EMC Considerations in Current Injection Transformer Systems

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Abstract: - Since Current Injection transformer systems are within the major group of the standard type test equipments in electrical industry, their performances are very important.

When designing a high current devices, there are many factors to be considered from which, 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 current injection devices has been made. This paper attempts to fill this void in our knowledge by considering various issues related to the EMC in a 25kA current injection transformer (CIT), using 2D electromagnetic fields (EMFs) simulation tools to calculate radiated fields around inside and outside of the system tank.

As matter of comparison of Finite Element Method (FEM) simulations to measurements, a short circuit test was carried out on a typical CIT This paper also reports the propagated and the generated near fields around the inside and the outside of the CIT, a series of measurements performed to demonstrate the importance of proper shielding for the electromagnetic interferences (EMI) within the control circuits, transformer windings, magnetic core and particularly the operator of the system.

Keywords: - EMC, EMI, Current injection transformer, Shielding, FEM

1 Introduction

As an electrical utility you have the right to demand that every piece of power equipment installed on your system meets your exact specifications. The reliability and safety of your system depends on all of the components performing as intended. As a manufacturer, the performance and conformance to industry standards of your product are of prime importance. Testing can assure that your product meets or exceeds performance standards.

Electrical equipment such as circuit breakers, protective relays, and meters are routinely tested to verify proper operation of current sensing elements. This testing is performed using high-current, low-voltage test equipment that provides a means of adjusting the value of current and also of measuring the operating time of the device under test.

CIT systems are within the major group of the standard type test equipments in electrical industry and their overall performances are very crucial. They are widely used for the standard tests of equipments: protection systems, fuses, circuit breakers, disconnectors, switching devices and etc.

When designing a high current devices, there are many factors to be considered from which, 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.

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 [1]. 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. may also cause strong electromagnetic radiation.

Considering the EMS problems, the controller in the control circuits of the CIT system 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 CIT system the power stage and the control board are placed in the same box (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 board of CIT system 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 CIT system 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 [2-4]. Up to the present time, as far as the authors are aware no report on electromagnetic compatibility (EMC) considerations for current injection devices has been made. This paper attempts to fill this void in our knowledge by considering various issues related to the EMC in a 25kA CIT, using 2D electromagnetic fields (EMFs) simulation tools to calculate radiated fields.

As matter of comparison of Finite Element Method (FEM) simulations to measurements, a short circuit test was carried out on a typical CIT system. This paper also reports the propagated and the generated near fields around inside and outside of the CIT system measurements performed to demonstrate the importance of proper shielding for the electromagnetic interferences (EMI) within the control circuits, transformer windings, magnetic core and particularly their effects on the operator of the system [5].

As a case study, the paper is also intended to discuss the experiments performed, by the5kA AC and 4kA DC current injection systems, to demonstrate the importance of proper shielding for the CIT system unit to avoid malfunctioning.

2 Simulation and experimental validation

Generally, the flow of flux density in a medium is three dimensions, x, y and z. the flux density resultant $B_R(t)$, is given by:

$$B_R(t) = \sqrt{B_x^2(t) + B_y^2(t) + B_z^y(t)} \qquad (1)$$

where: x, y and z denote the directions of the flux density components.

In this study we only use 2-D simulation and the z- dimension is assumed to be constant.

. A computer aided method that is based on magnetic vector potential and finite element equations [6] was used to obtain the magnetic fields distribution inside and outside of a 25kA CIT.

The data which was fed into the software system is the dimensions and geometry of the magnetic core, the B-H curve of the core material, the position and dimension of the exciting coils and the current densities in each coil at different instants of magnetizing cycle [7]. The characteristics of simulation consist of rectangular mesh $\left(7.5 \times 4\ cm^2\right)$ and with the output voltage of 7.5(V).

In order to eliminate the EMI, it was also assumed that the distance of the transformer core and its windings (source) and control circuit (victim) in the system tank is far enough.

The simulation result of the flux density pattern within the CIT system tank is shown in Fig. 1. It can be seen that the flux density varies in different part of the system tank ranging from 1.7mT to 434mT.

