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Original Article

Analysis of revised regulatory guidance on electromagnetic interference qualification for nuclear safety

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ABSTRACT

In this paper, we analyzed the revised guidance on electromagnetic (EM) interference qualification of Regulatory Guide 1.180 (Revision 2), which is published by the U.S. Nuclear Regulatory Commission for electromagnetic compatibility qualification for nuclear safety, by comparing it with that of the previous version. We confirmed that the test methods and the acceptance criteria of both CE101 and CE102 tests for conductive emission and RE102 test for radiating emission are changed in the recently revised Regulatory Guide 1.180 (Revision 2). Furthermore, we found that the revised Regulatory Guide 1.180 provides flexibility in the use of alternative methods for EM interference (EMI) qualification, in that a mix of the various base-standards is technically allowed. In addition, the primary revision of the updated Regulatory. Guide 1.180 is that MIL–STD–461G is to be adopted as the latest base-standard, instead of MIL–STD–461E. To evaluate the influence on EMI qualification for nuclear safety due to the endorsement of MIL–STD–461G, we thoroughly analyzed the modifications in the acceptance criteria and test methods for EMI qualification, and then validated the analyzed effect on the EMI qualification, which is caused by the revision of MIL–STD–461, by performing electromagnetic simulation for equipment under RE102 test.

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, the regulatory requirements should be met for nuclear safety. 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) should be performed under the test methods, and satisfy the acceptance criteria provided in the regulatory guidance approved for nuclear safety [1,2]. In detail, the 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 the 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 the acceptance criteria for EMC qualification.

The United States Nuclear Regulatory Commission (U.S. NRC) has published the secondly revised Regulatory Guide (Reg. Guide) 1.180 (revision 2 (Rev. 2)), which 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 the EMC qualification, the U.S. NRC has modified the test method and the acceptance criteria of several EMC tests in Reg. Guide 1.180 (Rev. 2). The primary revision of the updated Reg. Guide 1.180 is that MIL–STD–461G of the recent technical standards is adopted, instead of MIL–STD–461E [3,4]. Thus, the acceptance criteria and the test methods of EMC tests corresponding to the adoption of MIL–STD–461G in Reg. Guide 1.180 (Rev. 2) need to be thoroughly examined. Note that we here analyze the modified contents for EMI qualification corresponding to the revision of Reg. Guide 1.180, as follows.

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2. Revision of regulatory guidance for EMI qualification

Regulatory Guide 1.180 refers to various technical standards and reports, such as U.S. Military Standard 461 (MIL–STD-461), to introduce the test methods and the acceptance criteria for EMI and EMS tests. Table 1 presents the list of technical standards and research reports updated in Reg. Guide 1.180 (Rev. 2). These include the revision of the endorsed MIL–STD-461, International Electrotechnical Commission (IEC) standards 61000–3, 4, & 6, and the 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 numbers are ORNL/SPR–2015/485, ORNL/SPR–2015/254, and ORNL/SPR–2016/108, are included as new references in Reg. Guide 1.180 (Rev. 2) [5–14].

2.1. EMI tests based on Military Standards

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 comparing the measured result with the allowable EMI level. EMI tests are classified into the conducted emission (CE) and radiated emission (RE) tests, based on the interference manner of an EM source. In detail, the 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 precise, the 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 tests in Reg. Guide 1.180 (Rev. 2), we found that the emission tests of CE101, CE102, and RE102 have been adjusted. Table 2 presents the amendments to the EMI tests in the comparison between the revisions 1 and 2 of Reg. Guide 1.180. As shown in Table 2, the revisions in the conditions for the exemption and relaxation for the CE101 test were confirmed. In the case of the CE102 test, the frequency ranges, exemption conditions, and alternative test methods for the high-frequency band were revised. In addition, the frequency range for the RE102 test was revised. Otherwise, no revision was confirmed in the 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 (30 Hz–10 kHz) (the test frequency starts with the second harmonic frequency for AC power leads). To qualify EUT in the CE101 test, the measured strength of emission current should not exceed the allowable level in root mean square (rms).

