Nuclear Engineering and Technology 51 (2019) 1032–1036

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Proposing a low-frequency radiated magnetic field susceptibility (RS101) test exemption criterion for NPPs

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ARTICLE INFO

Article history:
Received 7 June 2018
Received in revised form
18 January 2019
Accepted 18 January 2019
Available online 18 January 2019

Keywords:
Electromagnetic compatibility (EMC)
Electromagnetic susceptibility (EMS)
Low-frequency radiated magnetic field susceptibility
Radiated susceptibility test method
RS 101 test exemption criterion

ABSTRACT

When the equipment which is related to safety or important to power production is installed in nuclear power plant units (NPPs), verification of equipment Electromagnetic Susceptibility (EMS) must be performed. The low-frequency radiated magnetic field susceptibility (RS101) test is one of the EMS tests specified in U.S NRC (Nuclear Regulatory Commission) Regulatory Guide (RG) 1.180 revision 1. The RS101 test verifies the ability of equipment installed in close proximity to sources of large radiated magnetic fields to withstand them. However, RG 1.180 revision 1 allows for an exemption of the low-frequency radiated magnetic susceptibility (RS101) test if the safety–related equipment will not be installed in areas with strong sources of magnetic fields. There is no specific exemption criterion in RG 1.180 revision 1. EPRI TR-102323 revision 4 specifically provides a guide that the low-frequency radiated magnetic field susceptibility (RS101) test can be conservatively exempted for equipment installed at least 1 m away from the sources of large magnetic fields (>300 A/m). But there is no exemption criterion for equipment installed within 1 m of the sources of smaller magnetic fields (<300 A/m). Since some types of equipment radiating magnetic flux are often installed near safety related equipment in an electrical equipment room (EER) and main control room (MCR), the RS101 test exemption criterion needs to be reasonably defined for the cases of installation within 1 m. There is also insufficient data regarding the strength of magnetic fields that can be used in NPPs. In order to ensure confidence in the RS101 test exemption criterion, we measured the strength of low-frequency radiated magnetic fields by distance. This study is expected to provide an insight into the RS101 test exemption criterion that meets the RG 1.180 revision 1. It also provides a margin analysis that can be used to mitigate the influence of low-frequency radiated magnetic field sources in NPPs.

1. Introduction

As digital Instrumentation and Control (I&C) systems are efficient and cost-effective, analog I&C systems have been upgraded and replaced with digital I&C systems. However, these digital I&C systems may have low electromagnetic susceptibility (EMS) due to their high frequency and low operating voltage [1]. In particular, electromagnetic interference (EMI) generated by power units can interfere with the functionality of digital I&C systems in an electrical equipment room (EER), main control room (MCR), and computer room (CR).

To address safety concerns, the U.S Nuclear Regulatory Commission (NRC) conducted a thorough evaluation of safety-related I&C systems and non-safety I&C systems, whose failure can affect safety functions in NPPs. When safety-related I&C equipment is designed to be installed in NPP units, EMC of equipment needs to be verified in test facilities. For this purpose, the test methods in Nuclear RG 1.180 Revision 1 are used to confirm the required insusceptibility level of equipment before installation [2].

One of the EMS tests specified in the U.S NRC RG 1.180 is the low-frequency radiated magnetic field susceptibility (RS101) test. The RS101 test verifies the susceptibility of equipment installed in close proximity to large radiated magnetic fields, and their ability to withstand them. However, RG 1.180 revision 1 allows for an exemption for low-frequency radiated susceptibility when the safety-related equipment is not intended to be installed in an area with strong magnetic field sources. Accordingly, because of the exemption, some equipment suppliers tend not to conduct the RS101 test if the equipment will be installed away from sources of magnetic fields. There is no specific exemption criterion. The

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https://doi.org/10.1016/j.net.2019.01.011

guideline allows an exemption just in the descriptive condition of proximity to the magnetic field sources. Minimum separation distances for safety-related items are required in IEEE 383, but there is no criterion in term of radiated magnetic field strength [3]. In addition, the RS101 test exemption criterion for close range is ambiguous.

EPRI TR-102323 revision 4 [4] presents a criterion for RS101 test exemption for equipment installed at least 1 m away from a source of large magnetic fields (>300 A/m).

