Analysis of Regulatory Guidance on Electromagnetic Compatibility Qualification

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1. Introduction

Due to the development of digital technology, various digital instrumentation and control (I&C) systems and power facilities have been applied to nuclear power plants. For safety-related digital I&C systems to be utilized in nuclear power plants, regulatory requirements shall be met. Among these regulatory requirements, electromagnetic (EM) compatibility qualification is one of the requirements related to environmental qualification for safety-related equipment. The evaluation of the EM compatibility (EMC) shall be performed under the test methods and acceptance criteria provided in regulatory guidance of the Korea Institute of Nuclear Safety (KINS), which is KINS/RG-3.09 [1]. EMC test is composed of the EM interference (EMI) test, where the level of EM emission affecting adjacent equipment is measured, and the EM susceptibility (EMS) test, where the vulnerability of functionality to EMI is evaluated.

To technically understand EMC qualification, it is important to comprehend the various technical standards and previous research focusing on the test methods and acceptance criteria for EMC qualification. The United States Nuclear Regulatory Commission (U.S. NRC) recently published the secondly revised Regulatory Guide (Reg. Guide) 1.180 (revision 2 (Rev.2)) that provides regulatory guidance on the categories, methods, and allowable interference levels and susceptibility threshold levels for EMC tests [2]. Based on the updated references (technical standards and research) related to EMC qualification, U.S. NRC has modified the test method and acceptance criteria of several EMC tests in the revised Reg. Guide 1.180. Thus, investigating the amendments of the revised Reg. Guide 1.180 possibly contributes to EMC qualification of I&C equipment applied to nuclear power plants. In this paper, we analyze the revised Reg. Guide 1.180 focusing on the EMI test especially.

2. Revision of EMI

Reg. Guide 1.180 is referred to various technical standards and reports such as U.S. Military Standard 461 (MIL-STD 461) to introduce the test methods and acceptance criteria for EMI and EMS tests. Table I presents the list of technical standards and research reports updated in the revised Reg. Guide 1.180. There exists the revision of endorsed MIL-STD 461, International Electrotechnical Commission (IEC) standards 61000-3, 4, 5, and Institute of Electrical and Electronics Engineers (IEEE) standards 1050, C62.41.1, C62.41.2, C62.45 in Reg. Guide 1.180 (Rev. 2). In addition, new research reports, whose titles are ORNL/SPR-2015/485, ORNL/SPR-2015/254, and ORNL/SPR-2016/108, is included as new references in Reg. Guide 1.180 (Rev. 2). [3-14].

2.1 Revision of EMI Tests Based on MIL-STD

The level of EM emission caused by either conduction or radiation from the equipment under test (EUT) is measured in EMI tests. The acceptability of the measured EMI is then evaluated by comparison with the allowable EMI level. EMI tests are classified into conducted emission (CE) and radiated emission (RE) tests based on an interfering manner of EM source. In detail, conducted emission tests are divided into low-frequency and high-frequency emission tests with respect to the frequency band of the EM source. To be more, radiated emission tests are classified into electric and magnetic field tests by the type of interfering EM wave.

After reviewing the revision of the EMI test in Reg. Guide 1.180 (Rev. 2), we found that the CE101, CE102, and RE102 were adjusted. Table II presents amendments to EMI tests in comparison between revisions 1 and 2 of Reg. Guide 1.180. As shown in Table II, the revision in the conditions of the exemption and relaxation for the CE101 test is confirmed. In the case of the CE102 test, the test frequency ranges, exemption conditions, and alternative test methods for high-frequency band were revised. In addition, the test frequency range for the RE102 tests was revised. For RE101 test, there is not any revision in RE101 test.

2.1.1. Conducted emissions in the low-frequency range (CE101)

The CE101 test measures the current emissions conducted by the alternating current (AC) and direct current (DC) power leads (including grounds and neutrals) of equipment and subsystems in the range from 30 Hz to 10 kHz (for AC power leads, the test frequency starts with the second harmonic frequency). To qualify EUT in the CE101 test, the measured strength of emission current should not exceed the allowable level (rms current value).

