EMC and earthing concept of the ITER EC-system

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Gyrotrons and High Voltage Power Supplies (HVPS) used on electron cyclotron (EC) systems are the source of large electromagnetic interference (EMI). Arcing events inside gyrotrons is the most frequently cited issue, but fast shutdown of a HVPS can produce similar effect. Even during normal operation, many diagnostics in the vicinity of the tokamak may be affected by the HVPS.

The Swiss Plasma Center (SPC) has performed an electromagnetic compatibility (EMC) analysis of the ITER EC-system, in collaboration with F4E and IO. The analysis is based on lessons learnt at SPC (TCV tokamak and Falcon test facility). A conceptual design of the ITER Building 15 earthing system is proposed and a list of requirements relevant to EMC and to the earthing of the complete EC equipment has been established.

The present article summarizes this work, presenting the key elements required to provide an optimal EMC environment to the ITER EC-system. Guidelines for a proper electrical installation of an EC-system in a fusion facility are issued, allowing for effective EMI mitigation and a reliable operation of the gyrotrons.

Key words: Gyrotron, High Voltage Power Supply, EMC/EMI, grounding/earthing, ITER

Foreword

The terms 'earth' and 'earthing' (GB) have been used rather than 'ground' and 'grounding' (US), although they are considered as equivalent.

1. Introduction

Nowadays, most High Voltage Power Supplies (HVPS) used to feed gyrotrons are based on the pulse step modulation (PSM) concept, or a close variant, that integrates series of switched low voltage power modules (PM) [1]. Usually, the earthing strategy is to connect the gyrotron to earth (for safety reasons) while the HVPS output is floating to avoid a return of part of the load current through the earth. This is unfortunately inevitable with a switched power supply (SPS), due to its AC nature and to parasitic capacitances. This fraction of the load current flowing through the earth is called stray current and is responsible for most of the EMI produced by an SPS [2].

The semiconductors in a PSM are switched at a fixed frequency in the kHz range. In terms of EMC, such a HVPS therefore generates interferences in the same range, also corresponding to that of most diagnostics and typical analog systems.

The Swiss Plasma Center (SPC) has operated for several decades a multi-megawatt electron cyclotron (EC) system providing heating and current drive to the TCV tokamak [3]. In parallel, since 2005 SPC has hosted a 1-MW test facility for the ITER gyrotrons and microwave components, known as Falcon [4]. Thus, SPC had to deal with many problems related to the operation of HVPS on gyrotrons and, as a result, has acquired extensive knowledge in this field [5]. In fact, many EMC issues were solved by improving the earthing infrastructure and/or the cabling method.

The work presented in this manuscript has been required by F4E because the gyrotrons and HVPSs located in ITER Building 15 (EC & IC) are not yet listed as potential sources of interferences in the ITER electrical design handbook (EDH) chapter dealing with EMC. In addition, the EDH does not state clear recommendations for the erection of the common bonding network (CBN), despite the fact that it is the basis of the EMC concept developed for ITER.

In the framework of this study, SPC had to assess whether the planned earthing infrastructure in the ITER Building 15 was sufficient to allow for a reliable operation of the ITER EC system. In particular, IO asked SPC to double check that no additional earthing material, like copper foils or metallic sheets, needed to be installed between the building floors or between the gyrotrons, to mitigate the interferences caused by the arcing events. The planned ITER building 15 earthing infrastructure was first studied and commented before establishing clear requirements for the EMC and the cabling of the ITER EC system.

There are many international standards dealing with EMC/EMI, among which the IEC 61000 series can be mentioned, and particularly IEC 61000-5-2 that presents the recommended practices for the installation and mitigation guidelines. In this manuscript, the specific issues of the ITER EC-system in terms of EMC are highlighted. They can be split into two categories: first, the interferences produced by the operation of the HVPS system, and second, those associated to the operation of two gyrotrons sharing one main high voltage power supply (MHVPS).