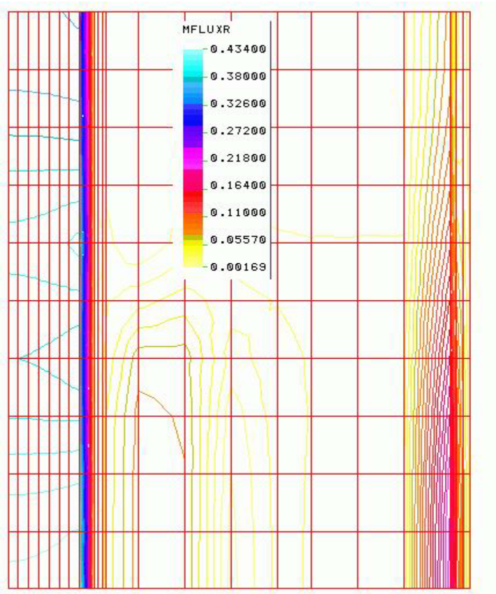

Fig.1 Distribution of the flux density (in Tesla) in the CIT tank with iron materials.

The magnetic field, produced from 25kA passing through a closed loop ring was also modeled as an equipment under test (EUT).

Fig. 2 shows the results of the field emission from EUT up to 0.5m radius. The emitted fields around the centre of the ring are between 0.24T to 0.1T.

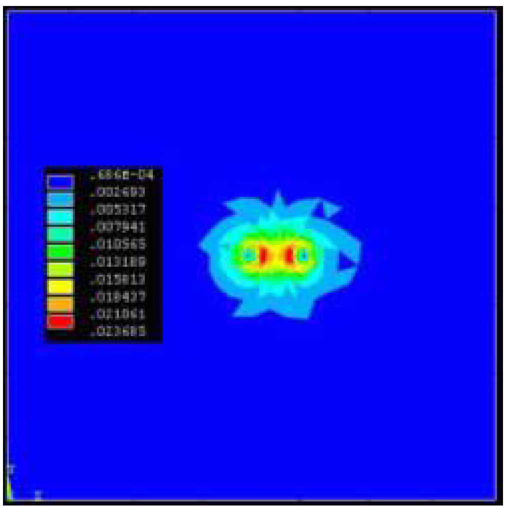

Fig.2 Distribution of flux density the loop with 25kA current up to 0.5m distance.

As a case study, in order to experimentally verify the computed flux density values, the three directional components (x, y, z) of the corresponding emitted and propagated magnetic fields around the inside and the outside of 4kA AC and DC CIT systems, under symmetrical and asymmetrical loops, were measured.

The flux density components were measured, using a Gaussmeter (BROCKHOUSE 460) with an accuracy of $\pm 0.1\mu T$.

The fields measuring zones correspond to those selected in the simulation model

Considering flux density (B) is directly proportional to the current (I), passing through the ring loop, and inversely proportional to the distance (d) as:

$$B = 2 \times 10^{-7} \times \frac{I}{d} \qquad (2)$$

The measurements of the AC and DC scattered flux densities, at 1kA, around the inside and the outside of the CIT tanks were carried out for symmetrical and asymmetrical loops as shown in Figs. 3 and 4 respectively. The results for symmetrical and asymmetrical loops are shown in Tables 1 and 2 respectively, whereas for the DC fields in the specified zones (A, B, C, …)relatively longer cable was used, as shown in Fig. 5. The DC results are shown in Table 3**.**

Fig.3 Symmetrical loop with AC CIT

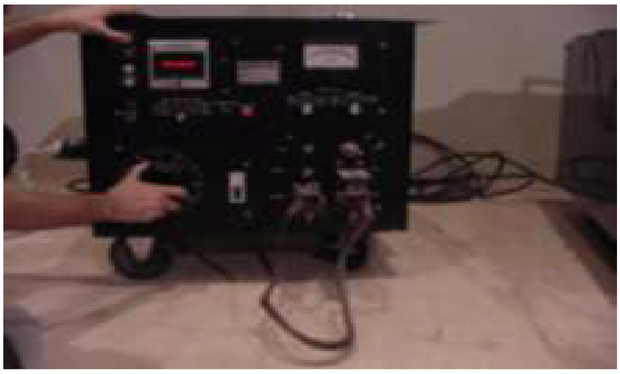

Fig.4 Asymmetrical loop with AC CIT.