Fig. 1 illustrates the revised acceptance criteria of the CE101 test in Reg. Guide 1.180 (Rev. 2). Table 2 shows that Reg. Guide 1.180 (Rev. 2) requires the design change including power quality control as an additional condition for 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, it is seen 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 criterion applied to DC power leads has not changed, the acceptance criterion applied to AC power leads has been 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 a power lead (both the dotted line and the solid line in blue change to the solid line in red 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)

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 2, the amendments to the CE102 test include the extension of the maximal test frequency from 2 MHz to 10 MHz, as depicted in Fig. 2, as well as the reduction of the test frequency range, where the exception is allowed conditionally, from (10 kHz–450 kHz) to (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 consider 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)

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 the allowable strength of electric field presented in Fig. 3:

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

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

References		Before revision	After revision
Documents of technical standards	U.S. Military standard	- MIL–STD–461E	- MIL–STD–461G
	IEC standard	- IEC 61000–3, Part 3 (2001)	- IEC 61000–3, Part 3 (2017) [5].
		- IEC 61000–4, Part 4 (1998)	- IEC 61000–4, Part 4 (2012) [6].
		- IEC 61000–6, Part 6 (1997)	- IEC 61000–6, Part 6 (2011) [7].
	IEEE standard	- IEEE Std. 1050 (1996)	- IEEE Std. 1050 (2004) [8].
		- IEEE Std. C62.41 (1991)	- IEEE Std. C62.41.1 (2002) [9].
		- IEEE Std. C62.45 (1992)	- IEEE Std. C62.41.2 (2002) [10].
			- IEEE Std. C62.45 (2002) [11].
Technical reports		N/A	- ORNL/SPR–2015/485 [12].
			- ORNL/SPR–2015/254 [13].
			- ORNL/SPR–2016/108 [14].

Table 2
Comparison of the 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 the design changes include power quality controls
	The conditions for relaxation	For AC-operated equipment with a fundamental current greater than 1 A, 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–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)	Conduct of the CE102 test in the frequency range (10 kHz–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)
	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

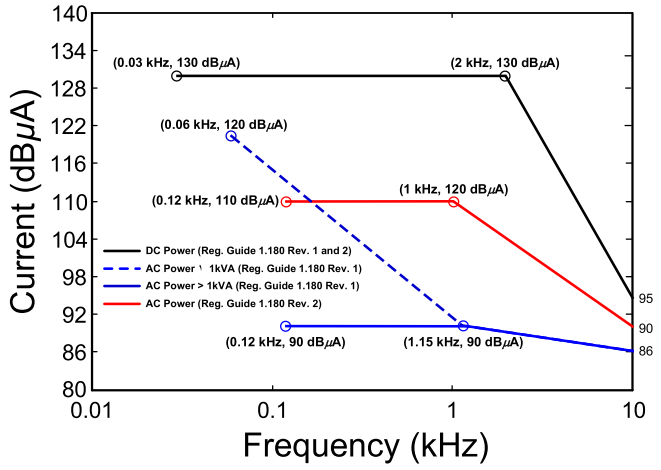

Fig. 1. CE101 operating envelopes.

2.2. EMI tests based on IEC standards

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 tests provided in MIL–STD–461. Thus, IEC standards are possibly employed for the alternatives to the CE102 and RE102 tests.

To understand the difference between revisions 1 and 2 of Reg. Guide 1.180, Table 3 shows the revision of EMI test methods based on IEC 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 (30 MHz–230 MHz), as well as from 37 to 47 quasi-peak voltage in the range (230 MHz – 1 GHz). Furthermore, the test frequency range is extended up to 6 GHz. We consider that the intention of this revision related to the extension of test frequency is similar to that of the revision of the RE102 test for the extension of the test frequency.

2.3. Alternatives to EMI tests

Table 4 summarizes the EMI emission tests in Reg. Guide 1.180 (Rev. 2). In the comparison between emission tests based on the military and IEC standards, the discrepancies expressed as "Gap between military and IEC standards bases" in Fig. 4 are founded, because the IEC standards do not provide any emission test corresponding to the CE101 and RE101 tests of the MIL–STD–461. To overcome this limitation in the application of IEC standards, the NRC has revised Reg. Guide 1.180 to provide flexibility in using the alternatives to qualify EUT in EMI tests. Table 4 presents the alternative tests for EMI qualification, proposed in revisions 1 and 2 of Reg. Guide 1.180. The alternatives in Table 4 are divided according to whether the exception conditions of the low-frequency emission tests are satisfied, or not.