The revised acceptance criteria of the CE101 test in Reg. Guide 1.180 (Rev. 2) are illustrated in Fig. 1. As

Table I. Comparison of the technical bases between revision 1 and 2 of Reg. Guide 1.180

		Before revision	After revision
Documents of technical standards	U.S. Military standard (MIL-STD)	- MIL-STD 461E	- MIL-STD 461G [3]
	IEC standard (IEC-STD)	- IEC-STD 61000-3, Part 3 (2001) - IEC-STD 61000-4, Part 4 (1998) - IEC-STD 61000-6, Part 6 (1997)	- IEC-STD 61000-3, Part 3 (2017) [4] - IEC-STD 61000-4, Part 4 (2012) [5] - IEC-STD 61000-6, Part 6 (2011) [6]
	IEEE standard (IEEE Std.)	- IEEE Std. 1050 (1996) - IEEE Std. C62.41 (1991) - IEEE Std. C62.45 (1992)	- IEEE Std. 1050 (2004) [7] - IEEE Std. C62.41.1 (2002) [8] - IEEE Std. C62.41.2 (2002) [9] - IEEE Std. C62.45 (2002) [10]
Technical reports		N/A	- ORNL/SPR-2015/485 [11] - ORNL/SPR-2015/254 [12] - ORNL/SPR-2016/108 [13]

Table II. Comparison of EMI test amendments

Condition		Reg. Guide 1.180 (Rev. 1)	Reg. Guide 1.180 (Rev. 2)
CE101	The conditions for exemption	The power quality requirements of the equipment are consistent with the existing power supply	The power quality requirements of the equipment are consistent with the existing power supply and design changes include power quality controls
	The conditions for relaxation	For AC-operated equipment with a fundamental current greater than 1 ampere, the envelopes may be relaxed as 20log10(fundamental current)	N/A
CE102	Test frequency range	10 kHz ~ 2 MHz	10 kHz ~ 10 MHz
	The conditions for exemption	Conduct of the CE102 test in the frequency range 10 kHz to 450 kHz may be omitted if the nuclear power plant has power quality controls in place (see the conditions for omission of the CE101 test above)	Conduct of the CE102 test in the frequency range 10 kHz to 150 kHz may be omitted if the nuclear power plant has power quality controls in place (see the conditions for omission of the CE101 test above)
	Alternative test of high frequency bands	FCC Class A certification is acceptable (450 kHz ~ 2 MHz)	N/A
RE102	Test frequency range	2 MHz ~ 1 GHz	2 MHz ~ 10 GHz

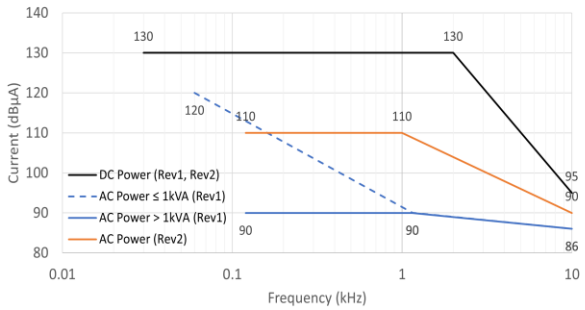


Fig. 1. CE101 operating envelopes

shown in Table II, Reg. Guide 1.180 (Rev. 2) requires the design change including power quality control as an additional condition for the exemption from the CE101 test. In addition, the relaxation, which implies the increase of the allowable emission level with an amount of 20log10(fundamental current) for AC power lines above 1 A, is excluded in Reg. Guide 1.180 (Rev. 2). Thus, considering the addition of exemption conditions and the exclusion of relaxation conditions, we think that the CE101 test has been conservatively revised in Reg. Guide 1.180 (Rev. 2).

Regarding the revision of the acceptance criteria in the CE101 test, whereas the acceptance criteria applied to DC power leads is not changed, that applied to AC power leads is revised. In the revision of the acceptance criterion applied to AC power leads, the EUT is evaluated by a single-allowable emission level regardless of the capacity of power lead (both the dotted line and the solid line in blue change to the solid line in orange in Fig. 1). This revision would allow EUT to be evaluated by a consistent criterion.

2.1.2. Conducted emissions in the high-frequency range (CE102)

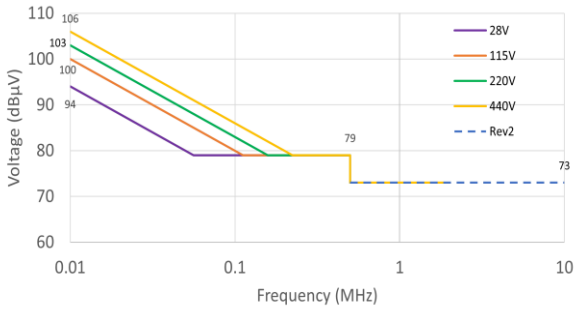


Fig. 2. CE102 operating envelopes

The CE102 test measures the voltage emissions conducted by the AC and DC power leads (including grounds and neutrals) of equipment and subsystems in the test frequency range. For EUT to be qualified in the CE102 test, the conducted emission on power leads should not exceed the acceptable rms voltage as shown in Fig. 2.