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2. EMI generated by normal HVPS operation

A HVPS based on the PSM concept basically consists in a series of low voltage PMs, each one supplied by an individual secondary winding of the main transformer, as represented on Figure 1. The output voltage is given by the interleaved pulse-width modulation (PWM) of all PMs [6]. This means that PWM is continuously applied on each PM. As a consequence, each PM produces some stray current through the parasitic capacitances that are located between the secondary windings and the electromagnetic screen of the main transformer. The PMs are therefore usually equipped with a common mode (CM) filter for EMI mitigation. A solution often adopted is to place the CM filters between the PMs, as illustrated, so they help reduce the size of the output filter.

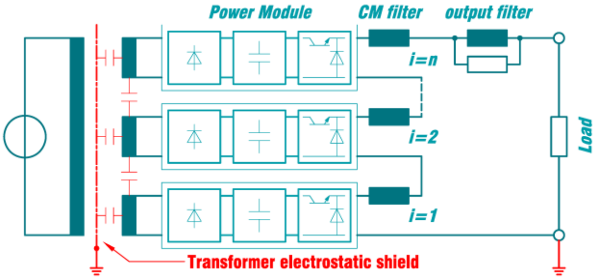

Figure 1: Block diagram of a HVPS based on the PSM concept, with parasitic capacitances in the power transformer.

Figure 2 shows a simplified diagram relevant to the study of the transient currents produced by the PM's switching. The stray current circulates through a second circuit via the earth (common mode, in red) with respect to the designed circuit (differential mode, in green). It is driven by the PM's internal voltage (U_0). As the CM filter is placed at the PM output, each PM has then a different CM circuit. The module closest to the earth (i=1) sees a higher CM current at the switch-ON of the PM, as it is damped by only one CM filter.

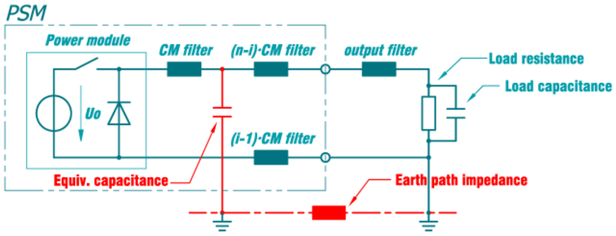

Figure 2: Simplified diagram for EMC analysis of a PSM

The CM filter generally consists in a parallel RL assembly. The resistor aims at reducing the peak current, whereas the inductor helps reducing the losses by conducting the current after the transients. The resistance value must be kept low enough to be coherent with the required output dynamic, i.e. charging the load capacitance (that is mainly that of the output cables) within the specified time. The resistance is therefore too low to damp the oscillating circuit formed by the stray capacitance and the CM filter inductance.

When the PSM concept is used for a HVPS with low current rating, e.g. the PS that feeds the gyrotron body (BPS) or that connected to the anode (APS) of a gyrotron with a triode electron gun, the CM filter helps to protect the semiconductors, since the transient current can be several magnitudes higher than the rated output current. In these applications, it can be necessary to place the CM filter upstream the PM internal voltage, in order to reach the desired performance at the PSM output in terms of dynamics and voltage ripple.

Assuming a PSM composed by n=100 PMs switching each at 3 kHz, it will generate stray currents with a repetition rate of 300 kHz. If a diagnostic is coupled with this PSM, its signal can then present picked-up noise with time intervals (t_i) of 3.33 µs, if the diagnostic is coupled with all CM circuits, or any multiple of t_i up to $n \cdot t_i$=333 µs, if the transient produced by only one PM is responsible for the interference.

Taking into account the typical values of the parasitic capacitances in the power transformers and the CM filter inductance, the frequency of the CM current is generally in the range from 0.3 – 3 MHz. Hence, if the operating bandwidth of the coupled diagnostic exceeds some tens of kHz, the interference cannot be eliminated by filtering the diagnostic signal. This example illustrates why it is necessary, in a plant where sensitive equipment is installed, to optimize the EMC of a HVPS based on the PSM concept by improving the cabling inside and outside the PS enclosure, and the earthing within the whole plant.