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

3. Practice of the revised Regulatory Guide 1.180

In the previous chapter, we analyze the difference between revisions 1 and 2 of the Reg. guide 1.180 for the EMI qualification. In this chapter, after reviewing the modified guidance for the EMI tests (CE101, CE102, RE101, and RE102 tests) in Reg. Guide 1.180 (Rev. 2), we explain the modification in the procedure and configuration of the EMI tests due to the update of the technical standard MIL–STD–461 endorsed in Reg. Guide 1.180.

3.1. Revision of MIL–STD–461

After examining what is revised for the EMI tests (CE101, CE102, RE101, and RE102 tests) in MIL–STD–461G compared with MIL–STD–461E, we conclude that the antenna positioning to measure the emission from EUT in the RE102 test has mainly been modified, as shown in Table 5 (the revision is highlighted using underlining). In the RE102 test of MIL–STD–461E, the strength of the electric field radiated from the enclosure and interconnecting leads of the EUT is measured by a receiving antenna whose 3 dB beamwidth covers the EUT at single and multiple location on only

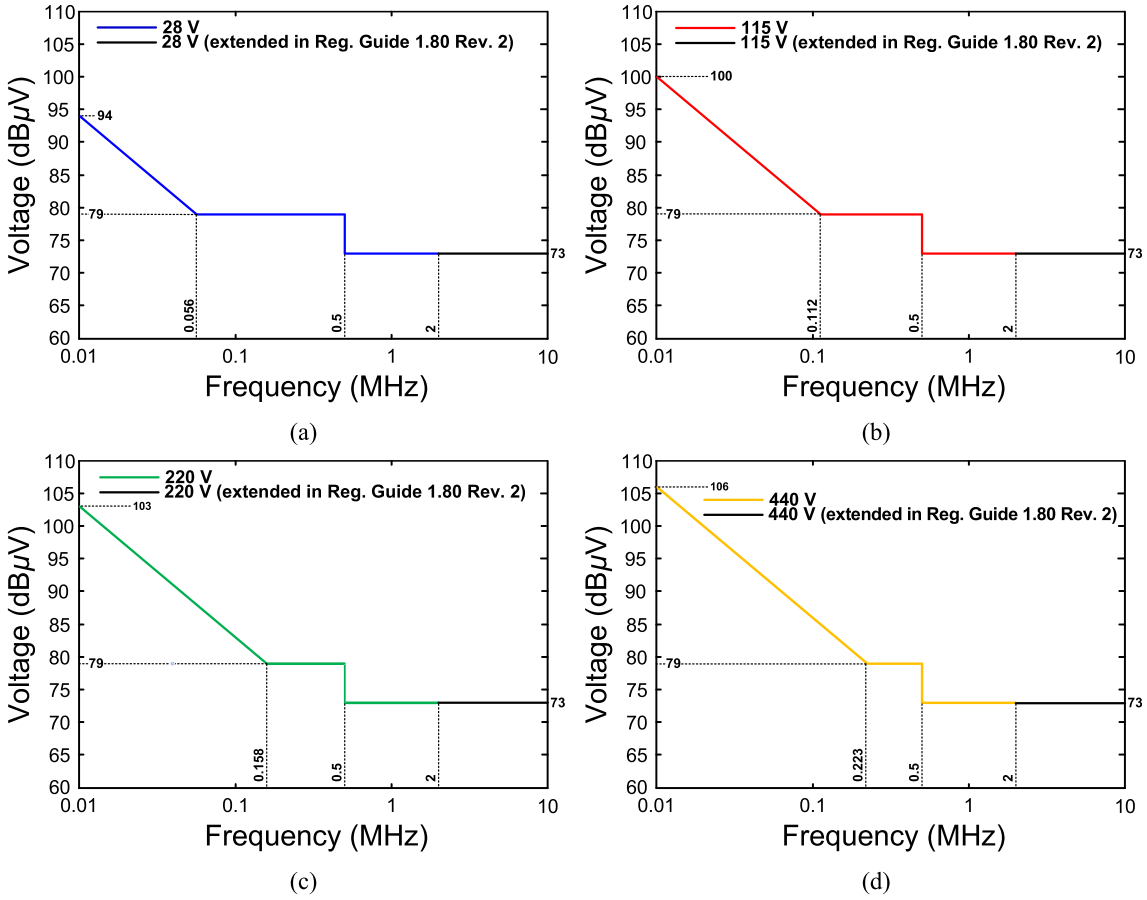

Fig. 2. CE102 operating envelopes for (a) 28 V, (b) 115 V, (c) 220 V, and (d) 440 V.