However, there is no RS101 test exemption criterion for equipment installed in close proximity (<1 m) to sources of smaller magnetic fields (<300 A/m). The RS101 test exemption criterion needs to be reasonably defined for distances within 1 m from the sources of magnetic fields (<300 A/m) because the magnetic field sources (field generating equipment) are often installed near safety related equipment in an EER and MCR. The best way to verify the RS101 test exemption criterion is to measure the low-frequency radiated magnetic fields being emitted around the safety-related equipment in NPPs.

In this study, we measured some of the high strength low-frequency magnetic fields radiated by sources that can be used in NPPs at various distances, and proposes an RS101 test exemption criterion that satisfies the RG 1.180 revision 1. A margin analysis to mitigate the influence of low-frequency radiated magnetic fields in NPPs was also performed.

2. Test guidance for the low-frequency radiated magnetic field susceptibility (RS101) test

2.1. Test standard (RS101 and IEC 61000-4-8, 9, 10)

In NPPs, low-frequency radiated magnetic field susceptibility (RS101) is tested to verify the susceptibility of equipment to radiated magnetic field emissions. The radiated susceptibility tests are conducted according to MIL-STD-461E RS101 [5], and IEC 61000-4 [6] of NRC RG 1.180 revision 1. The RS101 test ensures that equipment and subsystems are not susceptible to radiated magnetic fields in the frequency range 30 Hz–100 kHz. Under the RS101 test, such equipment should not exhibit any malfunction, degradation of performance, or deviation from specified indications, beyond the tolerances indicated in the individual equipment or subsystem specification, when subjected to a low-frequency radiated magnetic field level (RS101 Operating Envelope), as shown in Fig. 1.

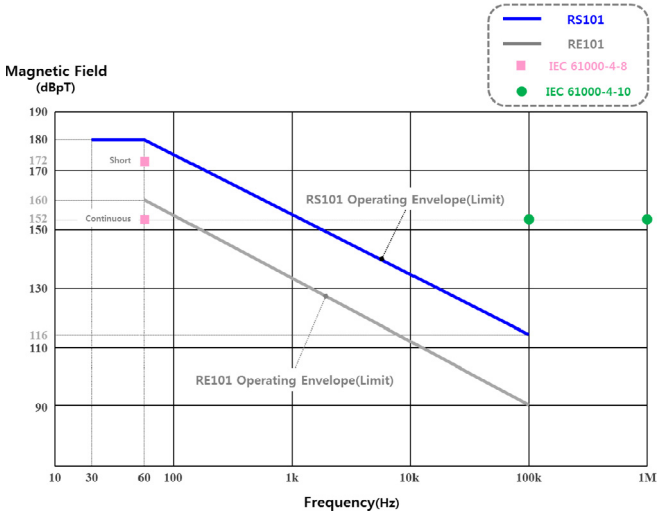

Fig. 1. Low-frequency radiated susceptibility testing limit.

The MIL-STD-461 RS101 test method is acceptable to the NRC to address the EMI/RFI susceptibility of safety-related I&C systems in NPPs. An alternative susceptibility testing program based on IEC 61000 is acceptable for establishing the susceptibility characteristics of safety-related I&C systems. The IEC counterparts of RS101 (Radiated susceptibility, magnetic field, 30 Hz to 100 kHz) test are IEC 61000-4-8, IEC 61000-4-9, and IEC 61000-4-10. Although there are differences in the scope and methodology between the RS101 test and IEC 61000-4-8, 9&10 tests, these tests collectively meet the goal of demonstrating equipment immunity to radiated magnetic fields.

The operating envelopes for the IEC 61000-4-8, 9, and 10 test methods, which are comparable to the MIL-STD-461 RS101 test method, are acceptable for locations where safety-related I&C systems either are installed or are likely to be installed. The locations include control rooms, electrical control rooms, remote shutdown panels, auxiliary instrument rooms where safety-related I&C system installations are planned. The operating envelopes are acceptable for analog, digital, and hybrid system installations.

2.2. RS101 test viewpoints

Some equipment suppliers tend not to conduct the RS101 testing because it can be exempted if the equipment is installed some distance away from the magnetic fields sources. However, a technical justification demonstrating for the RS101 test exemption is ambiguous. There are needs to define the exemption criterion when equipment is installed sources of magnetic fields. If there is sufficient data on the strength of radiated magnetic fields used in NPPs, the RS101 test exemption criterion needs to be reasonably defined for distances from the magnetic field sources. And the margin analysis can be used as a reference to judge whether the RS101 test is required or exempted.