As far as the safety of the system operator is concerned, the smaller field area, the safer is the operator. For instance, in the case of DC test the area covered by the field was expanded.

Since the operator unintentionally will be inside of field loop, he is threatened by the field effects. Although, under normal condition, due to the control circuit of the system, subtending of the operator near the produced fields is unavoidable.

On the other hand, good quality of the tank materials, low reflective and high absorption factor, gives rise to a lower EMI between inside and outside fields.

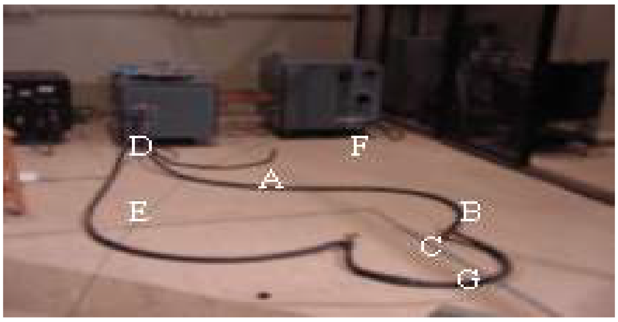

Fig.5 DC CIT, connected cable and EUT.

Table 1 Magnetic flux density around the AC CIT with asymmetrical element for 1kA.

Location	B_x(mT)	B_y(mT)	B_z(mT)	B_{xyz}(mT)	Coordination
Center & Semilevel	2.543	2.654	5.765	6.834	(0,0,0)
"	4.576	2.023	7.534	9.044	(-2,0,0)
"	5.659	4.639	7.732	10.646	(2,0,0)
Center & Up	0.9829	0.1515	0.0804	0.9978	(0,15,0)
Center & Down	3.497	0.7879	0.3159	3.5986	(0,-5,0)
Center & Up	3.078	2.358	0.1511	3.8988	(0,5,0)
Center & Down	0.8656	1.3929	0.9050	1.8730	(0,-15,0)
Center & Semilevel	1.183	1.8232	2.2926	3.1592	(0,0,10)
Outside & Semilevel	0.5880	0.8166	0.6193	1.1815	(0,0,20)
"	0.0143	0.0537	0.0034	0.0557	(0,0,50)
Current Control	0.0603	0.1330	0.1363	0.2002	(-30,0,0)
Amper meter	0.0267	0.0035	0.0217	0.0346	(0,40,60)
Timer	0.0464	0.0096	0.0464	0.0662	(-40,40,0)
Center & Semilevel element vertex	0.4895	4.670	12.522	13.373	(0,-15,25)

Table 2 Magnetic flux density around the AC transformer in symmetrical element testing for 1kA.

Location	B_x(mT)	B_y(mT)	B_z(mT)	B_{xyz}(mT)	Coordination
Curve Center	1.440	7.639	2.930	8.307	(0,0,0)
Curve Vertex	9.725	8.009	8.156	16.827	(0,0,30)
Center	6.327	0.4602	4.710	7.902	(0,0,15)
Outside	0.1159	0.0066	0.0127	0.1167	(0,45,30)
Current Controller	0.0675	0.1606	0.0054	0.1736	(-30,0,0)
Head of operator	0.0113	0.0024	.0375	0.0420	(-40,40,0)
Test Observer	0.0093	0.0027	0.0087	0.0130	(0,0,100)

Table 3 Magnetic flux density around the DC transformer in cable test for 1kA.

