Electromagnetic Compatibility Considerations for Control Circuits of Medium Voltage STATCOM

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Abstract: - Flexible AC Transmission Systems (FACTS) are used to solve the transmission lines problems. These devices can momentarily control voltage, active power and reactive power, on the basis of thyristor control or static converter.
Due to the extensive utilization of power electronics in the main part of FACTS devices structure, the compatibility of these devices with the internal and external propagation and generation of low-frequency and high-frequency disturbances within electromagnetic environment must be ensured.
Up to the present time, as far as the authors are aware no report on electromagnetic compatibility (EMC) considerations for FACTS devices has been made. This paper attempts to fill this void in our knowledge by focusing on various issues related to the EMC of the control systems of medium voltage Static Compensator (STATCOM), of FACTS devices, in a substation, using 2D electromagnetic fields (EMFs) simulation tools to calculate radiated fields.
As matter of comparison of Finite Element Method (FEM) simulations to measurements, this paper also reports the near field measurements performed to demonstrate the importance of proper shielding for the STATCOM control circuits to avoid malfunctioning.

Keywords: - FACTS, STATCOM, EMC, EMI, Shielding, FEM.

1 Introduction

The FACTS initiative was originally launched to solve the emerging system problems in the late 1980s due to restriction on transmission line construction, to facilitate the growing power export/import and wheeling transactions among utilities, with two main objectives: To increase the power transfer capability of transmission system and to keep power flow over designated routes. It is easy to see that the achievement of the two basic objective would significantly increase the utilization of existing (and new) transmission assets, and could play a major role in facilitating deregulation with minimal requirements for new transmission lines[1].

The development of FACTS controllers has followed two distinctly different technical approaches, both resulting in a comprehensive group of controllers able to address targeted transmission problems. The first group employs reactive impedances or a tap-changing transformer with thyristor switches as controlled element like SVC and TCSC. The second group uses self-commutated static converters as controlled voltage sources like STATCOM, SSSC, and UPFC [1, 2].

We focus on the second group that they employ self-commutated, voltage-sourced switching converters to realize rapidly controllable, static, and synchronous as voltage or current source. This approach generally provides uniform applicability for transmission voltage, effective line impedance, and angle control. It also offers the unique potential to exchange real power directly with the AC system, in addition to providing the independently controllable reactive power compensation, thereby giving a new powerful option for flow control and the counteraction of the dynamic disturbances.

In order to verify the accuracy of operation of the FACTS devices, the understanding of their structures [2, 5] is very important. The FACTS structure comprises of two deferent main parts: power circuits having power electronic switches, such as IGBTs and GTO and the other one control circuits of power converters including microprocessors, ICs, connectors, and other auxiliaries.

Since medium voltage STATCOMs are installed in the substations which other medium voltage ((MV) classified as between 1 and 33kV$_{rms}$) and high voltage (HV > 33kV$_{rms}$) and high current equipments: circuit breakers, disconnectors, transformers, and bus bars, are exist, therefore the resulted EMFs can drastically affect their operations. Further more electromagnetic interferences (EMI) between elements of control circuits can also cause problems in their functions.

When discussing EMC, one has to face two aspects simultaneously: EMI and electromagnetic susceptibility (EMS). EMC is the capability of an electrical device or system to operate in its electromagnetic environment without disturbing or being disturbed by it.

As far as the fundamentals of EMC are concerned, there is no significant difference between for a communication system and for power devices. However from application point of view the EMC problem in power devices has its features:

Considering the EMI problems, the switching frequency in an electrical system is much lower than in a communication system, but with much higher operation voltage, current and power. The main devices in the system will generate very high current and voltage slew rates, di/dt and dv/dt during their switching transient process, which will cause very strong transient noise voltage and current through the parasitic inductance and capacitance in the circuit [19]. Therefore the noises induced by main power devices and their related circuits become main EMI sources. As mentioned before, some high power supplies for instance, circuit breakers, disconnectors, transformers, and bus bars and etc. which are in chain with the installed FACTS devices in a substation may also cause strong electromagnetic radiation.