2.3. RS101 test exemption

Equipment that is not intended to be installed in areas including strong sources of magnetic fields such as transformers, motors, CRTs, cable bundles carrying high currents, and that follow the limiting practices endorsed in RG 1.180 revision 1, can be exempted from this test. If testing is not performed, the design conditions and features that address the equipment emission sources should be documented. In conjunction with this exemption a technical justification demonstrating why the RS101 test is not required should be documented.

The RS101 test exemption is based on proximity to magnetic field emitters, however, the proximity distance from magnetic field sources is not established. EPRI TR-102323 revisions 2, 3 & 4, which are not endorsed by the U.S NRC, have introduced the RS101 test exemption criterion as shown in Table 1. In EPRI TR-102323 revision 4, the RS101 test is required for equipment installed in close proximity (<1 m) to sources of large magnetic fields (>300 A/m). In other words, the RS101 test can be exempted for equipment installed more than 1 m away from sources of large magnetic fields (>300 A/m) but there is no test exemption criterion for equipment installed within 1 m of the sources of smaller magnetic fields (<300 A/m). There is insufficient data regarding the strength of low-frequency radiated magnetic fields. Typical examples of low-frequency radiated magnetic field strength at power plants are shown in Table 2 [7,8]. The measured radiated magnetic field emissions from the safety-related I&C systems in an EER, MCR and CR were bounded by RE101 operating envelope (emission limit). The highest magnetic fields displayed from the thirteen plants were recorded at the rear and front of power supplies [9].

Table 1
RS101 test exemption criteria.

Standard	Exempt Criteria	Note
RG 1.180 Rev.1 (2003)	Exemption based on proximity to magnetic field emitters	Revision 1 is endorsed by U.S NRC
EPRI TR-102323 Rev.2 (2000)	For equipment installed more than 1 m from sources of large magnetic fields (>600 A/m)	Revision 2 is not endorsed by U.S NRC
EPRI TR-102323 Rev.3 (2004) & Rev.4 (2013)	For equipment installed more than 1 m from sources of large magnetic fields (>300 A/m)	Revision 3 and 4 are not endorsed by U.S NRC

Table 2
Typical magnetic field strength of sources in power plants.

Sources	Magnetic field strength [A/m] (dBpT)	Measured Point
Computer	0.6–1.5 (118–125)	at 0 cm distance
Air Conditioner	0.2–0.5 (107–115)	at 0 cm distance
Stand Electric Fan	0.1–0.3 (105–112)	at 0 cm distance
Power Supply in Mark Vl of OPR1000	1.3–1.4 (124–125)	at 7 cm distance
Power Supply in CPC of OPR1000	0.3–0.4 (112–114)	at 7 cm distance
Power Supply in ENFMS of OPR1000	0.3–0.4 (112–114)	at 7 cm distance
Power Supply in PCS of OPR1000	0.4–0.5 (114–116)	at 7 cm distance
Power supply in PPS of APR1400	0.03–0.05 (92–96)	at 7 cm distance
Power supply in ESF-CCS of APR1400	0.03–0.04 (92–94)	at 7 cm distance
Distribution transformer in EER of OPR1000	0.002 (68)	at 7 cm distance
765 kV transmission line	0.3–0.8 (111–121)	at just below on the ground
Substation	0.09–0.5 (109–115)	at fence of substation

3. Measurement of low-frequency radiated magnetic field

3.1. Test configuration

The RS101 test requirement is applicable to equipment and subsystem enclosures, including electrical cable interfaces. The test equipment consists of a signal source, a radiating loop, a loop sensor, a measurement receiver or a narrowband voltmeter, a current probe, and Line Impedance Stabilization Networks (LISNs) as shown in Fig. 2. The test procedures are including calibration, EUT (Equipment under test) testing, and data presentation. When the MIL-STD-461 RS101 test procedures are applied, the loop sensor will be located 5 cm from the EUT face or electrical interface connector being probed.

3.2. Test results with distance-specific measurements

A best way to evaluate the low-frequency radiated magnetic field susceptibility of equipment installed within 1 m from the sources of magnetic fields is to measure the low-frequency radiated magnetic emissions. Some of the typical low-frequency magnetic field sources in NPPs include LCD monitors, power supplies (AC Slidac), mobile phones, cable reels, electrical fans, electric drivers, and others.

