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Ensuring Electromagnetic Compatibility in Nuclear Power Plant beyond Equipment Qualification Tests

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ABSTRACT

Electromagnetic compatibility (EMC) is defined as the capability of equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that same environment [1]. EMC regulatory requirements for instrumentation and control (I&C) equipment were not developed or in effect until the last few years. Therefore, there is a considerable number of plant equipment that has not been qualified for EMC. The current EMC regulatory requirements address new and modified equipment only, and do not call for testing of existing equipment. There is a gap, which has to be overcome, in order to understand the current level of EMC within the plant.

Equipment qualification normally implies formal tests in EMC chambers, which is not practical for the equipment already installed. This paper is a short overview of the preparation phase of a project that includes various EMC-related activities currently being performed in Krško nuclear power plant (NPP). The activities are categorized into two main groups: equipment immunity (susceptibility) tests, used as an assessment of the immunity of the existing equipment such as process cabinets, transmitters and similar, and zone mapping measurements, which are performed to record the electromagnetic environment of the selected plant areas.

There is no clear, detailed and unambiguous guidance on how to perform any of these tests. It takes a lot of engineering judgement to optimize them for a specific plant. Some of the most important questions addressed in this paper are 1) the selection of the plant areas for zone mapping measurements and susceptible equipment to be tested for immunity, 2) choice of electromagnetic disturbances, which shall be simulated during those tests, and 3) practical performance, i.e. harmonization of immunity tests with operation of other plant systems. It is necessary to decide which operation mode poses the “worst-case”, i.e. how and when the immunity tests and zone mapping measurement should be performed.

The paper also addresses troubleshooting of poor EMC design and installation practices, which can significantly reduce the number of EMC-related problems in a plant.

Keywords: *electromagnetic compatibility, electromagnetic interference, equipment testing, site surveys, in-situ tests*

1 INTRODUCTION

Regulatory Guide 1.180 [2][1] endorses test methods for evaluating electromagnetic emissions and immunity of new safety-related systems and modifications to existing safety-related systems. Revision 1 of this document was published in 2003. The average age of U.S. commercial reactors is around 36 years [3]. That means that most of the power plants have a significant portion of different I&C systems, which were installed prior to the publication of RG-1.180. Therefore, the existing equipment is not addressed by the regulatory requirements. It would be highly impractical to perform the same tests on existing equipment, as required for the new and modified equipment, including emission and immunity tests in an anechoic chamber. Hence, in order to assure that the existing process and control cabinets, pressure transmitters, positioners and similar equipment do not emit excessive emissions well above the limits defined in military and commercial standards, and that they can withstand expected noise levels, it is necessary to define a customized set of in-situ EMC tests.

This paper presents additional measures that can be taken in order to address the existing equipment. It describes the preparation phase of such an assessment, supported with the examples from the Krško NPP.

2 MOTIVATION FOR EMC ASSESSMENT

There are different results, which an assessment of this type can yield. Some power plants have recognized the benefits of wireless technologies [4], which can be used for online monitoring and transfer of operational parameters in inaccessible locations, remote controls of cranes and robots, communication systems and other. In that case, it is necessary to prove that the wireless signals will not interfere with the existing plant equipment.

Power plants commonly experience EMC related problems. The most relevant are spurious occurrences of alarms, but more serious consequences, like reactor scrams, are possible. The root cause for these problems and the associated equipment can't be determined. In that case, it is possible to target the specific equipment and thoroughly analyze its immunity.

Plant radios are commonly used in plants, but often they interfere with susceptible instrumentation. Their impact can be characterized with testing that can help to determine whether the existing exclusion zones are properly defined. It might be desirable to eliminate these exclusion zones, in order not to rely on administrative controls.

The results of the immunity tests and zone mapping can be used as input data for the EMC qualification tests of new equipment, instead of relying on generic data that can be found in the existing guidance [5]. Test and measurements of such type will help identify electromagnetic energy (EM) hotspots, which should be avoided as installation locations, or even as the potential health hazards. Other motives are possible as well.

3 IN-SITU IMMUNITY TESTS

In-situ immunity tests, performed on the equipment located in the plant areas, correspond to immunity tests performed in (semi)anechoic (reverberation) chambers or Open Area Test Sites (OATS), with some differences, which are discussed below.