Considering the EMS problems, the controller in the control circuits of the STATCOM normally has much higher threshold level and larger size than in communication system; it seems that EMS problems should be less serious than in a communication system. However it is not true, because:

(a) It has higher noise strength. Sometimes the noise strength can reach up to hundreds (thousands) volts, dv/dt and di/dt can reach more than 10^4 V/μs and 10^3 A/μs respectively.

(b) Since the main source is power stage, the noise spectrum has wide range especially in low frequency range that may extend to the low frequency range (down to several Hz). It is rather difficult to be suppressed by applying conventional methods, such as shielding, filtering etc.

(c) In the substation, the power stage and the control board are normally installed in a same cabinet, some times several different equipment may be connected each other or to their load through several cables with a high length. Therefore the coupling between the electromagnetic source and the victim circuit is of near–field and conduction.

Generally electromagnetic phenomena which can be expected to interfere with control system of STATCOM are:

1. supply voltage interruption, dips, surges and fluctuations;
2. transient over voltages on supply, signal and control line;
3. radio frequency fields, both pulsed (radar) and continuous, coupled directly into the equipment or onto its connected cables;
4. electrostatic discharge (ESD) from a charged object or person;
5. low frequency magnetic or electric fields.

Due to the above mentioned facts, the EMC research on FACTS devices is still at the very early stage.

Although, research activities on “EMC in power electronics”, “EMI in CMOS logic circuit”, “EMC in microprocessor”, have been carried out [7, 8, 10, and 16-18]. Up to the present time, as far as the authors are aware no report on EMC considerations for FACTS devices has been made. This paper attempts to fill this void in our knowledge by focusing on various issues related to the EMC: detection of electromagnetic field disturbances, shielding, filtering and grounding, for the control circuits of the STATCOM, of FACTS devices, in a substation with the help of FEM [3, 11, 13, and 14].

As a case study, the paper is also intended to discuss the experiments performed to demonstrate the importance of proper shielding for the STATCOM control circuits to avoid malfunctioning.

2. STATCOM STRUCTURE

There is a class of SVCs which is based on dc to ac converters in which a real alternating voltage (or current) can be produced from a direct voltage (or current) by the process of inversion in a solid-state DC to AC converter; the converter can be controlled to behave as if it were an idealized rotating machine. The class of SVCs which uses this principle has been assigned the name STATCOM. The basic behavior of a STATCOM is very similar to that of a synchronous compensator. If the voltage generated by the STATCOM is less than the voltage of the system bus bar to which it is connected, the STATCOM will act as an inductive load, drawing Mvar from the supply system. Conversely, a STATCOM will act as a shunt capacitor, generation Mvar into the supply system, when its generated voltage is higher than the system voltage.

Various types of inverter circuit and source have been suggested and examined [12]. The dc voltage sourced converter is the type which has received most attention in the practical realization of the STATCOM principle. A very simple inverter produces a square voltage as it switches the direct voltage source on and off. The inverter must use either conventional thyristors with forced commutation, or it must use devices which can be turned off as well as turned on, such as gate turn-off (GTO) thyristors, a new generation of devices which require less energy for the switching process like IGBT is becoming available with ratings that can be used for STATCOMs.

When acting of STATCOM in capacitive mode, the GTO device must be controlled to block the alternating current at its peak value, but are turned on without an immediate flow of current. The opposite happens in inductive mode; the devices turn off by natural commutation and are then blocked. When they are de-blocked, the maximum current flows immediately. Clearly GTOs must never be turned on simultaneously so that they do not short-circuit the dc source. The control of the GTO switching must therefore be accurate and extremely reliable.

The switching angles for turn-on and turn-off are normally chosen to be symmetrical with respect to the instant at witch the system voltage passes through zero and the output voltage waveform is a sequence of rectangular blocks. By varying the switching angle, α, both the fundamental magnitude and the harmonic spectrum can be varied. By adding further sets of GTOs and diodes additional steps can be added to the output voltage waveform, increasing the controllability of the fundamental and harmonic content of the waveform by coordinated control of the switching instants α_1 and α_2 [2].