The EMI generated by the PM switching can be mitigated by reducing the surface delimited by the CM current path [5]. This can be done by using a triaxial cable for the load connection and/or by connecting the transformer shield to the HVPS output rather than to the earth. The best solution depends on the HVPS design and the site conditions. Note that a solution consisting in connecting the transformer shield to the output terminal via an RC filter is not recommended, since it could result in a ringing circuit for the CM current.

3. Operation of a pair of gyrotrons

Gyrotron arcing events are known to generate severe interference. This is especially the case when several gyrotrons are operated as a cluster on the same MHVPS. In such a situation, several precautions shall be taken. First, it is essential, when a gyrotron is at rest, to disconnect both polarities of its cathode feeding line. Second, the cathode feeding cables shall be equipped with ferrite cores to improve the coupling between feed and return lines, preventing the circulation of transient currents between gyrotrons through the earth, especially in case of an arc.

Figure 3 illustrates the operation of two gyrotrons with different cathode currents (40 A and 36 A in this case), connected to the same MHVPS. The current difference is equally shared between the return paths (38 A and 38 A here), with some current (2 A) circulating through the earth. As a result, the induced magnetic field flux through the surface enclosed by the gyrotron cables (red dashed area on Fig. 3) is different from zero and can thus be a source of interference. Such a small current imbalance would be observed for instance during an automatic mode recovery, if implemented [7].

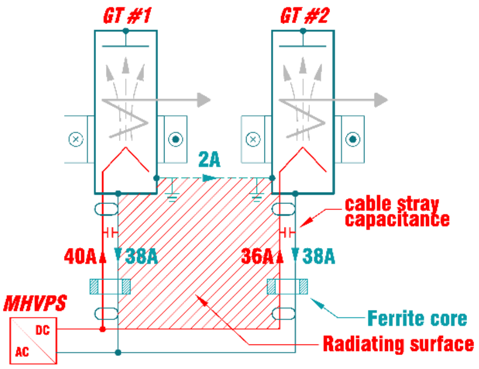

Figure 3: operation of a gyrotrons couple on a single HVPS

In all instances, a DC current circulating through the earth could become an issue in case of an arc: the fast extinction of this DC current may produce an important loop voltage in the area delimited by the cables. It is therefore recommended, as good practice, to route together, over the longest possible path, all power cables connected to a PS, so as to reduce the radiating surface of the earth current. In doing so, the stray magnetic field resulting from the current imbalance will also be minimized in the cables vicinity.

4. Gyrotrons with triode electron gun

Due to the procurement delay of the ITER MHVPS from the Indian Domestic Agency (IN-DA), it is foreseen to temporarily use one MHVPS delivered by F4E to feed two gyrotrons provided by the Japanese Domestic agency (JA-DA). F4E had thus to investigate the compatibility of the EU HVPS set, composed by one MHVPS and two BPSs, with triode type gyrotrons that come with their own APS and filament PS (FPS).

In particular, JA-DA has developed a special APS for the ITER EC-system [8]. Its design is not based on the PSM concept. It is composed by a DC generator (DCG) and two HV switches located in an external cabinet. This solution is similar to a high voltage (HV) push-pull, in which the switches connect the gyrotron anode either to the DCG or to the MHVPS (see Fig. 4). Note that the anode to cathode voltage (Vak), which drives the beam current, is not independently controlled by the DCG with respect to the MHVPS, since the DCG is referred to earth. In fact, when the bottom switch is closed, the anode is bonded to the cathode ($Vak=0$), so the electron beam is inhibited, but when the upper switch is closed, $Vak=U_{DCG}-U_{MHVPS}$, where U_{DCG} is the output voltage of the DCG and U_{MHVPS} is the one of MHVPS.