As summarized in Table II, the amendments to the CE102 test include that extension of the maximal test frequency from 2 MHz to 10 MHz as depicted in Fig. 2, as well as the reduction of the frequency range, where the exception is allowed conditionally, from 440 kHz (10 kHz ~ 450 kHz) to 140 kHz (10 kHz ~ 150 kHz). In addition, Reg. Guide 1.180 (Rev. 2) does not adopt Federal Communications Commission (FCC) certification as the alternative to the CE102 test. After reviewing the revisions, we think that the CE102 test has been revised somewhat conservatively in Reg. Guide 1.180 (Rev. 2).

2.1.3. Radiated emissions of electric field (RE102)

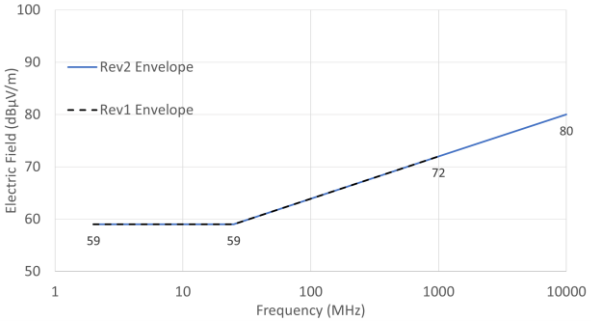


Fig. 3. RE102 operating envelopes

The RE102 test measures the electric field radiated from equipment and subsystems enclosures including all interconnecting leads in the test frequency range. The qualification of EUT is achieved by the measured strength of electric field under allowable strength of electric field presented in Fig. 3.

As explained in Table II, to evaluate the emission of electric field above 1 GHz is to be mandatory in Reg. Guide 1.180 (Rev. 2). We think this revision is because lots of digital equipment operating in the frequency above 1 GHz is possibly employed in nuclear power plants.

2.2 Revision of EMI Tests Based on IEC-STD

Reg. Guide 1.180 endorses various IEC standards as a technical standard in addition to MIL-STD 461. However, the endorsed IEC standards have a limitation in application to EMI tests because there is no emission test corresponding to the CE101 and RE101 provided in MIL-STD 461. Thus, IEC standards are possibly employed for the alternatives to CE102 and RE102 tests.

To understand the difference between revisions 1 and 2 of Reg. Guide 1.180, Table III shows the revision of EMI test methods based on IEC-STD 6100-6-4. The separation distance from EUT in measuring radiated emission changes from 30 m to 10 m. The allowable levels of the radiated emission in the given separation distance simultaneously change from 30 to 40 quasi-peak voltage in the range of 30 MHz ~ 230 MHz, as

well as 37 to 47 quasi-peak voltage in the range of 230 MHz ~ 1 GHz. Furthermore, the test frequency range is extended up to 6 GHz. We think the intention of this revision related to the extension of test frequency is similar to that of the revision of test frequency extension in the RE102 test.

2.3 Alternatives to EMI tests

Table IV summarizes the EMI emission tests in Reg. Guide 1.180 (Rev. 2). When comparing the emission tests based on the IEC-STD between the MIL-STD, the discrepancies expressed as 'Gap between MIL-STD and IEC-STD' in Table V is founded because the IEC-STD provides no emission test corresponding to the CE101 and RE101 tests of MIL-STD. To overcome this limitation in the application of IEC-STD, NRC revised Reg. Guide 1.180 to provide the flexibility in using the alternatives to qualify EUT in EMI tests. Table IV presents the alternative tests for EMI qualification, proposed in revisions 1 and 2 of Reg. Guide 1.180. The alternatives in Table IV are divided by whether the low-frequency emission tests can be excepted or not.

In Reg. Guide 1.180 (Rev. 1), if the exemption conditions for low-frequency emission tests (CE101, CE102, RE101) are met, the emission test based on either IEC-STD or FCC Part 15 can be applied as an alternative (in the assumption that the mixing of EMI test methods is not allowed). Otherwise, in Reg. Guide 1.180 (Rev. 2), the test frequency range in the CE102 test is revised from 10 kHz ~ 450 kHz to 10 kHz ~ 150 kHz. In addition, the FCC Part 15 does not allow to applied to the alternative for EMI qualification. One of the most remarkable revisions in Reg. Guide 1.180 (Rev.2) is that the mix of EMI test methods based on MIL-STD and IEC-STD for EMI qualification is allowed if the exemption conditions for low-frequency emission tests are not met. Reg. Guide 1.180 (Rev. 2) offers flexibility in EMI qualification in that the mix between EMI test methods with different technical bases is allowed.

