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Research on Electromagnetic Interference Protection of Nuclear Power Unit Equipment Under the Application of New Wireless Technology in Smart Nuclear Power

Intelligence is the trend of industrial development in today's world, which will inevitably affect the nuclear power field, thus promoting nuclear power industry from digital to intelligent forward. 5G and Wi-Fi6, as a new generation of wireless communication technologies, have important advantages in terms of technical performance and security due to the characteristics of dense personnel, wide equipment distribution, complex facility environment, and special materials used in nuclear power scenarios. Considering the high requirement of electromagnetic compatibility (EMC) in nuclear power environment, it is urgent to further study the electromagnetic interference and protection requirements of 5G, Wi-Fi6, and other new technologies on nuclear power unit equipment in nuclear power environment. In this paper, combined with relevant national document standards and industry standards, we will sort out the requirements of immunity about radiofrequency radiation (RFR) for the important equipment in nuclear power plants, and use signal generators to simulate new radio signals such as 5G and Wi-Fi6 to test the immunity of nuclear power instruments and meters. Combining the results of the test, we will study the EMC between new wireless technologies and nuclear power plant equipment from different factors, such as power, bandwidth, modulation, distance, and direction. And then, we will summarize the protection requirements about nuclear power equipment and propose interference protection measures. [DOI: 10.1115/1.4056814]

Keywords: 5G, Wi-Fi6, electromagnetic compatibility (EMC), radiofrequency radiation (RFR), wireless

1 Introduction

The electromagnetic waves generated by wireless devices risk interfering with the normal operation of equipment in the plant, so electromagnetic compatibility (EMC) in communication networks is an important consideration. Since 2010, in order to build a set of mature application and deployment of wireless communication system integrating voice, data, SMS, positioning, and other functions in nuclear power plants, research on the application of Bluetooth, Zigbee, WiFi, LTE, spread-spectrum, and other wireless technologies in nuclear power plants has been carried out at home and abroad, including nuclear power plant network environment safety, electromagnetic environment compatibility, wireless system design, and deployment.

At present, the commonly used nuclear power communication technologies in foreign countries include analog cluster technology, digital cluster technology, paging technology, and the most popular communication technology based on 802.11 series protocol, providing voice communication mainly, supplemented by short messages, small packet business applications, which basically satisfy the nuclear power plant's basic needs for communication and office work. The wireless communication technologies used in domestic nuclear power plants mainly include WiFi, wireless cluster, McWiLL, LTE, etc. Now, most of the wireless communication systems built in nuclear power plants realize voice communication, but the large-scale deployment of data communication and various intelligent applications has not yet been realized. In recent years, with the steady progress of 5G strategy in China, the deep integration of new-generation information and communication technology with artificial intelligence, big data, and cloud computing in the field of nuclear power is an intelligent way to realize nuclear power production methods, services, management, equipment, and products. It is one of the important measures to comprehensively improve the efficiency and safety of nuclear power plant production.

The latest wireless communication technologies such as 5G and Wi-Fi6 have the characteristics of high speed, low latency, and large capacity, which can meet the needs of more intelligent application scenarios of nuclear power plants. Considering the high electromagnetic compatibility requirements of nuclear power plant equipment, combined with relevant electromagnetic compatibility test standards and nuclear power industry standards, the electromagnetic interference test of nuclear power equipment is carried out by generating 5G, Wi-Fi6, and other new radio signals through signal generators in the environment of nuclear power plants. By transmitting interference signals with different modulation methods, bandwidths, distances, and other conditions to nuclear power equipment, further study the electromagnetic interference and equipment interference protection requirements of nuclear power plant control equipment caused by the application of the latest wireless communication technologies such as 5G and Wi-Fi6.

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Manuscript received October 28, 2022; final manuscript received January 29, 2023; published online March 10, 2023. Assoc. Editor: Xiuming Wang.