In-situ immunity tests can be performed almost exclusively during the outage, when the impact to plant operation is minimized. For the same reason, it is further recommended to limit these tests to the core offload window only. This limit could possibly interfere with the requirement that the equipment must be energized and have meaningful (nominal if possible) indications that can be observed. In addition, it is advisable to perform tests during the night shifts, not only for the above presented reasons, but also to be confident with a greater level of certainty that the equipment response is a result of the intentional electromagnetic and radio frequency interference (EMI/RFI) interference, and not some unrelated activity.

The first task is to decide which equipment should be tested. It should be based on the project motives, industry operational experience, importance of the equipment for plant safety and power production, estimation of the equipment susceptibility and severity of the EM environment, quantity of similar or identical components in the plant (discussed later) and other factors. The total number of the equipment must be limited due to the substantial duration of each test.

The monitored outputs for the equipment under test can be defined arbitrarily, but they mostly depend on the significance of the particular outputs. In the simple case of a pressure transmitter, it is reasonable to monitor the pressure value, locally or remotely. It is less straightforward what should be observed in case of complex process cabinets, but usually the choice is reduced to the local indications and displays, alarms, different parameters available on the plant computer and/or recorders in main control room (MCR). The acceptance criteria can also be arbitrarily defined, e.g. a predefined percentage of the process range for the monitored signals.

The injected EMI/RFI test levels can correspond to those defined for the MIL-STD-461 RS103 test (10 V/m over the whole frequency range), but it is possible to apply higher levels as well, in order to minimize test uncertainty, or to prove that it is possible to use different devices, like plant radios or tablets, within a closer distance of cabinets and other equipment.

In-situ immunity tests are intended to determine the response of the tested equipment, but not affect other equipment located in vicinity of the Equipment under Test (EUT). Thus, they are limited to the radiated immunity tests only. The radiated noise can be localized more easily compared to the conducted noise (also, some conductive immunity tests are defined as destructive). In order to do that, it is possible to reduce the distance between the emitting antenna and EUT, thereby reducing the effective radiated area of the EUT (sometimes this is inevitable because of lack of space), or simply by shielding the other equipment in the vicinity. The latter should include the equipment behind the antenna, as some antennas could have radiation patterns with significant back lobes. Shielding can be achieved by using copper nickel or similar fabric, which offers good shielding effectiveness up to the highest frequencies of interest. If it is recognized that the other equipment could cause any unwanted actuation, it should be disabled by putting it to test mode or by directly disabling executive components (for example, putting pump switches to pull-out positions).

The frequency range of in-situ immunity tests depends on the plant motives. It could be for troubleshooting of problems with plant radios, in which case the focus will be on 400 – 500 MHz range. If the plant wants to examine implementation of new wireless technologies, it will more closely study higher frequencies. The most common wireless data standards include Bluetooth and Wi-Fi, where it is important that both the existing equipment is not vulnerable in those frequency ranges, and also that all equipment that utilizes wireless technology can coexist in the same frequency band.

Different wireless technologies are characterized by different signal modulations. In order to shorten the test time, which can be crucial for realization of the tests during short system windows, it is practical to use conservative modulation schemes taken from military EMC tests. It can be assumed that it is more severe than all commercially used modulations. The RS103 test uses 1 kHz pulse modulation, 50% duty cycle, where the fast rise and fall time of the pulse produce significant harmonic content that affects analog and digital circuits. The more detailed explanation for why this modulation was chosen can be found in MIL-STD-461G [6].

In-situ immunity tests should be performed for different polarizations (vertical and horizontal) of the emitting antenna, although the worst case is usually the vertical polarization. Other polarizations between the horizontal and vertical one can be used as well, especially if it is dictated by the layout of the tested components, such as cables within the cabinet. By selecting only frequencies of interest, worst-case polarizations and modulations, reducing the dwell time (time at which the interfering signal is injected for a particular frequency), and by testing more components at the same time, it is possible to significantly reduce the total test duration (from a couple of hours to approximately 30 – 40 minutes per test), and to test more equipment in a given period, without making any compromise on trustworthiness of the results. The minimum dwell time is limited by the response time of the equipment and sampling time of the recording system (local recorder, plant computer or other). Additionally, the test should be automated by using a single signal generator and predefining the test frequencies. In that case, it is only necessary to change the emitting antennas depending on the frequency range, and change their polarization.