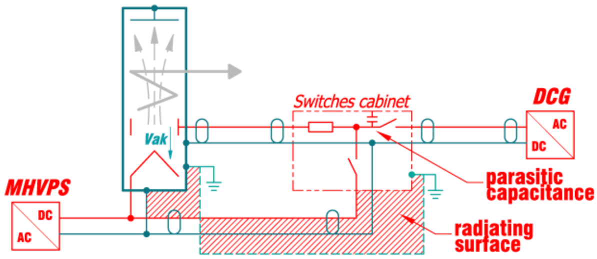

Figure 4: JA-DA APS schematic diagram, with, dashed in red, the radiating surface travelled by stray currents through the capacitance to earth

Besides the limited performance, this solution is inherently less effective than a PSM in terms of EMC. Indeed, when a PM is turned ON or OFF in a PSM, there appears a stray current driven by the internal DC voltage of the PM. Here, the HV switches work on the whole output voltage of MHVPS and APS, so the current peak at the switching time is potentially very high. Several resistors (only one is represented on figure 4) are therefore required to limit the current, in order to protect the switches, but also to improve the EMC. Note that these resistors would have to dissipate substantial amounts of energy in case of gyrotron RF power modulation at high-frequency.

The layout and the cabling of a PS set feeding a gyrotron with a triode electron gun raises specific issues. A key point for a good integration in terms of EMC is the way to access to the cathode potential for APS and FPS. A dedicated connection to the cathode on the gyrotron oil tank for APS and FPS is, in our opinion, the best solution [9].

There are actually two main EMC issues with the APS cabling that must be avoided, both linked to parasitic capacitances. First, the MHVPS output fluctuations (voltage ripple, output ramp-up and down, or arcing event) will drive current through the parasitic capacitance to earth of the APS equipment, as represented in Fig. 4. This capacitance is due to the natural capacitance between the switches assembly and the earth, and to the capacitance of the isolating transformer that feeds the control device of the switches. Second, the capacitance of the anode cable is seen from the MHVPS output as an additional load. If the feed and return paths are distant from each other, they will form a radiating surface, shown in dashed red on Fig. 5.

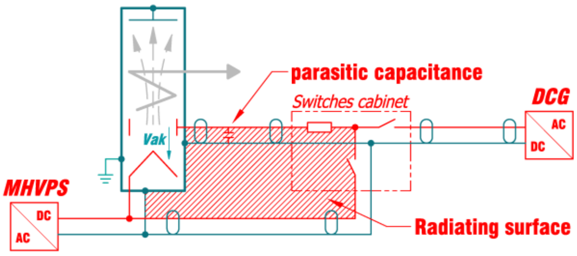

Figure 5: EMC issue due to capacitance of anode cable

When the APS is referenced to the cathode inside the oil tank, it is yet possible to nearly cancel the radiating surfaces highlighted on Fig. 5, by routing together both cables connected to the APS switches. The radiating surface highlighted on Fig. 4 is indeed reduced when the anode cable is accompanied by a parallel earthing conductor (PEC) to give a preferred path to the earth current [10], as illustrated on Fig. 6. A ferrite core encircling the PEC and the cable improves the coupling between the feed and return paths, and thus further reduces residual earth currents.

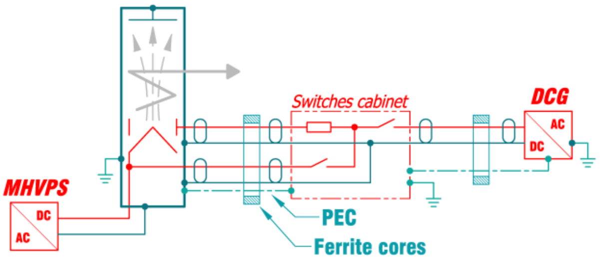

Figure 6: Recommended cabling layout for APS

5. Earthing infrastructure in ITER Building 15

The earthing architecture in the ITER Building 15 can be divided into four subsystems: a) the earthing mesh, b) the earth electrode, c) the bonding ring conductor (BRC) and d) the common bonding network (CBN). They are complementary: some are mainly dedicated to the protection of personnel and equipment against electrical hazards, others to the EMI mitigation. We are convinced that they will together provide a long-term reliable working environment, if the requirements we set-up below are fulfilled.