2 Electromagnetic Compatibility Standards and Requirements

2.1 Nuclear Power Electromagnetic Compatibility Related Standards. At present, the more authoritative nuclear power electromagnetic compatibility standards include TR-102323 Guidelines for Electromagnetic Compatibility Testing of Power Plant Equipment [1], RG1.180 Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems [2], and IEC 62003-2020 Nuclear Power Plants-Instrumentation, Control and Electrical Power Systems-Requirements for Electromagnetic Compatibility Testing [3].

Among them, EPRI TR-102323 stipulates that the susceptibility tests of nuclear power plant equipment shall adopt IEC 61000 series standard test methods, in the 10 KHz–40 GHz band, the test method adopts IEC 61000-4-3 [4] Testing and Measurement Techniques-Radiated, Radio Frequency, Electromagnetic Field Immunity Test standard; RG1.180 requires electromagnetic interference testing of nuclear power plant equipment in accordance with MIL-STD-461E and IEC 61000 standards, and clarifies that the immunity test level of safety-related instrumentation and control systems in nuclear power plants should be at least 10 V/m; IEC 62003-2020 stipulates that the radio frequency radiation (RFR) immunity test of nuclear power plant instrument control equipment and electrical equipment should meet the requirements of level 3 in IEC 61000-4-3, the test field strength is 10 V/m, and the upper limit of the test frequency is 6 GHz.

The above standards recommend that the electromagnetic interference test of nuclear power equipment adopts the IEC 61000-4-3 standard. In this standard, it is stipulated that the transmitted signal uses a 1 kHz 80% amplitude modulated sine wave.

2.2 Specific Requirements for Immunity of Nuclear Power Plant Equipment. Compared with the repealed IEC 62003-2009, IEC 62003-2020, released by the International Electrotechnical Commission in 2020, expands the scope of application of the standard, strengthens the description of the electromagnetic environment, and provides clear instructions when selecting customized test levels.

Chapter 7 of IEC 62003-2020 stipulates that the radio frequency radiation immunity test of instrument control equipment and electrical equipment of nuclear power plants shall meet the requirements of level 3 in IEC 61000-4-3, the test field strength is 10 V/m, and the upper limit of test frequency to reach 6 GHz.

3 Results and Discussion

3.1 Research on Test Methods. In the nuclear power plant environment, the electromagnetic interference of nuclear power instrumentation and control equipment comes from two aspects, one is the interference caused by the operation of other nuclear power instrumentation and control equipment around, and the other is the interference caused by wireless communication signals such as 5G and Wi-Fi6. This paper mainly studies the electromagnetic interference of 5G, Wi-Fi6, and other wireless communication signals caused by different modulation methods (such as 256QAM/OFDM), different signal bandwidths, different powers, distances, and other factors to nuclear power instrumentation and control equipment, and compares with the interference test of sweep signal (1 kHz 80% amplitude modulated sine wave, 80 MHz–8 GHz).

In the environment of the nuclear power plant, 5G and Wi-Fi6 signals mainly come from the base stations and terminals. In the indoor environment of the plant, the base station adopts medium range base station or local area base station, while Wi-Fi6 adopts wireless AP.

The transmitting power of base station medium range base station is 33 dBm, and that of local area base station is 24 dBm [5]. The minimum coupling loss from medium range base station to user equipment (UE) is 53 dB, the minimum coupling loss from local area base station to UE is 45 dB, and the maximum transmitting power of Wi-Fi6 wireless AP is 20 dBm. Considering that the installation position of wireless AP can cover a wider area and it is far from the nuclear electrical instrument control equipment, the transmitted signal power passes through the wireless transmission loss, and the signal reaching the instrument control equipment is very small.

Therefore, the comprehensive analysis shows that the signal power of 5G, Wi-Fi6 base station, or wireless AP in the instrument control equipment is generally below −20 dBm. Because its installation position is relatively fixed, compared with the user terminal that can be moved close to the nuclear instrument control equipment (the transmitting power is generally 26 dBm), the electromagnetic interference effect can be ignored.

