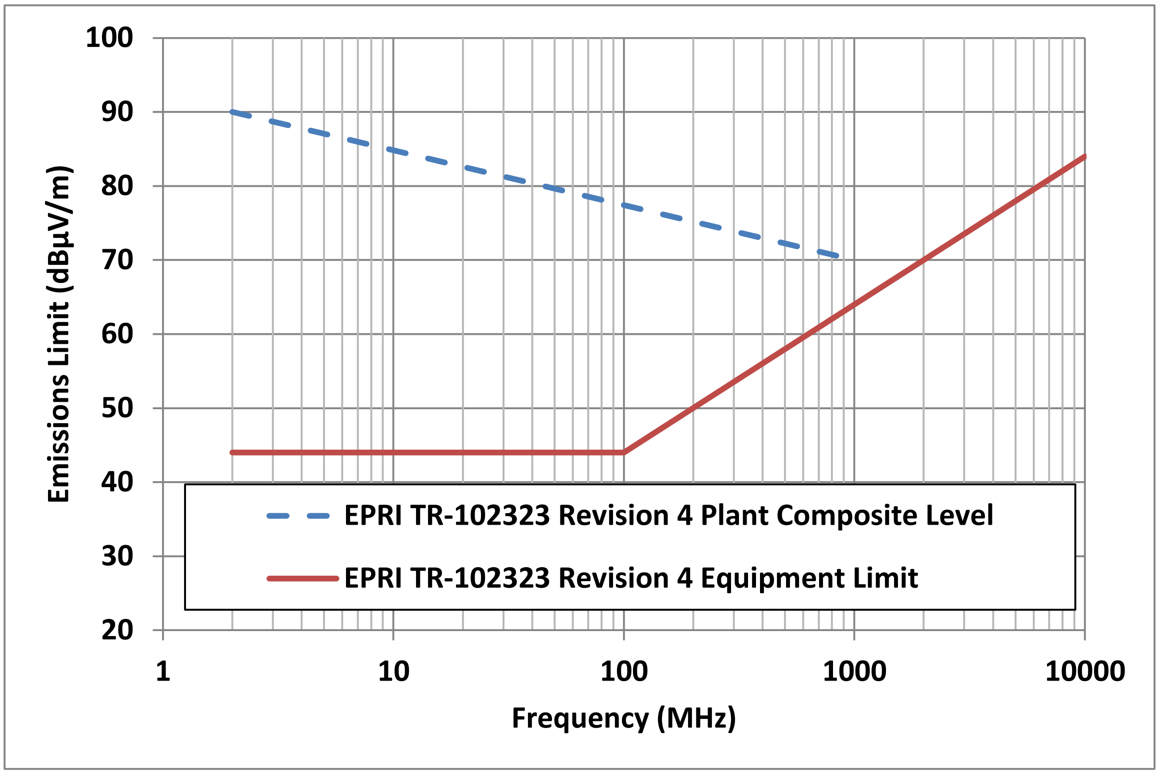

Figure 7. EPRI TR-102323 RE102 equipment emissions limit and plant composite level

5.2 Map the Area Before and After Installation

In addition to employing best design practices and reducing emissions as much as is reasonable prior to installation, both EPRI and the NRC support modification of emissions limits using mapping data from the point of installation. In the case of an existing system replacement, it is acceptable to collect conducted and radiated emissions data, and utilize the existing plant environment as the qualification limit for the new equipment.

In the event that a site or OEM wishes to utilize site mapping data, it is best to collect this data well in advance of any qualification effort. Having the data on hand during qualification will allow for immediate comparison to emissions and susceptibility limits and thresholds and facilitate an immediate determination of passing or failing performance.

5.3 Utilize Test Exemptions when Applicable

In both NRC and EPRI guidance, exemptions exist for both the CE101 and RE101 tests. In the case of CE101, both NRC Regulatory Guide 1.180 Revision 1 and all revisions of EPRI TR-102323 allow for exemption from the requirements of CE101 provided that two criteria are met. First, the power quality requirements of the equipment are consistent with the existing power supply; and second, the equipment will not impose additional harmonic distortions on the existing power distribution system that exceed 5% total harmonic distortion (THD) of voltage or other power quality criteria established with a valid technical basis.

Because CE101 is based on current, semi-conductor devices often fail this test due to intermittent current consumption characteristics, which create large current harmonics. However, modern inverters and VFDs utilize multistage diode bridges to generate their outputs and are extremely efficient, generating little to no distortion of their power supply. It is not unusual to see a well-designed VFD which produces less voltage THD fully loaded than at idle.

In the case of the RE101 test, the exemption is based on proximity of sensitive equipment to the proposed installation location. EPRI TR-102323 states that the RE101 test is required for equipment which is a source of large magnetic fields (> 300 A/m) installed in close proximity (< 1 m) to magnetically sensitive equipment. If the installation location for the equipment is known, a determination of the necessity of the RE101 test can easily be made.

5.4 Propose Alternative Qualification Envelopes

The guidance encompassed by NRC Regulatory Guide 1.180 Revision 1 and EPRI TR-102323 is not specific to inverters or VFDs, and some of the limitations of this guidance have been enumerated herein. However, the IEC has published standards specific to inverters and VFDs such as 61800-3 which specifies limits and testing methods for VFDs. The test methods are in alignment with current guidance for nuclear I&C equipment, but the limits are relaxed as compared to I&C qualification envelopes, and also include test methods for in-situ testing. Onsite testing is needed since many of these devices are a subset of a much larger piece of equipment which is too large to fit in a traditional EMC test environment.

While the existing nuclear guidance does not endorse the limits in 61800-3[6], the IEC is currently working on IEC standard 62003 for nuclear safety-related equipment, and it is expected that it will include an informative annex on VFD and inverter testing which addresses these challenges.

6 CONCLUSIONS

Currently, guidance and limits for the EMC qualification of power electronics such as inverters, battery chargers, and VFDs is insufficient. While it is conservative, it does not consider the higher level of emissions which these devices can produce, or the harsher environments in which they typically operate. This often causes severe failures of the equipment when compared to the existing guidance and limits, significant time and expense to correct these issues, followed by extensive engineering justification for the remaining failures.

Modern inverters and VFDs employ switched mode topologies which produce harmonics from approximately 10 kHz to 200 MHz, which most commonly cause conducted and radiated emissions failures in those frequency ranges.

The best method for qualifying these devices is to follow a holistic approach to EMC which includes understanding the guidance currently in place, along with its limitations, ensuring that the system is designed for EMC, and building appropriate justification as necessary for emissions which exceed the limit using EPRI plant levels and/or site mapping data from the point of installation in the plant.

In the future, guidance from other industry fields, as well as additional data from mapping efforts needs to be integrated into existing EMC guidance to ensure that emissions from power electronic equipment are controlled, and that EMC guidance specific to their application exists.

7 REFERENCES

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