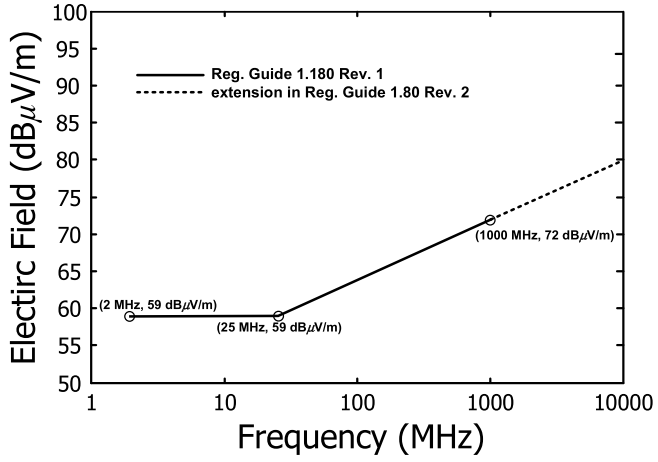

Fig. 3. RE102 operating envelopes.

the horizontal plane (parallel to the ground plane) at a height of 1.2 m above the ground. Accordingly, the RE102 test in accordance with MIL–STD–461E has the limitation that the radiating emission is only evaluated at the constant height of 1.2 m. The constraint of evaluating coverage in the RE102 test can lead to potential defects in the EMC qualification for safety functions, because the height of equipment varies in nuclear power plants. To resolve the aforementioned limitation of the RE102 test in accordance with MIL–STD–461E, the MIL–STD–461G states that the radiating electric field of EUT should be measured in the entire area covering the whole enclosure and interconnecting leads of the EUT. As presented in Table 5, the modification from 'entire width' to 'entire area' provides important meaning; in accordance with MIL–STD–461G, the measurement of electric-field strength in RE102 test should be accomplished not at a constant height of 1.2 m, but at various heights, to evaluate the emission radiated from the whole surface of the EUT.

Table 3
Amendments to the radiated emissions envelopes of IEC 61000–6-4.

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

Table 4
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 CE102 (450 kHz–2 MHz) and RE102 tests based on MIL-STD–461 - Alternative 2: Perform emission tests based on IEC 61000–6-4 - Alternative 3: Perform emission tests to satisfy FCC Part 15 Class A requirements	- Alternative 1: Perform CE102 (150 kHz–10 MHz) and RE102 tests based on MIL-STD–461 - Alternative 2: Perform emission tests based on IEC 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–461, which are the basis for EMI emission tests, are allowed.	- CE101, CE102 (10 kHz–150 kHz), and RE101 tests are performed with MIL–STD–461. - Others emission tests are performed based on IEC 61000–6-4.

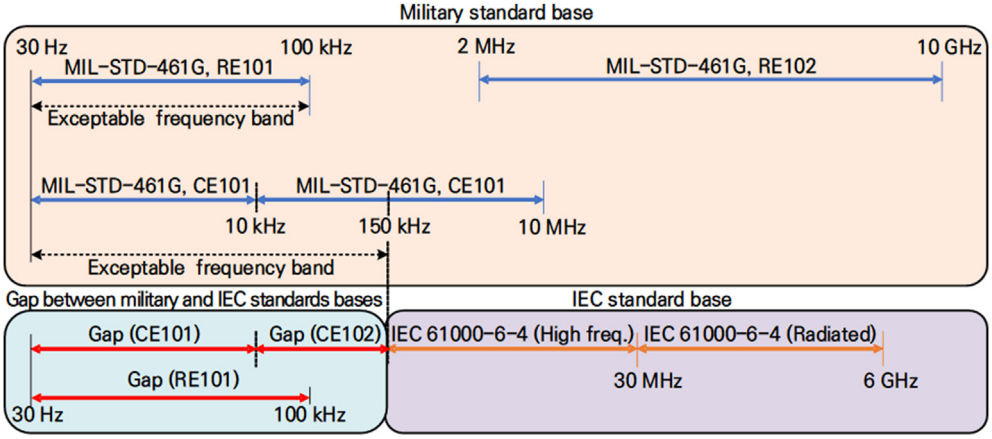

Fig. 4. Frequency range of the EMI tests based on the military and IEC standards.