This paper mainly studies the electromagnetic interference and interference protection requirements generated when mobile user terminals are close to nuclear instrument control equipment. Since mobile user terminals do not work at full load transmitting power all the time, it is difficult to achieve extreme conditions of full load transmitting power. Therefore, the vector signal source is used to transmit 5G and Wi-Fi6 signals to carry out electromagnetic interference to nuclear instrument control equipment instead of the extreme electromagnetic interference conditions generated by mobile user terminals.

5G NR and 802.11ax (Wi-Fi6) wireless signals are generated by vector signal source N5172B and can be freely configured with signal parameters such as different modulation modes and bandwidths. The transmitted signals are shown in Table 1. The test conditions for different powers and different distances are based on the actual environment of the nuclear power plant and the 10 V/m field strength required by the standard at different distances, and then conduct tests around the device under test by using field strength meter.

$$E = \sqrt{377^* \frac{P}{4\pi R^2}} \tag{1}$$

Table 1 Types of signals emitted by signal sources

Signal	Frequency	Power	Test project
1 kHz 80% amplitude modulated sine wave	80 MHz–8 GHz	1 W	Broadband scanning interference test
Wi-Fi6	2400–2483.5 MHz 5150–5350 MHz 5725–5850 MHz	20 dBm	RFI signal interference test
5G	703–733 MHz 758–788 MHz 2515–2675 MHz 4800–4900 MHz 3400–3500 MHz 3500–3600 MHz	26 dBm	

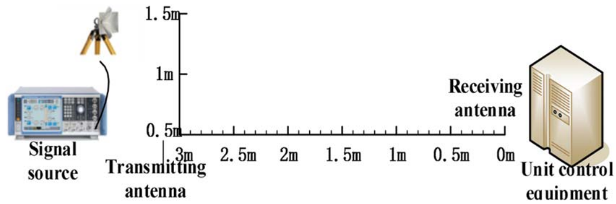

Fig. 1 Test system

In the equation, E is the electric field intensity, and the unit is V/m; P is the power at the transmitting antenna port, in the unit of W; R is the distance between the transmitting antenna and the nuclear power equipment under test, in the unit of m; the free-space wave impedance is 377 Ω.

According to standard IEC61000-4-3 and IEC 61000-6-2, test method requirements performed a sine wave sweep interference test with 80% amplitude modulation at 1 kHz. IEC 61000-6-2 specifies a maximum radiation immunity rating of 10 V/m in industrial environments, which is analyzed at a test distance of 0.5 m, and the power at the end of the interfering signal antenna port is about 30 dBm (1 W). Anti-interference tests are carried out for the signal interference of Wi-Fi6 wireless AP and 5G mobile phone terminals, wireless AP devices with antenna gain of less than 10 dBi emit equivalent omnidirectional radiated power of no more than 20 dBm [6]. The transmission power of the 5G mobile phone terminal is 23 dBm, and the power of Class 2 is 26 dBm [7], and the limit of high power is used in this test verification, i.e., the power transmitted by the 5G mobile phone terminal signal is 26 dBm.

According to the parameters shown in Table 1, use the signal source to transmit signals respectively (Fig. 1).

Setup the test system according to the test scenario, and the test steps are as follows:

Step 1: Keep the height of the transmitting antenna level with that of the tested device, and the distance between the transmitting antenna and the tested device is 0.5 m.

Step 2: Use the signal source to transmit the interference signal, the test frequency is the center frequency of the specified transmission frequency band, the test time is 1 min, observe the working status of the interfered equipment, and record the working status and received power of the equipment when abnormal conditions occur.

Step 3: If the device under test interferes with the maximum radiation power, adjust the signal power to reduce the signal transmission power in steps of 3 dBm (the steps can be adjusted according to the actual situation on-site to ensure the accuracy of the threshold), and repeat the test in step 2 until the interference threshold is found.