Location	B_x(mT)	B_y(mT)	B_z(mT)	B_{xyz}(mT)
A	0.1327	1.261	0.0780	1.270
B	0.0110	0.8800	0.0211	0.8080
C	0.3200	1.535	0.1431	1.575
D	0.1355	1.935	0.1355	1.949
E	0.2136	1.3901	0.0100	1.400
F	0.0112	0.0298	0.0046	0.0322
G	0.2910	0.6930	0.0213	0.7530

Table 4 shows the numerical values of the of the flux density components produced by the scattered fields inside of the system tank, near the core (A) values and far from the core (around the control boar) (B) values

Table 4 The values of the flux density inside the AC CIT:

Location	B_x(mT)	B_y(mT)	B_z(mT)	B_{xyz}(mT)
A	2.784	3.974	1.124	4.980
B	0.2654	0.2873	0.321	0.5060

3 The effects of EMFs on the system operator and the control system

3.1 The biological effects

There is evidence the electromagnetic fields can have effects one living cells, tissues and organisms.

Some people have attributed a diffuse collection of symptoms to low levels of exposure to electromagnetic fields in their environment. Reported symptoms include headaches, anxiety, depression, nausea, fatigue and loss of libido.

These diseases are different due to protection system, body immunization and shape of tissues in various ages.

It has also been reported that electromagnetic fields can cause cancer disease, although there is a little relation between cancer and electromagnetic fields (in frequency 50-60 Hz) [8]. According to some researches, Cell membrane is sensitive to low frequency fields, as they change some biochemical processes through cell membrane such as changing of exchange between potassium and calcium [8]. Even these fields can cause irregularity in DNA structure.

The cancer cells that are in front of electromagnetic fields with low frequency (lower than 300Hz) grow abnormally. A high electromagnetic radiation with low frequency from about 10mT creates magnetophosphin properties. Magnetophosphin is a visible sense that when the eyes are close suddenly appears low light [8].

- Electromagnetic fields from 100mT up to 1T cause instigation in muscles (Blood circulation) and nervous that cause brain insufficiency.

- Electromagnetic fields about 0.76mT don't have harmful effects on creatures [8].
- Electromagnetic field effects on eye tissues, grow (Weight increasing), sleep and tiredness, brain power and electrovansphalogram [8].

3.2 Radiation field effects on control circuit of the CIT

Control circuit of the CIT consists of: a timer, pulse generator for triggering of power electronic elements with logic gates, microprocessors, connection cables and etc.

EMI with electronic circuits can cause to change the control signals [9].

As it is evident in Fig. 6, the unwanted noises, due to radiation fields, combine with sending signals, the data 0001 convert to 1111 [10]. The radiation fields can also induce a voltage on the ground point of the control circuit, giving rise to change the ground voltage (Fig. 7).

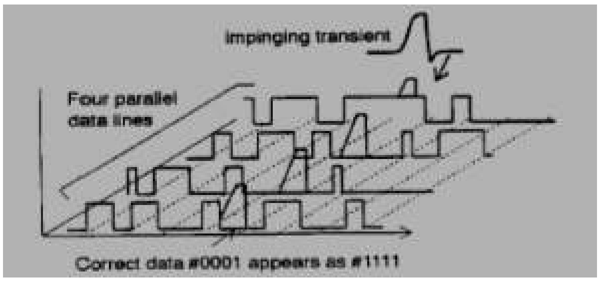

Fig.6 Changing of control data with combination of unwanted transient signals [10].

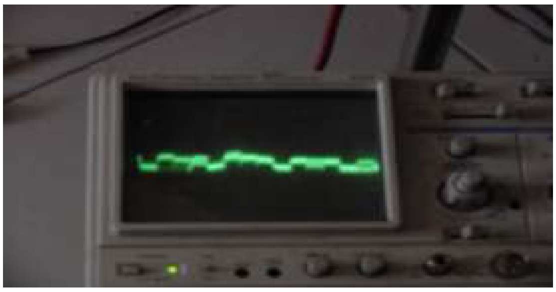

Fig.7 Non-ideal earthing of control system due to induced voltage

3 CIT Shielding and its operator

The shielding between the transformer core and the control circuit of the system is very important, indeed shielding is a part of ensuring the CIT with respect to EMC.