Three single-phase converters can be connected, one per phase, to from a three phase converter. The three single phase converters can be controlled in a coordinated way to generate a balanced three-phase set of voltage. When the primary objective of the STATCOM is to respond to balanced load conditions, it is convenient to use the same voltage source for all three phases; the three converters can take the form of a Graetz bridge. For practical application of some kind of STATCOM, the Graetz bridges must use several GTOs in series in each leg of the bridge to obtain an adequate rating. The GTOs in each leg must be arranged to turn on and off at precisely the same instant to ensure voltage sharing between the individual GTOs.

For three level converters, the harmonic magnitudes become $\frac{4}{\pi}.\frac{\cos(n\alpha)}{n}.V_{dc}$ for nth harmonic [1, 12]. Consequently, individual harmonics can be forced to have zero magnitude by appropriate choice of switching angle α. Thus the 3rd harmonic becomes zero when $\alpha = 30$, because Cos90=0. Pulse width modulation is an extension of this simple concept of harmonic control. The GTOs are repetitively turned on and blocked during each half cycle. The sequential switching instants are selected in a coordinated manner, to satisfy simultaneous requirements [1].

However, the control of power electronic switches is very crucial and can lead to improper functioning of STATCOM.

3 Simulation and Measurement of Radiated EMFs

Considering the EMC issues, In order to estimate the radiated EMFs around the victim (control system) initially, a simple model of four MV panels, with nominal current of 1250A, was considered and the stray fields were simulated, using FEM software ANSYS5.4, shown in Fig.1 and Fig. 2. It is clearly evident from Fig. 1 and Fig. 2 that, the radiated fields by the MV panels are considerably high. This implies that the correct function of the control circuits of the STATCOM is under question.

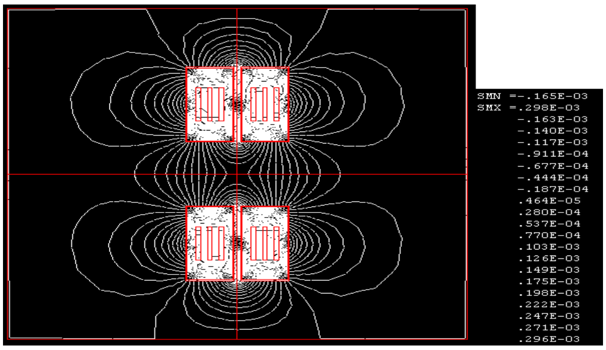

Fig.1 Flux distribution around the panels, at nominal current of 1250A.

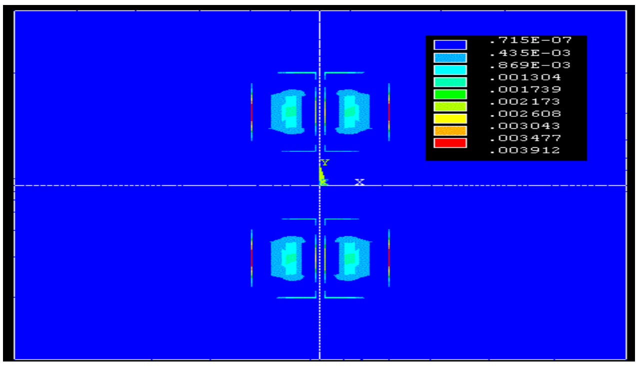

Fig.2 Flux density distribution around the panels, at nominal current of 1250A.

The field theory is governed by Maxwell's equations:

$$\nabla \times \{H\} = \{J\} + \{\frac{\partial D}{\partial t}\}, \quad (1)$$

$$\nabla \times \{E\} = -\{\frac{\partial B}{\partial t}\}, \quad (2)$$

$$\nabla.\{B\} = 0, \quad (3)$$

$$\nabla.\{D\} = \rho, \quad (4)$$

where H, D, E, B, ρ, J are magnetic field intensity vector, electric flux density vector, electric field intensity vector, magnetic flux density vector, electric charge density, and total current density vector respectively. Maxwell’s equations as well as magnetic vector potential method are fundamental basis of the fields simulation.