Table 5
Comparison of the test setup between MIL–STD–461E and –G.

The test setup	MIL–STD–461E	MIL–STD–461G
RE102 EUT testing - Antenna positioning	For testing from 200 MHz up to 1 GHz, place the antenna in a sufficient number of positions, such that the entire width of each EUT enclosure and the first 35 cm of cables and leads interfacing with the EUT enclosure are within the 3 dB beamwidth of the antenna. For testing at 1 GHz and above, place the antenna in a sufficient number of positions, such that the entire width of each EUT enclosure and the first 7 cm of cables and leads interfacing with the EUT enclosure are within the 3 dB beamwidth of the antenna.	For testing from 200 MHz up to 1 GHz, place the antenna in a sufficient number of positions, such that the entire area of each EUT enclosure and the first 35 cm of cables and leads interfacing with the EUT enclosure are within the 3 dB beamwidth of the antenna. For testing at 1 GHz and above, place the antenna in a sufficient number of positions, such that the entire area of each EUT enclosure and the first 7 cm of cables and leads interfacing with the EUT enclosure are within the 3 dB beamwidth of the antenna.

3.2. Practice of the revised MIL–STD–461

It is important to check the effect on the evaluation result of the RE102 test by applying MIL–STD–461G to EMI qualification, because lots of equipment, qualified by Reg. Guide 1.180 (Rev. 1) based on MIL–STD–461E, have been procured in the nuclear power plants under operation and construction. Therefore, we electromagnetically simulated the open cabinet (EUT) including a radiating source on an open surface to check how much the evaluation result of RE102 test (electric-field strength) is altered when the location of the receiving antenna changes vertically [15]. In the configuration of the electromagnetic simulation, as shown in Fig. 5, we assume that a radiating source (dipole antenna at 100 MHz) for electromagnetic radiation exists at the postulated locations P_s ($x = 0$ m, $y = 0.4$ m, $z = h_s$) on the front open-surface of the cabinet, and then the receiving antenna at the height of h_a is located at the distance of 1 m from the EUT, to measure the radiated electric-field strength. In the electromagnetic simulation, focusing on 'the entire area' presented in Table 5, we examine the strength of the received electric field in variation of the vertical location h_a for several h_s.

Fig. 6 shows the strength of the received electric field at 100 MHz derived from electromagnetic simulation, where the electric-field strength is a function of h_a for three cases of $h_s =$ (100, 300, and 500) mm. Based on Reg. Guide 1.180 (Rev. 2), we depict the maximally allowable electric-field strength (63.9 dBμV/m) at 100 MHz as a dashed line to identify whether the EUT satisfies the acceptance criterion of the RE102 test or not for various h_a. It is seen that the strength of the detected electric field changes depending on the height h_a of a receiving antenna, as well as the height h_s of an emission source. For the case of $h_s = 300$ mm, the EUT partially satisfies the acceptance criterion of the RE102 test, under the condition that the height h_a of the receiving antenna ranges from 0.109 m to 0.157 m. This implies that the RE102 test should be performed in the entire area of the EUT, as presented in the MIL–STD–461G, because the emission of the electric-field is influenced by the height h_a of the receiving antenna, and the height h_s of an emission source. Accordingly, if tall equipment is under RE102 test based on MIL–STD–461E,

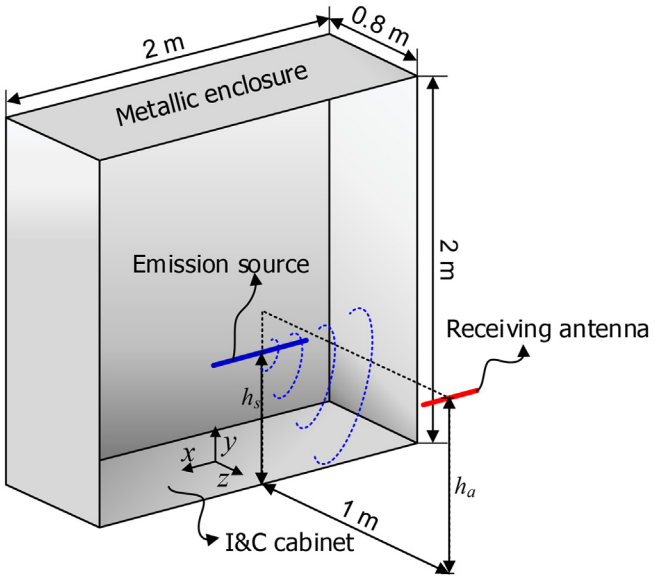

Fig. 5. Configuration of the RE102 test for electromagnetic simulation.