The low-frequency radiated magnetic field strengths of each source were measured by distance as shown in Fig. 3. The test results of the measured magnetic field strengths are shown in Fig. 4 and Table 3. All of the measured low-frequency radiated magnetic field strengths were less than the RS101 envelope in RG 1.180 revision 1. The largest field strength measured was 11.9 A/m (143 dBpT) at 0 cm (attached) which is lower than the 300 A/m (171 dBpT) at 1 m criterion in EPRI TR-102323 revision 4. The source of this largest measured magnetic field was AC Slidac; Thus, to maximize the strength of the low-frequency field for the test, a large current was intentionally applied to the AC Slidac. Most of the measured field strengths were less than 6.31 A/m (138 dBpT).

Through distance-specific measurements, it was confirmed that the strength of the low-frequency radiated magnetic fields sharply decreased as the distance from the source increased. When the equipment was installed more than 30 cm away, the strength of the low-frequency radiated magnetic fields was even less than the RS101 lowest limit (0.5 A/m, 116 dBpT) at 100 kHz frequency. Therefore, if magnetic field sources such as electrical fans, LCD Monitors and power supplies is separated by more than 40 cm from

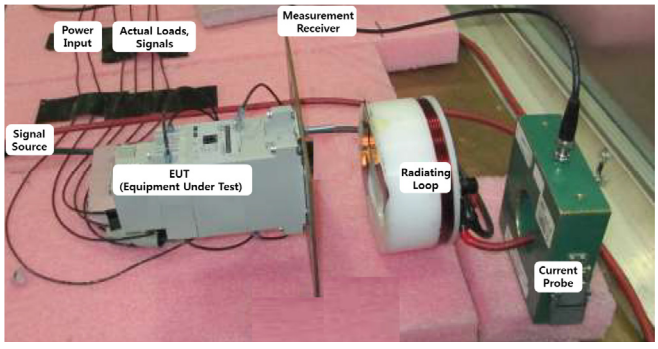

Fig. 2. RS101 test Configuration.

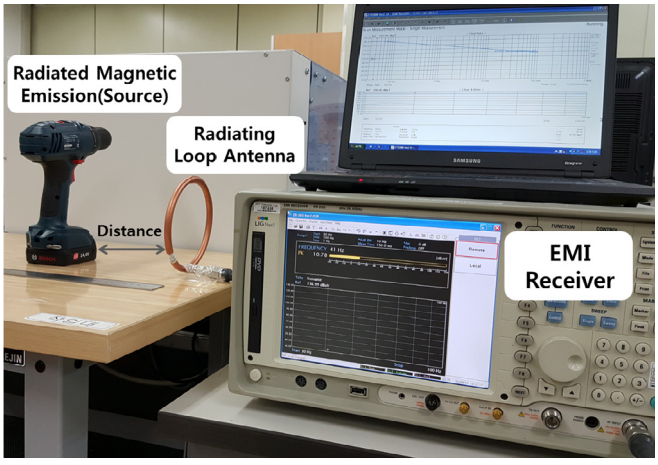

Fig. 3. Measurement of low-frequency radiated magnetic field emissions.

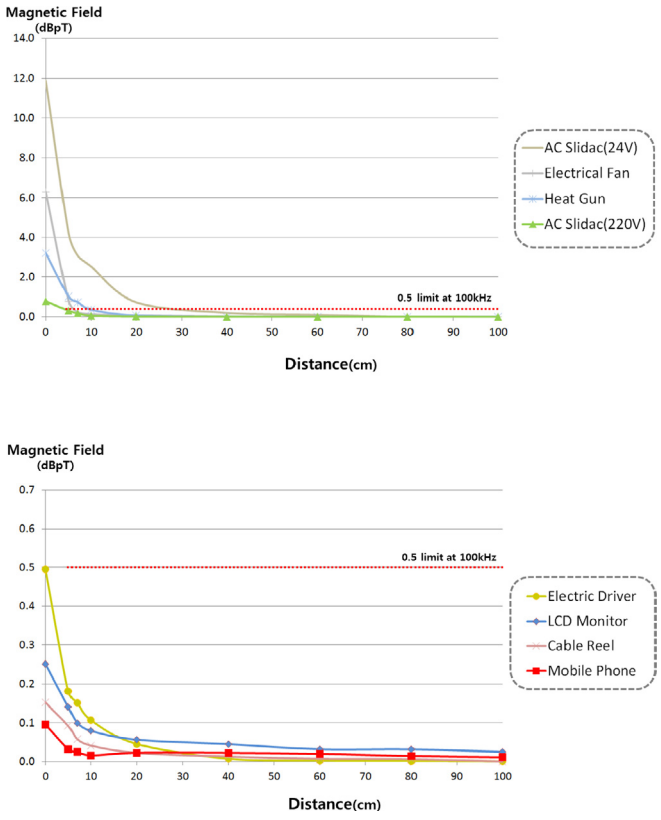

Fig. 4. Low-frequency radiated magnetic field strength over distance.

the safety-related I&C systems in NPPs, the RS101 test can be securely exempted.