However, the values of the three directional components (x, y, z) of the flux density corresponding to the bus bar, circuit breaker or power electronic components of victim, around the control panel of STATCOM, were measured, in different selected points, using a Gauss meter (BROCKHOUSE 460) with an accuracy of $\pm 0.1 \mu T$ and the results shown in Table 1.

Table 1: Comparison of the Measuring values of the flux density around 20kV equipments of 63/20kV substation

(X,Y,Z) (m)	B_X (mT)	B_Y (mT)	B_Z (mT)	B_{XYZ} (mT)
(0,0,0)	1.747	0.3943	1.236	2.176
(4,4,1)	0.2367	0.1204	0.08997	0.2804
(8,8,1.5)	0.01257	0.0023	0.0711	0.0722
(10,10,0)	0.0178	0.0018	0.00430	0.0184
(8,4,1)	0.0168	0.0321	0.0034	0.0364
(12,3,1)	0.0049	0.0009	0.0087	0.0100
(5,7,0)	0.2154	0.0023	0.0148	0.2159

Considering critical (transient) states due to the circuit breaker switching and the STATCOM thyristors switching, high magnitudes of electric and magnetic fields occur.

The magnetic fields produced during normal and critical conditions will deteriorate the performance of the control system devices: microprocessor, logic circuits, and connector, by inducing spurious voltage giving rise to unwanted output behaviors, as shown in Fig.3.

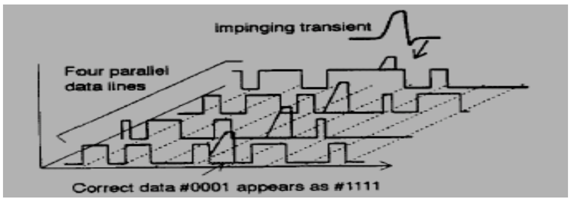

Fig.3: Transient affecting data transfer [10].

Applying the Faraday's law, the voltage induced by an external magnetic field in a single turn loop is:

$V = A\, dB/dt$, (5)

where A is the loop area in m^2 and B is the flux density normal to the plane of the loop in Tesla.

4 EMI in Control Boards

The estimation of the EMF propagation produced by the individual components of the control boards can be obtained by the following tips [6]:

(a) The maximum electric field strength ,E_{max}, from such a loop over a ground plane (Fig. 4) at 10m distance is proportional to f^2

(b) $E_{max} = 263.\ 10^{-12}\ (f^2.\ A\ .\ I_s)$, (6)

where A is the loop area in cm^2 ,

f (MHz) is the frequency of I_s the source current in mA.

(c) The E_{max} allowing +6dB for ground plane reflections at 10m due to cable radiated (Fig. 5) is directly proportional to frequency:

$E_{max} = 1.26\ .\ 10^{-4}\ .\ (f\ .\ L\ .\ I_{CM})$, (7)

where L is the cable length in meters and

I_{CM} is the common-mode current at f MHz in mA flowing in the cable.

According to Equations (6) and (7) the amplitude of E_{max} is more noticeable at switching frequency (up to 1MHz). The electromagnetic modeling and hardware measurement of simultaneous switching noise in high speed systems was thoroughly studied [15].

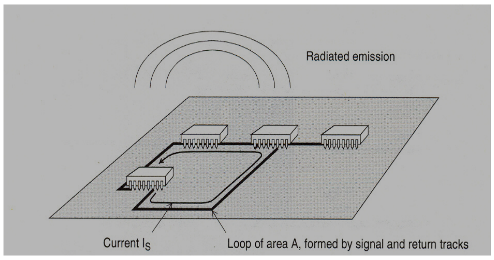

Fig.4 PCB radiated EMFs [6].