In case that susceptibility is identified, several options are possible. If the equipment was conservatively tested with the doors open, or without its enclosure in general, it is possible to retest it in a less vulnerable configuration, which is usually the default one. Another option is to modify the equipment in order to improve its immunity. This includes the use of additional shielding, gaskets, EMC cable glands, ferrites, filters and other methods. Abovementioned methods of improvement of the equipment immunity are presented later in more details. If none of those measures is effective, it is always possible to define an exclusion zone around the susceptible equipment.

One of the most important advantages of these tests, compared to the EMC qualification tests, is that they reflect the authentic installation, whereas qualification tests only try to replicate it. It is common that the equipment itself is designed in accordance with the best EMC practice, but it fails immunity or emission tests due to the poor installation. Although it is a general rule to perform qualification tests in the same configuration, as it will be installed, and to install it in the same configuration as it will be tested, there are usually deviations from the rule. For that reason, it makes sense even to perform in-situ immunity test of the equipment that has been previously qualified, in case that there are large concerns over the way the installation was performed.

On the other hand, in-situ test repeatability is limited because the background emissions can vary, the equipment and structures in vicinity can affect results, and because the in-situ tests do not follow well-defined test setups and procedures, like qualification tests.

It is possible to test one representative component and assume that other identical or comparable equipment will behave similarly. If possible, it is recommended to choose one, which is assumed the most susceptible in its installation configuration, for example, because it contains the largest portion of exposed cables. Another criterion for the electronic equipment could be aging, whereby the older components may be more susceptible.

Figure 1 shows an example of an immunity test performed in NEK. It illustrates the statements presented above. The cabinet is tested with the doors open, which is a conservative assumption. The antenna is directed toward the cabinet cards that are assumed to be the most susceptible. The injected field strength is measured using an electric field probe in the cabinet's front plane. This cabinet is tested from both the front and back side. The same figure also shows that the equipment in vicinity is properly shielded using conductive fabric.

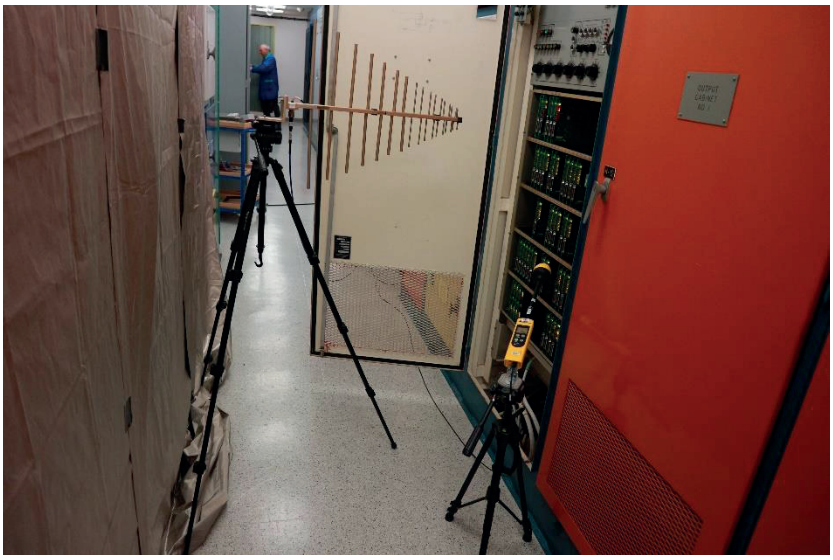

Figure 1 Immunity Test of Solid State Protection System (SSPS) Cabinet in MCR

4 BENCH IMMUNITY TESTS

Sometimes it is not possible, or desirable, to test equipment in-situ in the plant. In that case, it is possible to perform an alternative bench test, either in a laboratory, or in a workshop. Again, there are several advantages and disadvantages of this approach.