Step 4: Change the distance between the transmitting antenna and the device under test (0.5 m, 1 m, 1.5 m, …, 3 m) and different azimuth angles (0 deg, 45 deg, 90 deg, …, 315 deg), repeat steps 1–3 to complete the electromagnetic interference test at different distances and orientations.

3.2 Test Results. A total of 39 devices were tested this time, and four devices were disturbed to vary degrees. The device types were relay cabinets, vibration detection cabinets, ABB conductivity meters, and speed control cabinets. Among them, the 5G and Wi-Fi6 signals interfered with the speed control cabinet. In addition, according to the IEC 61000-4-3 standard, the sine wave single carrier signal with a modulation depth of 80% at 1 kHz interfered with these four devices. The rotational speed control cabinet is disturbed in the frequency range of 100 MHz–7 GHz, and the relay cabinet, vibration detection cabinet, and ABB conductivity meter are disturbed in some frequency bands of the entire test frequency range.

The experimental data show that under the same test requirements, the anti-interference capabilities of different devices are far different. Among them, the interference of the speed control cabinet is more obvious, and the frequency sweep interference is almost the entire frequency band of electromagnetic interference. And the interference value is far lower than the 10 V/m test requirement standard. From this, it can also be seen that the device is extremely sensitive to radio signals.

3.3 Analysis of Test Results. Based on the results of this test, the degree of electromagnetic interference of nuclear power instrumentation and control equipment was analyzed.

(1) The whole frequency band 80 MHz–8 GHz is subjected to the 1 kHz modulation depth of 80% of the amplitude modulation sine wave frequency step of 1% frequency sweep signal interference test, the test distance is 0.5 m, the test orientation is 0 deg, 45 deg, …, 315 deg. Among the four devices with interference tested, the interference field strength threshold of the relay cabinet, vibration detection cabinet, and ABB conductivity meter is between 3 V/m and 10 V/m. The transmit power at the interface of the interference antenna is between 18 dBm and 29 dBm. Move the interference transmit antenna to a distance of 1 m or more, and no interference occurs. There is interference in the whole frequency band of the speed control cabinet, the interference field strength threshold is between 1 V/m and 8 V/m, and the transmit power of the interference antenna port is between 10 dBm and 27 dBm. Details are provided in Tables 2 and 3.

When using 5G NR and Wi-Fi6 wireless interference signals with digital modulation, the test distance is 0.5 m, the test azimuth is 0 deg, 45 deg, …, 315 deg, the NR signal uses band 41/71 frequency, and the modulation method is QPSK/64QAM, the signal bandwidth is 20 MHz and 100 MHz. The Wi-Fi6 signal modulation method is 256QAM, and the signal bandwidth is 80 MHz for interference testing. The test interference threshold field strength is

Table 2 Interference test results

Device	Interference frequency	Modulation method	Interference distance	Threshold field strength	Transmission power
Relay cabinet (back)	550 MHz	AM	0.5 m	7.8 V/m	27.0 dBm
	1 GHz	AM	0.5 m	2.9 V/m	18.5 dBm
	2 GHz	AM	0.5 m	8.7 V/m	28.0 dBm
	3 GHz	AM	0.5 m	9.0 V/m	28.3 dBm
Vibration detection cabinet	180 MHz	AM	0.5 m	7.3 V/m	26.5 dBm
	300 MHz	AM	0.5 m	7.0 V/m	26.1 dBm
	350 MHz	AM	0.5 m	5.4 V/m	23.9 dBm
	400 MHz	AM	0.5 m	6.1 V/m	24.9 dBm
ABB conductivity meter	850 MHz	AM	0.5 m	7.4 V/m	26.6 dBm
	900 MHz	AM	0.5 m	7.7 V/m	26.9 dBm