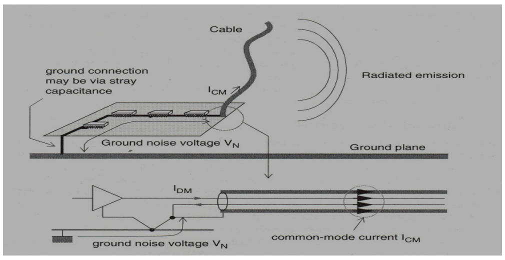

Fig.5 Connector radiated EMF [6].

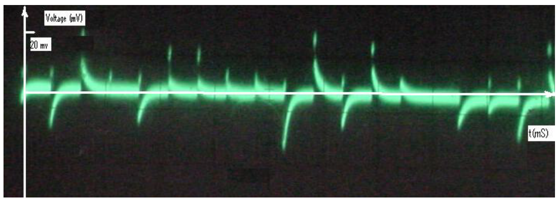

Fig.6 ground signal around microprocessor

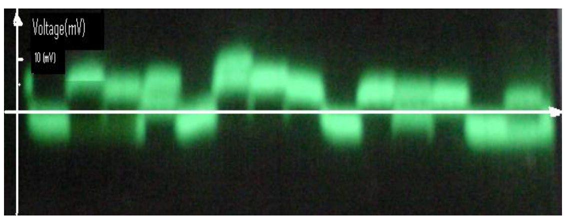

Fig.7 ground signal around capacitor

As shown in Fig.4 and Fig.5, these spurious electric fields can cause interference between the components leading to unsuitable performance of the components.

In this study, an example of this phenomenon was the effects of interference on the quality of ground signal, shown in Fig.6 and Fig.7. It can be depicted that the ground signals have amplitudes with unexpected waveform shapes.

In addition, the radiated magnetic fields from the MV equipments will also affect the ground signals of the control boards.

To satisfy the EMI conducted standard limits, the filter has to provide the necessary attenuation, in the bandwidth specified by the standards for those noise components above the given limit [9, 17].

Another fundamental solution to minimize the EMI conducted standard limits is grounding for the operation of the control circuits of the STATCOM, as the grounding provides a reference point for the control circuits [6, 9].

5 EMF Radiations Shielding: SE Calculation, Field Simulations and Measurements

It is desirable to obtain explicit characterization of a shield for the control system against the radiated EMFs produced by the MV panels, circuit breaker and IGBTs of the STATCOM in both transient and stable conditions.

As an acquired solution to the radiated EMF effects on the control circuit, four shielded enclosures, from copper, iron, steel and zinc materials having similar characteristics in stable conditions but different shielding effectiveness, in transient states, were considered.

The Shielding Effectiveness (SE) for different materials is:

$$SE = \mathrm{A} + \mathrm{R} + \mathrm{C_R}\ (\mathrm{dB})$$
$$\mathrm{A} = 1.31\,\mathrm{t}\sqrt{\mu_r\,\sigma_\mathrm{r}\,\mathrm{f}}\ , \qquad (8)$$
$$R = 168 - 10\log\left(\frac{\mu_\mathrm{r} f}{\sigma_r}\right)$$

where A is the absorption factor, R is the reflection factor and C_R is the correction factor for reflection, all expressed in dB.

If $A \geq 6$dB, then C_R, can be neglected. C_R is significant only for thin shield and for frequencies below about 20 kHz [4].

The SE Equation (8) is only valid for the far fields, whereas the spurious radiated EMFs from the above mentioned systems are near fields, so Equation (8) can only be used for the rough calculation of SE for near fields.

The calculation of SEs for the materials, with the thickness of 1mm at 50Hz and ignoring C_R, were calculated. The calculated values are shown in Table 2.

Table 2: Calculated values of SE, at 50Hz conditions

Materials	σ_r	μ_r	A	R	SE
Copper	1	1	0.0093	151.01	151.02
Iron	0.17	1000	0.12	113.3	113.4
Steel	0.1	1000	0.093	111.01	111.1
Zinc	0.29	1	0.005	145.63	145.64

In case of transient states, at f=1MHz, although A increases, SE is decreased. For instance, steel has SE=81.1 (A=13.1, R=68) and copper has SE=109.31 (A=1.31, R=108). It is worth noting that the SE values in both materials are decreased in transient states.