The performance of the shield depends upon the type of radiation to be shielded and on the integrity of the shield.

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, has already been considered [11].

Generally, electromagnetic waves incident upon a discontinuity will be partially reflected, and partly absorbed by the material. The Shielding effectiveness (SE) is the sum total of these two effects, plus a correction factor to account for reflections from the back surface of the shield.
The overall expression for SE is written as:

$$SE = A + R + C_R \ (dB) \qquad (3)$$

$$\mathrm{A} = 1.31\,\mathrm{t}\sqrt{\mu_r\,\sigma_\mathrm{r}\,f} \quad (dB) \qquad (4)$$

$$R = 168 - 10\log\left(\frac{\mu_\mathrm{r} f}{\sigma_r}\right) \ (dB) \qquad (5)$$

where A is the absorption factor, R is the reflection factor and C_R is correction factor of multi reflections, that has been computed according to the following equation:

$$C_R = 20\log(\mathrm{abs}(1 - \mathrm{N} \times 10(\text{-A}/10) \times (\cos(0.23\mathrm{A}) - \mathrm{j}\sin(0.23\mathrm{A})))) \ (\mathrm{dB}) \qquad (6)$$

N is complex number:

$$N = \frac{(1 - m^2)^2 - 2m^2 - j2\sqrt{2m}(1 - m^2)}{[1 + (1 + \sqrt{2m})^2]^2} \qquad (7)$$

$$m = 0.545\sqrt{\sigma_\mathrm{r}\frac{f}{\mu_r}} \qquad (8)$$

It is necessary to understand that authentication of above equations is for far fields, whereas the spurious radiated EMFs from the above mentioned systems are near fields, so Equation (3) can only be used for the rough calculation of SE for near fields.

However exact SE refers to numerical techniques in electromagnetic. For example in our simulations, SE with help of FEM software based on the following Maxwell's equations is described

$$\nabla \times \{H\} = \{J\} + \{\frac{\partial D}{\partial t}\}, \qquad (9)$$

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

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

$$\nabla.\{D\} = \rho. \qquad (12)$$

4.1 Shielding Design

The structure of shielding were defined as: normal shielding and active shielding which the farmer acts as coverage the surface of the equipment to reduce the emissions of electromagnetic fields and the latter can reduce the emission of electromagnetic fields by minor sources creating the electromagnetic fields against the distortion main source. However, in this study normal shielding was used. However, in this study, normal shielding was only considered.

4.1.1 System Tank

In order to attenuate the EMI between inside and outside of the system tank, aluminum material, with suitable thickness, can reduce the leakage flux due to high relative conductivity of aluminum (0.61) and unity relative permeability, while for iron are 0.17 and 1000 respectively. Comparing Fig. 8 with Fig. 1, it is clearly evident that the scattered fields suppressed by 21% in the aluminum tank with respect to the iron tank.

However, the simulation results show that, the eddy current losses in the aluminum tank is 17% increases, compare to that of the iron tank.

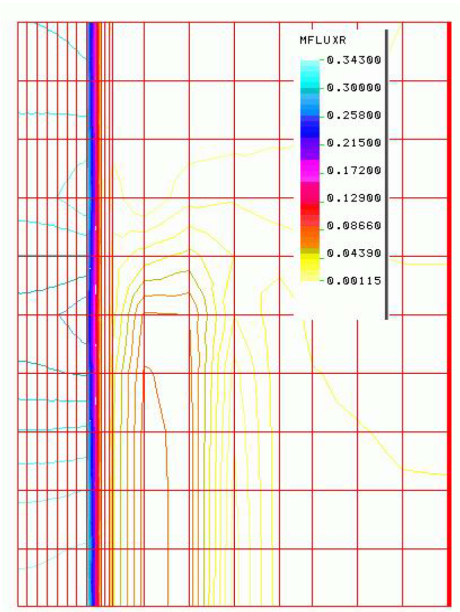

Fig.8 Flux density distribution, Using of Aluminum tank

4.1.2 Inside of the CIT

The electromagnetic zones inside and outside of the CIT system, were identified each of which was separated by a simple barrier, using zinc material, having thickness of about 0.1cm, $\mu_r = 1$, $\sigma_r = 0.29$ and f=50Hz.