Table 3 Test results of full-frequency interference of speed control cabinet

Interference frequency	Threshold field strength	Transmission power	Threshold field strength	Interference frequency	Transmission power
100 MHz	1.9 V/m	14.8 dBm	750 MHz	2.3 V/m	16.4 dBm
200 MHz	1.6 V/m	13.3 dBm	800 MHz	2.7 V/m	17.8 dBm
250 MHz	1.4 V/m	12.1 dBm	850 MHz	2.0 V/m	15.2 dBm
300 MHz	1.9 V/m	14.8 dBm	900 MHz	1.5 V/m	12.7 dBm
350 MHz	4.5 V/m	22.3 dBm	950 MHz	1.4 V/m	12.1 dBm
400 MHz	6.3 V/m	25.2 dBm	1 GHz	3.6 V/m	20.3 dBm
450 MHz	5.8 V/m	24.5 dBm	2 GHz	1.2 V/m	10.8 dBm
500 MHz	1.9 V/m	14.8 dBm	3 GHz	4.2 V/m	21.7 dBm
550 MHz	1.2 V/m	10.8 dBm	4 GHz	8.0 V/m	27.3 dBm
600 MHz	1.5 V/m	12.7 dBm	5 GHz	4.0 V/m	21.2 dBm
650 MHz	2.3 V/m	16.4 dBm	7 GHz	2.7 V/m	17.8 dBm
700 MHz	3.1 V/m	19.0 dBm	/	/	/

Table 4 Specific information of terminal interference of speed control cabinet

Interference pattern	Modulation method	Signal bandwidth	Interference distance	Azimuth angle	Threshold field strength	Transmission power
5GNR 700 MHz	QPSK/OFDM	20 MHz	0.5 m	0 deg	2.7 V/m	17.8 dBm
5GNR 2500 MHz	64QAM/OFDM	100 MHz	0.5 m	0 deg	1.7 V/m	13.8 dBm
Wi-Fi6 2.4 GHz	256QAM/OFDMA	80 MHz	0.5 m	0 deg	2.6 V/m	17.5 dBm

between 1 V/m and 3 V/m, and the power at the transmitting port of the interference antenna is between 13 dBm and 18 dBm. Details are provided in Table 4.

The test results show that the interference threshold of the tested interfered equipment is below the 10 V/m limit specified by the standard, i.e., the anti-electromagnetic interference capability is lower than the standard limit. The relay cabinet, vibration detection cabinet, and ABB conductivity meter are interfered with by narrow-bandwidth signals, but not by digitally modulated broadband signals such as 5G NR and Wi-Fi6. Therefore, under the condition of the same transmit power and disturbed field strength, the narrow bandwidth 1 kHz sine wave amplitude modulation signal is more likely to cause electromagnetic interference to the nuclear power instrument and control equipment than the broadband digital modulation signal.

(2) The interference threshold field intensity of the relay cabinet, vibration detection cabinet, and ABB conductivity meter is close to the field intensity of 10 V/m stipulated in the standard for the four nuclear electrometer control devices with interference tested in this study. After the RF electromagnetic field immunity test in the laboratory environment, in the industrial environment of the nuclear power plant, due to the impact of the field environment, the requirements for the anti-interference capability of the equipment should be higher. The speed control cabinet has obvious interference to radio signals, and most of the frequency field intensity of interference is around 3 V/m, so the equipment belongs to the sensitive equipment.

According to the standard TR-102323 Appendix N, under the interference threshold field strength of the equipment, the margin of 8 dB should be considered as the anti-interference field strength threshold of the equipment, so the protection distance should be increased. The test distance is 0.5 m. According to Eq. (1), the electromagnetic interference protection distance is 1.3 m after the field strength of the test interference threshold increases by 8 dB margin.