For the verification of the shielding performances of the four materials, the near fields at stable and transient conditions were modeled by 2-D FEM simulations using ANSYS 5.4.

The simulations are based on the edge element method and mainly magnetic vector potential method. The former method constitutes the theoretical foundation of low frequency EMF element.

The vector potential method is applicable for both 2-D and 3-D EMFs. Considering static and dynamic fields and neglecting displacement currents (quasi-stationary limit), the following subset of Maxwell's equations apply:

$$\nabla \times \{H\} = \{J\}, \qquad (9)$$

$$\nabla \times \{E\} = -\{\frac{\partial B}{\partial t}\}, \qquad (10)$$

$$\nabla . \{B\} = 0. \qquad (11)$$

The basic equation to be solved is in the form of:

$$[\overline{C}]\{\dot{u}\} + [K]\{u\} = \{J_i\}. \qquad (12)$$

The terms of this equation are defined below; the edge flux formulation matrices are obtained from these terms follow with boundary conditions.

-Degree of freedom:

$$\{u\} = \begin{Bmatrix} \{A_e\} \\ \{v_e\} \end{Bmatrix}, \qquad (13)$$

where $\{A_e\}$ and $\{v_e\}$ are magnetic vector potentials and time integrated electric scalar potential respectively.

-Coefficient matrices:

$$[\overline{K}] = \begin{bmatrix} [K^{AA}] & [0] \\ [K^{vA}] & [0] \end{bmatrix}, \qquad (14)$$

$$[K^{AA}] = [K^L] + [K^N] + [K^G], \qquad (15)$$

$$[K^L] = \int_{Vol} (\nabla \times [N_A]^T)^T [v] (\nabla \times [N_A]^T - [N_A][\sigma]$$

$$(\{v\} \times \nabla \times [N_A]^T)) d(vol), \quad (16)$$

$$[K^G] = \int_{Vol} (\nabla \cdot [N_A]^T)^T [v] (\nabla \cdot [N_A]^T) d(vol), \quad (17)$$

$$[K^N] = 2 \int_{vol} \frac{dv_h}{d(|B|^2)} (\{B\}^T (\nabla \times [N_A]^T))^T (\{B\}^T (\nabla \times [N_A]^T))$$

$$d(vol), \quad (18)$$

$$[K^{VA}] = -\int (\nabla [N]^T)^T [\sigma] \{v\} \times \nabla \times [N_A]^T \, d(vol), \quad (19)$$

$$[C] = \begin{bmatrix} [C^{AA}] & [C^{Av}] \\ [C^{Av}]^T & [C^{vv}] \end{bmatrix}, \quad (20)$$

$$[C^{AA}] = \int_{vol} [N_A][\sigma][N_A]^T \, d(vol), \quad (21)$$

$$[C^{Av}] = \int_{vol} [N_A][\sigma] \nabla \{N\}^T \, d(vol), \quad (22)$$

$$[C^{vv}] = \int_{vol} (\nabla \{N\}^T)^T [\sigma] \nabla \{N\}^T \, d(vol), \quad (23)$$

-Applied loads:

$$\{J_i\} = \begin{Bmatrix} \{J^A\} \\ \{I^t\} \end{Bmatrix}, \quad (24)$$

$$\{J^A\} = \{J^S\} + \{J^{pm}\}, \quad (25)$$

$$\{J^S\} = \int_{vol} \{J_s\}[N_A]^T \, d(vol), \quad (26)$$

$$\{J^{pm}\} = \int_{vol} (\nabla \times [N_A]^T)^T \{Hc\} \, d(vol), \quad (27)$$

$$\{I^t\} = \int_{vol} \{J_t\}[N_A]^T \, d(vol), \quad (28)$$

where $[N_A]$, $\{N\}$, $\{J_s\}$, $\{J_t\}$, vol, $\{H_c\}$, v_o, $[v]$, $\frac{dv_h}{d(|B|)^2}$, $[\sigma]$, and $\{v\}$ are matrix of element shape function for $\{A\}$, vector of element shape function for $\{V\}$, source current density vector, total current density vector, volume of the element, coercive force vector, reluctivity of free space, partially orthotropic reluctivity matrix, derivative of reluctivity with respect to the magnitude of magnetic flux squared, orthotropic conductivity, and velocity vector respectively.