4. Margin analysis for RS101 test exemption

4.1. RS101 and RE101 margin analysis

Since the limits of low-frequency radiated magnetic fields are different depending on the frequency, a margin analysis is required to check tolerance to the magnetic fields. The margin analysis can be used as a reference to judge whether the RS101 test is required or exempted. Two kinds of margin analysis (RS101, RE101) have been introduced to evaluate the influence of the low-frequency radiated magnetic fields. The RS101 margin between the RS101 operating envelope (limit) and the maximum value of measured magnetic fields for each frequency by distance are shown in Table 4 and Fig. 5. The RE101 margin between the RE101 operating envelope (limit) and the maximum value of the measured field for each frequency by distance is shown in Fig. 6. The margin values decreases as the distance from the magnetic field decreases, and the margin values increases as the distance from the magnetic field increases. The RE101 margin can provide a more conservative and confident validation of the radiated magnetic field susceptibility than the RS101 margin, because the RE101 operating envelope is lower than the RS101 operating envelope.

4.2. Proposal of RS101 test exemption criterion

Generally, an EER, MCR or CR does not have very large motors or transformers. Furthermore, safety-related I&C systems are usually not installed within 1 m of large motors or transformers which generate a very large magnetic field (>300 A/m, 171 dBpT). If magnetic field sources such as electrical fans, LCD Monitors and power supplies have a sufficient margin of RE101, the RS101 test can be exempted.

Therefore, the RS101 test can be exempted when the safety-related I&C system is separated by more than 40 cm from magnetic field sources, or the RE101 margin is secured.

5. Conclusion

The low-frequency radiated magnetic fields generated by sources in power units can influence the reliable operation of I&C systems. The low-frequency radiated magnetic field susceptibility (RS101) test evaluates the susceptibility of equipment installed in close proximity to sources of large radiated magnetic fields, and its ability to withstand such fields. Some equipment suppliers tend not to conduct the RS101 testing because it can be exempted if the equipment is installed some distance away from the magnetic fields sources. EPRI TR-102323 revision 4 presents specific criterion for when RS101 can be exempted, which is when equipment is installed at least 1 m away from the sources of large magnetic fields (>300 A/m). However, there is no exemption criterion when equipment is installed within 1 m of sources of smaller magnetic fields (<300 A/m). Since magnetic field sources are often installed near safety related equipment in an EER and MCR, the RS101 test exemption criterion needs to be reasonably defined for distances

Table 3
Low-Frequency Radiated Magnetic Field Strength of each Source by Distance.