The positive side is that bench tests offer better flexibility, as they are not time limited, and therefore, it is possible to compare different installation configurations. However, they do not reflect the existing plant location. Similar to qualification tests, bench tests will likely identify potential problems of the component itself, but they will fail to answer whether the installation is adequate.

Bench tests are limited to components that can be found in the plant warehouse. Plant cabinets, on the other hand, are usually unique components, and they can only be tested in-situ.

Some of-the-shelf products could be already qualified, and their qualification reports are readily available. In that case, it is important to check whether the test methods, test scope, test levels, acceptance criteria and other factors are appropriate for the intended use. The highest test frequency increases as the new wireless standards emerge, and it is possible to find equipment that was tested, but up to only 1 GHz.

5 ZONE MAPPING

Zone mapping, sometimes also referred to as site survey, is a passive measurement of the electromagnetic environment levels in a power plant. It is not reasonable nor possible to perform it in all plant areas. The areas of interest include rooms where the susceptible I&C equipment is located, as well as areas with potentially excessive EM emissions. In addition to that, it is important to include areas where the related plant modifications, especially digital upgrades, are foreseen. The tests are based on emission tests described in MIL-STD-461 (CE101, CE102, RE101 and RE102) and corresponding commercial standards, yet they are slightly modified to fit the zone mapping purpose.

In contrast to in-situ immunity tests, zone mapping should be performed during on line operation. Otherwise, during outage, a large number of equipment is de-energized and does not contribute to the plant EM emission levels.

The plant EM environment is never in a steady state. Infrequent EM phenomena and/or transients could appear during plant startup, surveillance tests and while starting significant loads. Thus, zone mapping should be scheduled simultaneously with these activities. These kind of measurements are always challenging to perform. Measurement of the plant emissions in the different frequency ranges requires use of different measuring equipment, in particular various antennas. The main reason is that different antennas have different gain profiles across different frequency ranges. Often, it is necessary to decide which phenomena shall be recorded during the short duration of the transients. Some (un)intentional emitters, such as plant radios and welding machines, can also easily be included in this survey.

Radiated emissions are preferably made with two opposite antenna directions. Firstly, in direction away of the equipment, to measure emissions seen by a cabinet or instrumentation. Second measurement would be in the opposite direction toward the equipment, in order to measure emissions of that same equipment. In both cases, it should be accounted that there is background emission level, i.e. the hypothetical cabinet is not the only contributor.

Zone mapping is not strictly related to radiative emissions. It is possible to obtain conductive emissions in an unobtrusive way as well, by using current clamps. Transient phenomena should be captured in the time domain, in contrast to the other measurements for which frequency domain is more suitable.

Although it could be said that each new modification affects the plant EM environment, it is not intention to repeat this assessment too often, except in case of major changes.

6 TROUBLESHOOTING

Electromagnetic interference can affect a victim in many ways, but usually the majority of the problems can be associated to a smaller number of causes, as the famous Pareto principle states.

As already indicated in previous sections, there are several options when susceptibility has been detected, whether during an immunity test or simply identified as a deviation from good practice by visual inspection. In the first case, before taking any corrective measures, it is advisable to repeat the portion of test during which the susceptibility was detected and to confirm that it was caused by the immunity test. The exact frequency for which the interference occurred should be determined.

It is possible to modify the installation or even the equipment itself to address the susceptibility. One of the simplest troubleshooting steps and tools to reduce or isolate most radiated emissions is to apply additional shielding. There are several different ways to use shielding to reduce interference caused by radiated emissions. For cabinets with glass doors, or different indicators, it is possible to apply metallic transparent foil. If there is a susceptible transmitter, it could be possible to put it in a metallic enclosure. Furthermore, it is desirable to replace nonmetallic enclosures with metallic. If it is necessary to protect equipment from magnetic fields, a material with high permeability should be used.

One of the most common examples of vulnerable equipment are pressure transmitters, which are, according to reports, often susceptible to radiated emissions in frequency range of plant radios. There are several identified mechanisms for how the radiated emissions can affect such instrumentation. It is possible that the EM noise penetrates the enclosure of the transmitter, which usually have a lid that is tightened to its body. The second mechanism is indirect. It involves noise coupled to the cables that enters equipment as a conductive interference, and possibly reradiates noise within its enclosure. The exact mechanism for a specific case can be determined by retesting the EUT in different configurations.