According to Equations (3) to (7), SE= 157.96 dB, A=0.4978, R=145.63, and C_R=11.83 were obtained. These specifications give excellent shielding performance for our purposes.

The source and the victim, inside of the CIT system, were shielded by double layers zinc. The scattered fields around the back side of the zinc were reduced by about 27% and nearby of the control board. On the other hand, the fields in the other side of the shield (between the core and the shield) increased by about 64%. This was due to the windings leakage flux and the reflected flux of the shield.

The shield was rolled around the source. The results showed a further attenuation of the fields reducing to about 70%. Table 5 shows the measured values.

Table 5 Scattered flux density inside of AC CIT

Location	Zinc Shield	B_x(mT)	B_y(mT)	B_z(mT)	B_{xyz}(mT)
The space of board and core	No	0.2654	0.2873	0.3210	0.5060
The space of board and shield	Yes (flat sheet)	0.2424	0.2418	0.1284	0.3656
The space of shield and core	Yes (flat sheet)	0.0390	0.6127	0.5575	0.8293
The space of board and shield	Yes (circle sheet)	.0947	.0944	.0632	0.1479
The space of shield and core	Yes (circle sheet)	.0125	0.2251	.1840	0.2910

4.1.3 Outside of the CIT (Operator Barrier)

In order to protect the operator from the electromagnetic field exposure, simple and portable shields, with different shapes made of zinc material were designed and constructed.

Initially, the field produced by the current loop and scattered in the outside environment of the CIT system, at the presence of the operator, without shielding, was measured. The zinc shield as a plane sheet was put in front of the operator, and the scattered fields were measured again.

Table 6 Magnetic flux density outside of AC transformer around the operator

Location	Zinc Shield	B_x(mT)	B_y(mT)	B_z(mT)	B_{xyz}(mT)
Operator in controlling current	No	1.0631	0.4401	1.913	2.233
The space of operator and shield	Yes (falt sheet)	0.0910	0.2258	0.2128	0.3234
The space of shield and EUT	Yes (falt sheet)	1.101	0.4415	1.7908	2.1478
The space of operator and shield	Yes (ellipse sheet)	0.0581	0.1455	0.1149	0.1943
The space of shield and EUT	Yes (ellipse sheet)	0.9451	0.2547	1.498	1.7894

The results showed that the scattered field exposure to the operator was reduced by about 85%, whereas, with the elliptical shield the operator exposure field was reduced further by 91%. These field reductions were due to the fact that, the field lines reflected from the shields and diverted to other paths, resulting in change of the field distribution. The measuring values of the field components and its resultant are shown in Table 6.

5 Conclusion and suggestions

In this paper we have presented EMC-base solutions to current injection transformer systems.

The conclusions are as follows:

1- We have shown the practical approach to minimize electromagnetic interference between the transformer (source) and the control circuit (victim).

2- We have introduced symmetrical and asymmetrical load phenomenon to CIT, from which the effects of scattered fields radiated from symmetrical and asymmetrical conductive elements on the system operator, was investigated. It was found that the position of asymmetrical element would affect the intensity of the radiated field on the system operator.

3- Considering the ratio of 1:25, the 25kA field simulation results were in quite good agreement with 1kA measuring field results.

4- Using aluminum tank would reduce the scattered field by 21% compare to iron tank, but eddy current loss would increase by 17%.

By using a simple and portable shield the system operator exposure to the field radiations was drastically reduced, particularly with shield having elliptical shape.

Although, the investigation completed to date represents only an initial study and addresses only a very small part of EMC problems in CIT systems. It does not yet into account all shielding materials, and structures (Honeycomb vents shielding), against radiation exposures, the effects of active shielding on flux dispersion (mechanical forces) and control circuit of the CIT system.

At this point, it is relevant to point out that, for not absorbing of flux leakages, it is better that control system be far from of electromagnetic sources.

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