According to the threshold value of 10 V/m of IEC 61000-4-3, the threshold value of 10 V/m is lower than the threshold value of 10 V/m, i.e., the threshold value of 10 V/m is higher than the threshold value of IEC 61000-4-3, and the threshold value of 10 V/m is higher than the threshold value of IEC 61000-4-3. According to Eq. (1), taking the minimum test interference threshold for a single device, the protective distance of relay cabinet equipment should be set as 1.7 m, vibration detection cabinet equipment as 0.9 m, and ABB conductivity meter equipment as 0.7 m. For equipment of speed control cabinet, as it is sensitive equipment, interference protection distance of 4.2 m is set for digital modulation broadband signals such as 5G NR and Wi-Fi6 as well as narrowband sine wave modulation signals.

3.4 Suggestions on Electromagnetic Interference Protection. In the environment of nuclear power plants, the degree of informatization is getting higher and higher, and electromagnetic wave is the main transmission medium for transmitting information, which leads to the electromagnetic environment of nuclear power plants becoming more complex and the electromagnetic compatibility requirements between equipment becoming higher and higher. According to the above test conclusions, it is suggested to adopt the following methods to avoid risks:

(1) Sensitive devices and wireless devices maintain a certain spatial isolation: setup isolation protection fences for sensitive devices and warning signs forbidding communication devices from approaching;
(2) Setup shielding between sensitive and wireless devices: setup shielding cover for extremely sensitive equipment, setup isolation protection fence, and setup warning signs prohibiting communication equipment from approaching. If ventilation is needed for shielding to cover, try to use small round holes instead of long air holes;
(3) Determine the degree of anti-interference of different nuclear power equipment: when purchasing nuclear power plant equipment, the supplier shall provide the electromagnetic anti-interference test report of the equipment;
(4) The current interference source can produce electromagnetic radiation: keep the signal line away from the current interference source when there is emission inside the system equipment of the nuclear power plant;

(5) Attenuation of interfering signal power: add a filter circuit to each port of sensitive equipment to prevent the noise that has been coupled to the port from entering the equipment.

4 Conclusion

By conducting electromagnetic interference tests on nuclear power equipment, this paper finds out the interference of new radio signals such as 5G and Wi-Fi6 on the facilities and equipment of nuclear power control units, and determines the sensitive equipment in the facilities and equipment of nuclear power control units, and clarified the sensitive frequency bands and interference thresholds of sensitive equipment. For this test, the speed control cabinet equipment interfered with by 5G/Wi-Fi6 signals is verified to have a minimum field strength threshold of 1.7 V/m, which is lower than the standard requirements. In order to prevent it from interference from the new radio signal, the corresponding protection distance is increased, and the protection distance is calculated according to the minimum interference field strength threshold of 2.1 m. Considering the extreme case of actual use, the new radio signal terminal equipment such as 5G and Wi-Fi6 is 0.1 m away from the nuclear power unit equipment, and the transmission power of its terminal should be limited to 10 mW. In the nuclear power plant environment to carry out electromagnetic interference verification test, some equipment cannot withstand 10 V/m field strength, in order to ensure the safety of equipment uses, it is recommended that nuclear power plants in the construction of wireless communication system before the nuclear power unit equipment conduct a comprehensive electromagnetic compatibility test to determine the electromagnetic immunity strength of various types of equipment. Based on the results verified by this test gives suggestions on electromagnetic interference protection requirements for sensitive equipment. It has reference significance for the electromagnetic interference protection of new radio technologies such as 5G and Wi-Fi6 in the large-scale application of nuclear power plants, and further helps smart nuclear power to realize more intelligent applications in the future.

Acknowledgment

The authors would like to thank Yan Zhang of the Chongqing Academy of Information and Communications Technology for helpful discussions on topics related to this work. Testing of this work was supported by CGN and Chongqing Academy of Information and Communications Technology.

Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent not applicable. This article does not include any research in which animal participants were involved.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

Nomenclature

The Electric Field Intensity Algorithm

E = the electric field intensity, the unit is V/m
P = the power at the transmitting antenna port, the unit is W
R = the distance between the transmitting antenna and the nuclear power equipment under test, the unit is m
$377\ \Omega$ = the free-space wave impedance

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