The magnetic flux density is the first derived result. It is defined as the curl of the magnetic vector potential. This evaluation is performed at the integration points using the element shape function:

$$\{B\} = \nabla \times [N_A]^T \{A_e\}, \quad (29)$$

where $\{B\}$, and $\{A_e\}$ are magnetic flux density, and nodal magnetic vector potential respectively.

Applying the two methods for the near field simulations for the STATCOM shield enclosures based on the mathematical Equations (9) to (29).

Considering Fig.1 and Fig.2 for normal condition (50Hz), initially a shielded enclosure was modeled for a copper sheet placed near the MV panels with bus bars carrying 1250A. Fig.8 shows the flux distribution.

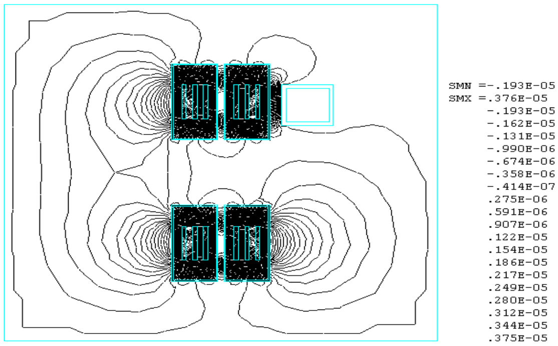

Fig.8: Radiated flux lines from the panels with copper shielded control circuits, at 50Hz.

One of the most problematic areas in EMC system design is switching of the related equipments, mainly switching of the IGBTs of the STATCOM. In the critical conditions, a magnetic dipole carrying the current of 1250A at 1MHz with the shielded THE STATCOM control circuits close to it, was modeled.

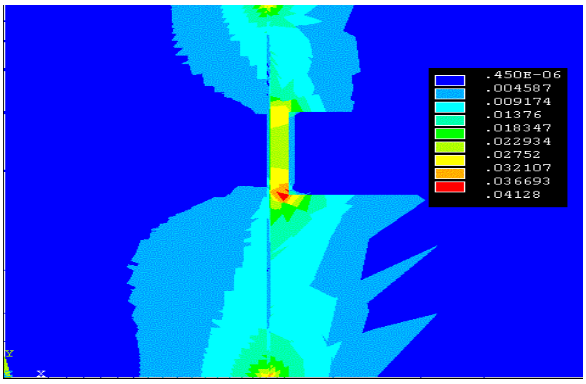

Fig.9: Radiated flux density from magnetic dipole, around the copper shielded control circuits.

The shielding enclosures for the materials: zinc, iron and steel, under the critical conditions, were modeled with the same analysis. The flux density patterns for the three materials shown in Fig. 10 to Fig. 13, also prove to be suitable for protecting the control circuits from the unwanted fields. It can be noticed that the flux density patterns do not follow exactly the same routs. However, as far as the shielding concerns, this does not have any effects on control circuits.

As matter of comparison of FEM simulations to measurements, the magnitudes of flux density around the shielded control system was measured by the Gauss meter, in normal and switching conditions having instantaneous field variations. The test method was used similar to previous work [20].

The measured values of the fields comply with the corresponding simulations results. The discrepancies are less than 10%.