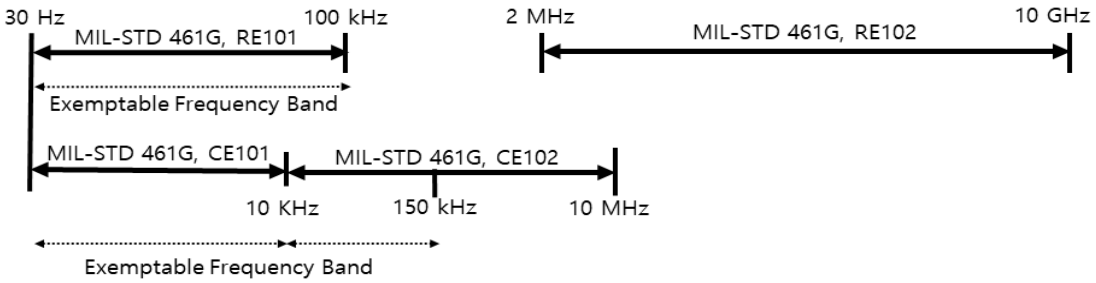
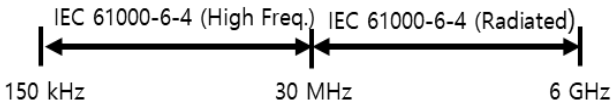
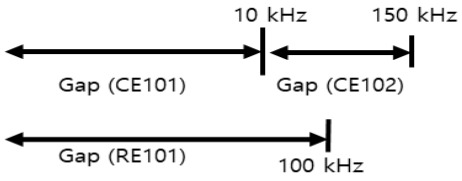
Table III. Amendments to radiated emissions envelopes of IEC-STD 61000-6-4

Reg. Guide 1.180 (Rev. 1)		Reg. Guide 1.180 (Rev. 2)	
Frequency Range	Test Level(dBμ V/m)	Frequency Range	Test Level(dBμ V/m)
30 MHz ~ 230 MHz 230 MHz ~ 1 GHz 1 GHz ~ 3 GHz 3 GHz ~ 6 GHz	30 quasi-peak at 30m 37 quasi-peak at 30m N/A N/A	30 MHz ~ 230 MHz 230 MHz ~ 1 GHz 1 GHz ~ 3 GHz 3 GHz ~ 6 GHz	40 quasi-peak at 10m 47 quasi-peak at 10m 76 peak at 3m 80 peak at 3m

Table IV. Alternatives for EMI qualification

	Reg. Guide 1.180 (Rev. 1)	Reg. Guide 1.180 (Rev. 2)
If the exemption conditions of the low frequency emission tests (CE101, CE102, RE101) are met	- Alternative 1: Perform MIL-STD CE102 (450 kHz to 2 MHz), RE102 tests. - Alternative 2: Perform emission tests based on IEC-STD 61000-6-4 - Alternative 3: Perform emission tests to satisfy FCC Part 15 Class A requirements	- Alternative 1: Perform MIL-STD CE102 (150 kHz to 10 MHz), RE102 tests. - Alternative 2: Perform emission tests based on IEC-STD 61000-6-4
If the exemption conditions of the low frequency emission tests (CE101, CE102, RE101) are not met	- Only CE101, CE102, RE101, and RE102 tests of MIL-STD, which are the basis for EMI emission tests, are allowed.	- CE101, CE102 (10 kHz to 150 kHz), RE101 tests are performed with MIL-STD. - Others are performed emission tests based on IEC-STD 61000-6-4 (IEC-STD + MIL-STD)

Table V. Test frequency range of EMI tests on MIL and IEC standards

Test	Test frequency range
MIL-STD	
IEC-STD	
Gap between MIL-STD and IEC-STD	

2.4 Contribution

KINS published KINS/RG-3.09, endorsing the same technical basis to those of Reg. Guide 1.180, as domestic regulatory guidance on EMC qualification. We think our analysis on the revised Reg. Guide 1.180 will provide useful information to revise KINS/RG-3.09 because the Reg. Guide 1.180 (Rev. 2) reflects the latest technical standards. In advance, we think it is also necessary to build the regulatory position related to how to apply the revised regulatory guidance for EMC qualification to the previously qualified equipment.

3. Conclusions

We investigated the modification of the test method and acceptance criteria related the EMI tests included in the revised Reg. Guide 1.180 because the revision possibly provides useful information for EMI qualification. After analyzing the revised Reg. Guide 1.180, we confirmed that test methods and acceptance criteria of the CE101, CE102, RE102 tests are changed in revision 2 of Reg. Guide 1.180, where the updated technical bases are reflected. Furthermore, we found that Reg. Guide 1.180 (Rev. 2) provides the flexibility in using the alternative methods for the EMI qualification in that the mix of the different technical standards is allowed. From the analysis results, we conclude that the revision of KINS/RG-3.09, which is the domestic regulatory guidance on EMC qualification, is recommended to be reflected the latest technical bases. Thus, it is required to build the regulatory position related to how to apply the revised regulatory guidance for EMC qualification to the previously qualified equipment.

4. Acknowledgement

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea. (No.2106005)

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