Distance	AC Slidac (24 V)	Electric Fan	Heat Gun	AC Slidac (220 V)	Electric Driver	LCD Monitor	Cable Reel	Mobile Phone
0 cm	11.885 A/m (143.1 dBpT)	6.310 A/m (138.0 dBpT)	3.214 A/m (132.1 dBpT)	0.795 A/m (120.1 dBpT)	0.495 A/m (115.9 dBpT)	0.251 A/m (110.0 dBpT)	0.154 A/m (106.2 dBpT)	0.096 A/m (101.7 dBpT)
5 cm	5.012 A/m (136.0 dBpT)	0.794 A/m (120.0 dBpT)	1.017 A/m (122.2 dBpT)	0.316 A/m (112.2 dBpT)	0.182 A/m (107.2 dBpT)	0.141 A/m (105.0 dBpT)	0.094 A/m (102.1 dBpT)	0.032 A/m (92.1 dBpT)
7 cm	3.083 A/m (131.8 dBpT)	0.251 A/m (110.0 dBpT)	0.750 A/m (119.5 dBpT)	0.180 A/m (107.5 dBpT)	0.151 A/m (105.6 dBpT)	0.100 A/m (102.0 dBpT)	0.058 A/m (98.4 dBpT)	0.025 A/m (89.8 dBpT)
10 cm	2.523 A/m (130.0 dBpT)	0.141 A/m (105.0 dBpT)	0.366 A/m (113.3 dBpT)	0.061 A/m (98.9 dBpT)	0.107 A/m (102.6 dBpT)	0.079 A/m (100.0 dBpT)	0.042 A/m (96.0 dBpT)	0.016 A/m (86.2 dBpT)
20 cm	0.738 A/m (119.4 dBpT)	0.079 A/m (100.0 dBpT)	0.073 A/m (99.3 dBpT)	0.021 A/m (91.5 dBpT)	0.045 A/m (95.1 dBpT)	0.056 A/m (97.0 dBpT)	0.024 A/m (92.0 dBpT)	0.023 A/m (89.2 dBpT)
40 cm	0.207 A/m (108.3 dBpT)	0.025 A/m (90.0 dBpT)	0.012 A/m (83.6 dBpT)	0.009 A/m (87.2 dBpT)	0.008 A/m (79.8 dBpT)	0.045 A/m (95.0 dBpT)	0.014 A/m (88.9 dBpT)	0.023 A/m (89.2 dBpT)
60 cm	0.107 A/m (102.6 dBpT)	0.016 A/m (86.0 dBpT)	0.012 A/m (83.4 dBpT)	0.012 A/m (88.6 dBpT)	0.003 A/m (70.4 dBpT)	0.032 A/m (92.0 dBpT)	0.008 A/m (86.3 dBpT)	0.020 A/m (88.1 dBpT)
80 cm	0.002 A/m (69.7 dBpT)	0.013 A/m (84.0 dBpT)	0.003 A/m (70.5 dBpT)	0.015 A/m (87.5 dBpT)	0.002 A/m (68.1 dBpT)	0.032 A/m (92.0 dBpT)	0.008 A/m (86.3 dBpT)	0.014 A/m (85.2 dBpT)
100 cm	0.002 A/m (66.0 dBpT)	0.013 A/m (84.0 dBpT)	0.003 A/m (70.1 dBpT)	0.004 A/m (84.0 dBpT)	0.001 A/m (63.2 dBpT)	0.025 A/m (90.0 dBpT)	0.001 A/m (81.5 dBpT)	0.011 A/m (83.2 dBpT)

Table 4
Margin of Low-Frequency Radiated Magnetic Field Strength of each Source by Distance.

Distance	AC Slidac (24 V)	Electric Fan	Heat Gun	AC Slidac (220 V)	Electric Driver	LCD Monitor	Cable Reel	Mobile Phone
0 cm	386.21 A/m (30.5 dBpT)	348.49 A/m (35.0 dBpT)	394.89 A/m (41.9 dBpT)	397.30 A/m (53.9 dBpT)	35.00 A/m (37.1 dBpT)	354.55 A/m (63.0 dBpT)	49.94 A/m (49.8 dBpT)	50.00 A/m (54.4 dBpT)
5 cm	388.97 A/m (32.8 dBpT)	354.01 A/m (53.0 dBpT)	397.08 A/m (51.9 dBpT)	397.77 A/m (61.8 dBpT)	35.32 A/m (45.8 dBpT)	354.66 A/m (68.0 dBpT)	50.00 A/m (53.9 dBpT)	50.07 A/m (63.9 dBpT)
7 cm	395.02 A/m (42.2 dBpT)	354.55 A/m (63.0 dBpT)	397.35 A/m (54.5 dBpT)	397.91 A/m (66.5 dBpT)	35.35 A/m (47.4 dBpT)	354.70 A/m (71.0 dBpT)	50.03 A/m (57.6 dBpT)	50.08 A/m (66.2 dBpT)
10 cm	395.58 A/m (44.0 dBpT)	354.66 A/m (68.0 dBpT)	397.73 A/m (60.7 dBpT)	398.03 A/m (75.1 dBpT)	35.39 A/m (50.4 dBpT)	354.72 A/m (73.0 dBpT)	50.05 A/m (60.0 dBpT)	50.08 A/m (69.8 dBpT)
20 cm	397.36 A/m (54.6 dBpT)	354.72 A/m (73.0 dBpT)	398.03 A/m (74.7 dBpT)	398.07 A/m (82.5 dBpT)	35.45 A/m (57.9 dBpT)	354.74 A/m (76.0 dBpT)	50.07 A/m (64.0 dBpT)	50.08 A/m (66.8 dBpT)
40 cm	397.89 A/m (65.7 dBpT)	354.77 A/m (83.0 dBpT)	398.09 A/m (90.4 dBpT)	398.08 A/m (86.8 dBpT)	35.49 A/m (73.2 dBpT)	354.76 A/m (78.0 dBpT)	50.08 A/m (67.1 dBpT)	50.08 A/m (66.8 dBpT)
60 cm	397.99 A/m (71.4 dBpT)	354.78 A/m (87.0 dBpT)	398.09 A/m (90.6 dBpT)	398.08 A/m (85.4 dBpT)	35.50 A/m (84.9 dBpT)	354.77 A/m (81.0 dBpT)	50.08 A/m (69.7 dBpT)	50.08 A/m (67.9 dBpT)
80 cm	398.10 A/m (104.4 dBpT)	354.79 A/m (89.0 dBpT)	398.10 A/m (103.5 dBpT)	398.08 A/m (84.5 dBpT)	35.50 A/m (89.8 dBpT)	354.77 A/m (81.0 dBpT)	50.08 A/m (70.1 dBpT)	50.09 A/m (70.8 dBpT)
100 cm	398.10 A/m (108.0 dBpT)	354.79 A/m (89.0 dBpT)	398.10 A/m (103.9 dBpT)	398.09 A/m (90.1 dBpT)	35.50 A/m (89.8 dBpT)	354.78 A/m (83.0 dBpT)	50.09 A/m (74.5 dBpT)	50.09 A/m (72.8 dBpT)