a) earthing mesh, also referred to as 5x5 m grid

The ITER Building 15 is equipped with a built-in earthing network to protect people and installations against lightning hazards. It allows equipment bonding through connecting points available on a 5x5 m grid in the concrete floors (slabs) and on the inner side of the external walls. The specifications ensure that the voltage drop during a lightning discharge remains admissible for a person in contact with two earthed devices. Note that the earthing mesh shall not be used as an earthing electrode for the medium voltage (MV) AC parts of the MHVPS, because the current in case of short-circuit (31.5 kA) is considered as excessive for the rebar in concrete.

b) earth electrode, also referred to as earthing belt

The earthing mesh is connected to a buried conductor that encircles the ITER Building 15 and all adjacent buildings. This conductor is the effective and only earth electrode. It allows spreading the electrical charges of the lightning current in the earth as well as providing low impedance for the current return to the MV AC substation via the earth. The earth electrode ensures a low step voltage in the vicinity of the building both in case of lightning and short-circuit.

c) bonding ring conductor (BRC) and the equipotential network according to NF C13-200

The bonding ring conductor, sometimes referred to as the interior ring bonding-bus or the earthing bus conductor or the internal earthing belt is the key element of the equipotential network required by the French standard NF C13-200. This additional earthing network is on Level 1 of the ITER Building 15. It is connected to the earth electrode via terminals located on each natural down conductor (structural metallic beam). It is built so as to ensure the shortest earthing path, thereby providing the lowest impedance, to keep the earth potential in the admissible range in case of short-circuit to earth.

Every MV AC part of the MHVPS (AC cells, transformers, enclosures, etc.) is to be connected to the BRC.

d) meshed common bonding network

The meshed common bonding network, referred to as mesh-CBN or simply as CBN, aims at providing an optimal EMC environment. Any metallic part inside the ITER Building 15, in particular, all cable trays shall be interconnected and bonded to the earthing mesh (5x5 m grid. In this way, the electric cables will always be accompanied by an effective PEC acting like a shelter for the EMI mitigation.

The CBN principle consists in bonding all metallic structures both horizontally and vertically, as often as possible, so the CBN results in an extremely meshed 3D assembly embracing the whole building. Doing this, the impedance between any pair of points inside the building is always minimized. Such a mesh saves the installation of additional conductors between floor levels, like copper foils, thanks to the integration of the metallic cable trays into the CBN, which run in all directions inside the building.

A well-distributed CBN is thus the key element for the EMI mitigation in the ITER Building 15. The erection, verification, and validation of the proper integration of all metallic items (cable trays, heating, ventilation and air conditioning conduits, water pipes, control frames etc.) into the CBN must be considered with the utmost attention.

The basic rules driving the implementation of the CBN concept can be found in the ITER electrical design handbook (EDH), from which Fig.7 is extracted. SPC has summarized these rules, with the addition of some relevant practices, and turned them into clear statements written as requirements, that are reported in Table 1.