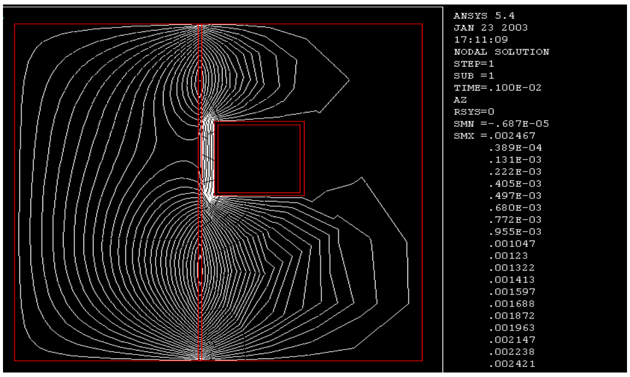

Fig.10: Radiated flux lines from magnetic dipole, around the iron shielded control circuits.

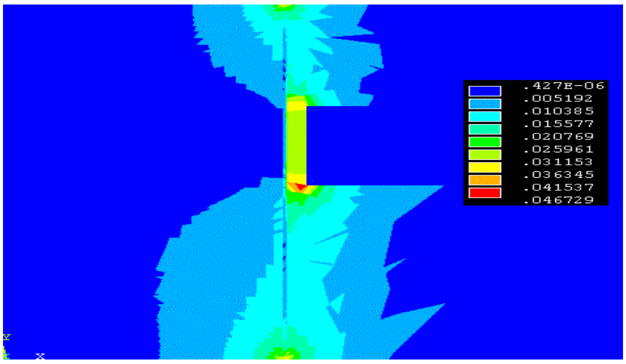

Fig.11: Radiated flux density from magnetic dipole, around the iron shielded control circuits.

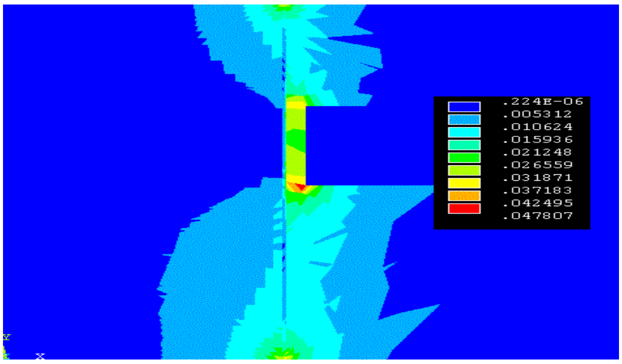

Fig.12: Radiated flux density from magnetic dipole, around the steel shielded control circuits.

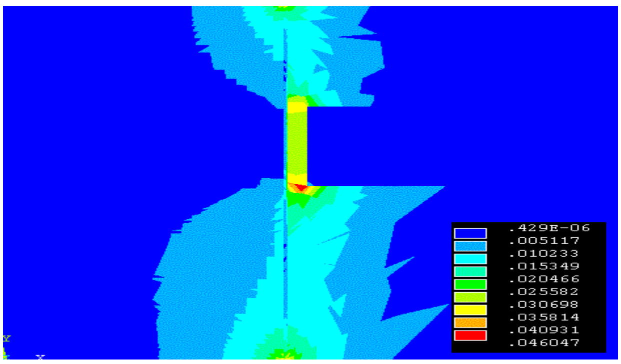

Fig.13: Radiated flux density from magnetic dipole, around the zinc shielded control circuits

6 Discussion and Conclusion

In this paper various EMC issues related to the Control Circuits of Medium Voltage STATCOM has been discussed.

The simulation and measurement results showed the magnitudes of the emission EMFs, related to the circuit breaker or power electronic components of the STATCOM, around the control system of the STATCOM are noticeable.

As an acquired solution to the EMF effects on the control circuits, four shielded enclosures from different materials: copper, iron, steel and zinc with similar characteristics, in stable conditions, but different shielding effectiveness, in transient states, were considered.

Although, the investigation completed to date represents only an initial study and addresses only a very small part of EMC problems in FACTS devises. It does not yet into account all operating conditions of STATCOM, all frequencies and harmonics, the effects of the mounting structure or the adjacent devices and sources which will interact to produce the local electromagnetic environment.

Furthermore, the flexible and practical applications of basic EMC techniques, filtering and grounding, against EMI for the control system were reviewed. It is desirable to expand these techniques in the next research challenge.

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