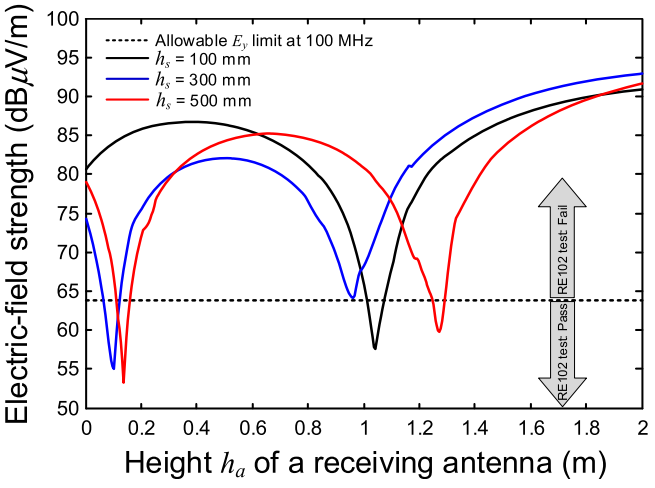

Fig. 6. Radiating emission derived from electromagnetic simulation in variation of h_s and h_a.

strong radiating emission might possibly not be measured, because MIL–STD–461E allows the measurement of the electric field on only the horizontal plane (parallel to the ground plane) at a height of 1.2 m from the ground.

4. Conclusion

We studied the test method and the acceptance criteria related to the EMI tests in the revised Reg. Guide 1.180 to obtain useful information for EMI qualification. After analyzing the revised Reg. Guide 1.180, we confirmed that test methods and the acceptance criteria of the CE101, CE102, and RE102 tests are changed to reflect the updated technical bases. Furthermore, we found that revised Reg. Guide 1.180 provides flexibility in using alternative methods for the EMI qualification, in that a mix of different-based technical standards is allowed. Finally, we explained the modification in the procedure and configuration of the EMI tests due to the update of the endorsed technical standards in the revised Reg. Guide 1.180. Then, using the electromagnetic simulation for RE102 test, we analyzed the influence on the evaluating EMI qualification led by updating the technical base of MIL–STD–461.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Korea Institute of Nuclear Safety, Guidelines for evaluating electromagnetic and radio-frequency interference in safety-related instrumentation and control systems, KINS/RG-N03.09 (2019).
[2] U.S. NRC, "Guidelines for evaluating electromagnetic and radio-frequency interference in safety-related instrumentation and control systems," regulatory guide 1.180, Rev 1 (2003).
[3] U.S. DOD, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, MIL–STD–461E, 1999.
[4] U.S. DOD, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, MIL–STD–461G, 2015.
[5] IEC Std. 61000–3, Electromagnetic Compatibility (EMC) - Part 3, Limits, IEC, 2017.
[6] IEC Std. 61000–4, Electromagnetic Compatibility (EMC) - Part 4: Testing and Measurement Techniques, IEC, 2012.
[7] IEC Std. 61000–6, Electromagnetic Compatibility (EMC) - Part 6, Generic Standards, IEC, 2011.
[8] IEEE Std. 1050, IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations, IEEE, 2004.
[9] IEEE Std, C62.41.1, IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits, IEEE, 2002.
[10] IEEE Std. C62.41.2, IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V or Less) AC Power Circuits, IEEE, 2002.
[11] IEEE Std. C62.45, IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V or Less) AC Power Circuits, IEEE, 2002.
[12] Oak Ridge National Laboratory, Task 2–limits for high-frequency conducted susceptibility testing–CS114, ORNL/SPR–2015/485 (2016).
[13] Oak Ridge National Laboratory, Task 4–EMI/RFI issues potentially impacting electromagnetic compatibility of I&C systems, ORNL/SPR–2015/254 (2015).
[14] Oak Ridge National Laboratory, Task 5–technical basis for electromagnetic compatibility regulatory guidance update, ORNL/SPR–2016/108 (2016).
[15] Ansys HFSS [Online]. Available: http://www.ansys.com.