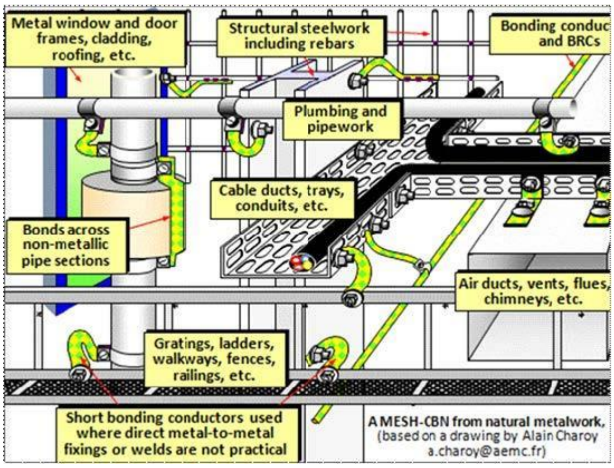

Figure 7: The meshed CBN as presented in EDH, part 4

Fig. 8 gives an overview of the connections to earth for a set of two MHVPSs. One can observe that some elements are connected both to the BRC via the equipotential network and to the CBN, e.g. both transformers of MHVPS1. This is justified by the fact that the BRC is designed to sustain the current in case of short-circuit while the CBN, which relies on the earthing mesh is intended for EMI mitigation. The transformer cores are thus connected to the BRC via 150 mm^2 bare copper conductor, while the connections to the CBN are done with 25 mm^2 wires. This double connection is imposed by the strict application of the French standard NFC 13200, in contrast with the practices that are in use for instance at TCV and Falcon. However, whatever the current capability of the earthing mesh, we could assume that the earth fault current will circulate through the cables screens, since the ITER EDH requires that "*the 22kV network cables shall have their screens connected to earth at both ends*". Moreover, the earth fault current would never be higher than 500 A, as it is limited by the neutral point earthing transformer.

	Requirements relevant for EMC in relation with CBN
REQ-01	All metallic items shall be interconnected including all cable trays, pipes, ducts, conduits, cabinets, enclosures, fences, structural metalwork, metal cladding (spatial shielding), etc.
REQ-02	When metal-to-metal bond is not possible, short and wide braid straps shall be used (<0.5 m long, >25 mm wide and min 25 mm^2). Bare copper round conductor or busbar can also be used if $\geq$ 25 mm^2.
REQ-03	When the length of the strap cannot be shorter than 0.5 m, at least two straps shall be installed, possibly spaced by less than 0.5 m.
REQ-04	The bonding conductors shall run both vertically and horizontally to create a complete 3D equipotential network throughout the ITER Building 15.
REQ-05	Vertical and horizontal spacing between bonding conductors, in any 3D section of the meshed CBN, shall be smaller than 4 m.
REQ-06	Any metal panels in the walls or in the floors shall be electrically bonded to their adjacent panels using screws every 1 m around their perimeters.
REQ-07	Every CBN section shall be connected as many times as possible to the earthing mesh.
REQ-08	Every electrical bond shall be reliable and corrosion-free with no paint or any other insulating surface coating on bonded metal surfaces.
REQ-09	No part of the CBN shall ever be used as an electrical path for any electrical device no matter the power level.
REQ-10	CBN shall be checked after any installation works in the building (visual inspection, verification of cross sections, surface conductivity, etc.)

Table 1: Example of requirements written by SPC for the earthing of the ITER EC-system.