Depending on the identified failure, it could be adequate to shield the cables (as in Figure 2), the transmitter, or both. Shielding of the cables is usually the simplest solution, and it can be done by using metallized flexible conduit.

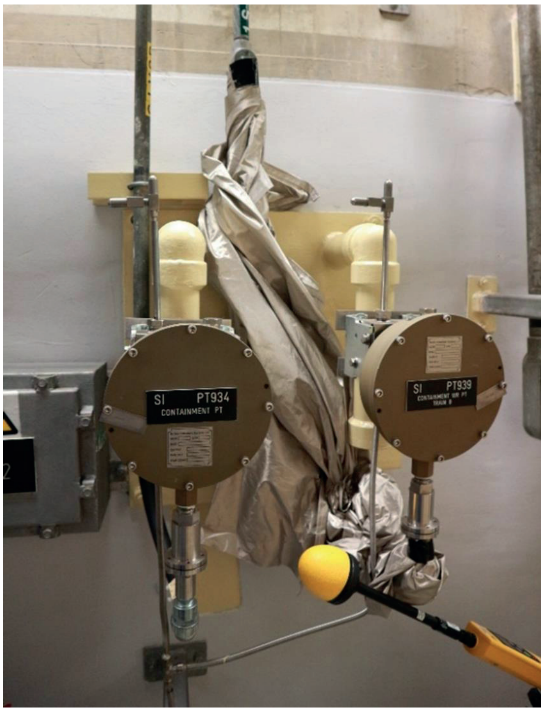

Figure 2 Retesting of the Pressure Transmitters with Provisionary Shielded Flexible Conduit

It is important to check whether EMC gaskets installed on the cabinet doors, or on the instrumentation lids, are installed appropriately. Large apertures, those used for ventilation, or simply consequence of a door design, can significantly reduce the shielding effectiveness.

Another simple fix could be the installation of ferrites around the cables. Such a fix can decrease the noise coupling, as well as the radiation of EM energy from the cables on which the ferrites are installed. Basically, a ferrite acts as a low-pass filter that blocks high-frequency current, thus attenuating the high-frequency noise. The frequency characteristics depend on selection the of the ferrite material.

Other methods could be more intrusive and it is not necessary advantageous to apply them, even if they can improve equipment immunity. For example, varistors can protect equipment from overvoltages, but they can also fail shorted and make the equipment inoperable. It is necessary to determine in advance which modifications are acceptable. The last solution, if none of discussed methods gives adequate results, is to declare an exclusion zones, or to replace the equipment with an alternative, immune model.

Following the implementation of one or more solutions discussed above, it is necessary to repeat the immunity test at least for the frequency and polarization for which the interference was detected.

7 CONCLUSION

Electromagnetic compatibility involves numerous different phenomena in a typical nuclear power plant. The consequences of interference range from nuisance to plant personnel up to reactor scrams and large economical losses. Existing regulation only partially addresses this problem.

There are different methods that concentrate on the existing I&C systems. They are categorized, similar to the EMC qualification tests, to immunity tests and emission tests.

It is challenging to develop a procedure for such in-situ tests. They have to take into account that it is not acceptable to affect the normal operation of the power plant. For now, there is no strict guidance on how to perform these tests, hence each power plant will come up with a unique plan. This paper presents some of the factors that should be taken into consideration for a successful performance of such an EMC assessment.

The test scope depends on the plant motives. Usually these are the implementation of wireless technologies, troubleshooting of specific EMC-related problems or gathering of input data for qualification tests. It is crucial to harmonize it with other plant activities, and be aware that the majority of the in-situ immunity tests can be performed during the outage period only, which is usually short.

The suggestions given in this paper are based on a similar project that is currently in progress at Krško NPP. Most of the recommendations are general and they can be applied on the other plants as well. Once the tests are finished, the results and conclusions will be presented in later papers. The described tests will help Krško NPP to be more confident that the tested equipment is immune to a specific EM interference, but it does not encompass all possible cases.

The electromagnetic environment is continuously changing, and there are new technologies on the horizon. It is important to keep pace with them in order maintain an appropriate level of electromagnetic compatibility in the plant, once it is established.

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