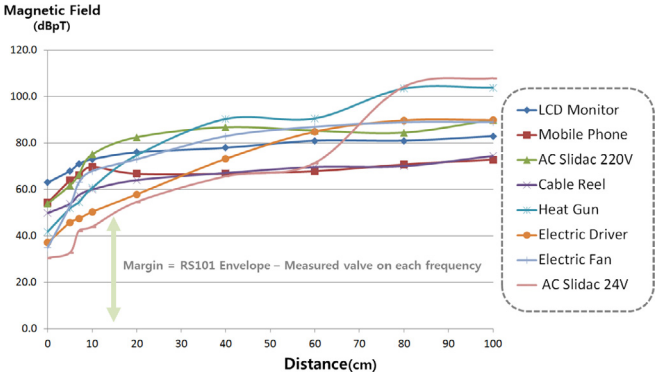

Fig. 5. Margin analysis on RS101 envelopes.

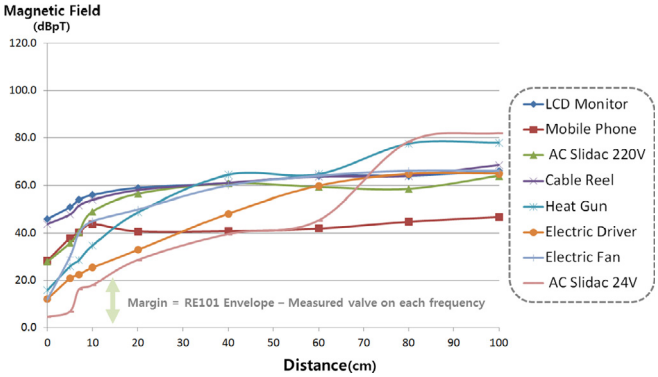

Fig. 6. Margin analysis on RE101 envelopes.

within 1 m. Also, there is insufficient data on the strength of radiated magnetic fields used in NPPs.

Some of the sources of high radiated magnetic fields in NPPs include LCD monitors, power supplies, mobile phones, cable reels, electrical fans, and others. In this study, all of the measured strengths of low-frequency radiated magnetic fields were bounded by the envelope of RS101 in RG 1.180 revision 1. The largest measured magnetic field strength was 11.9 A/m (143 dBpT), and the strength of the low-frequency radiated magnetic field decreased rapidly as the distance from the radiated magnetic field increased. A margin analysis was also conducted, based on the low-frequency radiated magnetic field strength measured from various magnetic field sources by distance. It was determined that the RS101 test can be exempted when the safety-related I&C system is separated by 40 cm from the magnetic field sources, or the RE101 margin is secured.

This study is expected to provide RS101 test exemption criterion that can mitigate the influence of low-frequency radiated magnetic fields. When applied to determine low-frequency radiated magnetic field susceptibility, this RS 101 test exemption criterion can provide a highly reliable basis for determining magnetic field susceptibility in NPPs.

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