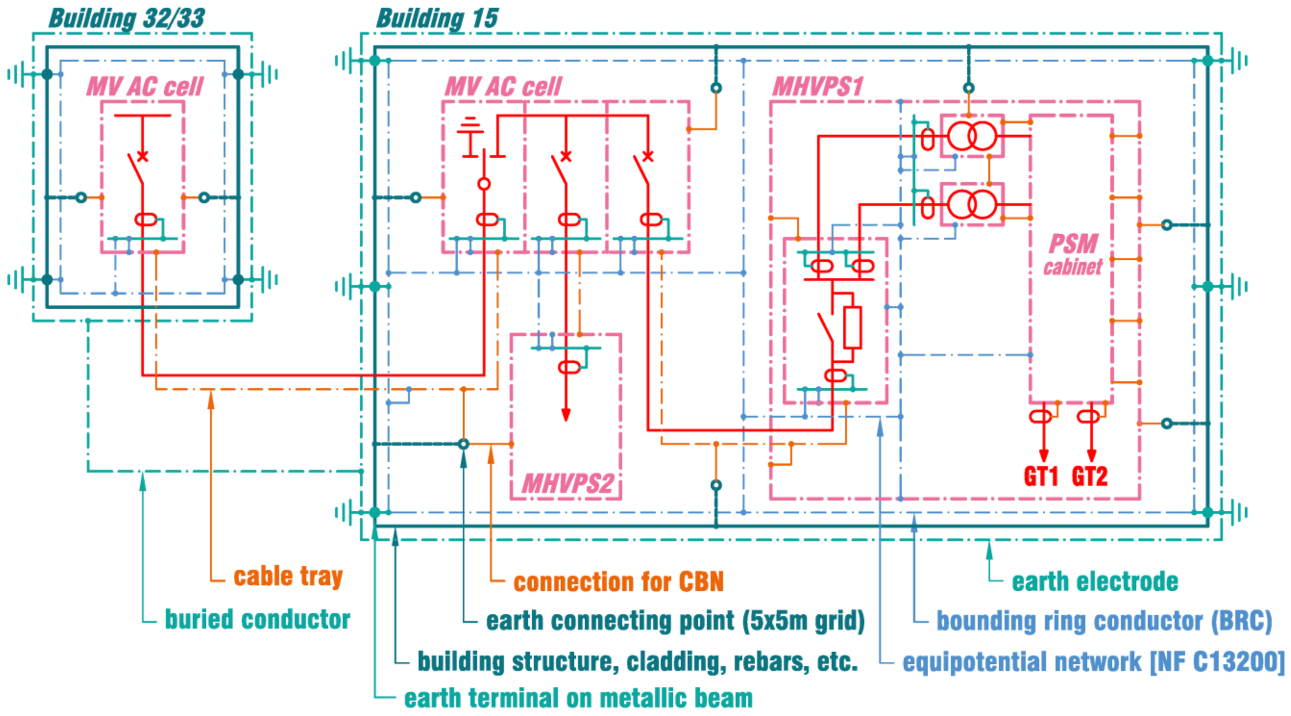

Figure 8: Single line diagram of a set of two MHVPSs with all types of connections to earth

7. Conclusion

This work was required as there is no specific standard for the construction of an EC-system. During the execution of the contract between SPC and F4E, it appeared that discrepancies between national and international applicable standards may lead to difficulties to comply with the goal of providing the best achievable EMC environment. As discussed, the HVPS installation in ITER must comply with the French standard NFC 13200. This standard is actually intended for power substations, in which earthing is considered only for the mitigation of the electrical hazards, regardless the interference that may result from an improper earthing scheme in terms of EMC.

The compliance with NFC 13200 has been required by F4E after the design and the layout of the EU ECPS were completed, to secure receiving the authorization to operate from the regulation authority. The implementation of this standard required an important effort since it significantly deviates from the specific standard for the erection of a HVPS based on the PSM topology (IEC 60215). Beyond the requirement to connect items both to the BRC and to the CBN, this standard also applies to the dimensions of the enclosures and even to the isolation distances to be observed inside the HVPSs enclosure. For instance, if IEC 60215 is applied the isolation distances inside a 55kV HVPS enclosure can be smaller than 20 cm, whereas they shall be larger than 90 cm, whenever NFC 13200 shall be strictly respected.

This paper presents the more relevant findings of the work performed by SPC. The redaction of the EMC requirements lists provided to F4E highlighted that the earthing architecture shall be considered as a fundamental component of the EC-plant during each phase of the project (concept, execution, commissioning, and operation), knowing that EMC performance depends on the whole environment, from the building foundation up to the installation of any metallic work inside the building (beams, pipes, ducts, frames, cable trays, etc.).

One of the main outcomes of this work is the issue of clear recommendations for the erection of the CBN, which is the basis of the EMC concept developed for ITER. We have also pointed out that EMC and EMI mitigation do not only rely on cabling and earthing techniques. Some points shall be taken into account on the gyrotrons operation too. In ITER, it is mandatory to always operate the pair of gyrotrons connected to a single MHVPS at the same working point, to avoid stray currents in the earth. This is particularly important regarding the operation of triode type gyrotrons. Indeed, if both gyrotrons are connected to the MHVPS, but only one is operating, the return of the cathode current will be divided between both cathode feeding cables, which is the worst case of current imbalance.

In this paper, we have only presented the requirements relevant to the construction of the CBN, but in the reports provided to F4E the earthing of each item included in the ITER EC-system was addressed, in particular the gyrotrons, their mechanical support, the transmission lines, and all ancillary systems.

The pertinence of the EMC and earthing concept proposed by SPC cannot easily be validated by tests at an early stage of the ITER EC-system commissioning. On the one hand, the EMI mitigation depends on the entire earthing infrastructure (the CBN must be completed and maintained over the lifetime of the plant), and on the other hand the EMI emission depends on the completeness of the plant.

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