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Suppression of High - Frequency Disturbances in Low - Voltage Circuits Caused by Vacuum Circuit Breaker Operation in Medium - Voltage Indoor Substation

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In a high - or medium - voltage substation, the operation of circuit breakers can induce high - frequency over voltages in low - voltage circuits known as an electromagnetic interference (EMI). The radiated and/or conducted EMI can be the cause of damage or malfunction of low- voltage electronic equipment. This paper focuses on the effects of EMI produced due to switching of medium vacuum circuit breakers (MVCB) on the functioning of numerical relays and measuring devices which are in the vicinity of 6.6 kV Vacuum circuit breaker and remedy for reduction of effects of EMI. In this paper, a unique and cost - effective solution has been suggested and implemented to bring down the EMI effects by installation of ferrite core on control cable bunch and effective galvanized iron (GI) sheet shielding between source (MVCB) and victim (numerical relay and meter).

Keywords: *MV switchgears, High-frequency (HF) disturbances, Electromagnetic interference (EMI), Ferrite cores and shielding.*

1.0 INTRODUCTION

In the era of compact substations, high-or medium-voltage switchgears are equipped with low-voltage devices for measurements, protection, control, telecommunication and automation of power systems.

Generally, high-voltage transients are generated due to lightning surges or switching surges in electrical power systems. Switching surges are generated due to switching on and off of high-or medium voltage circuit breakers (CB). The switching operation induces high-frequency transients in high-voltage networks, which cause overvoltages in low-voltage circuits.

All MV circuit breakers generate high-frequency disturbances during open to close operation. Depending on the technology used, the disturbances are more or less important as shown in Figure 1.

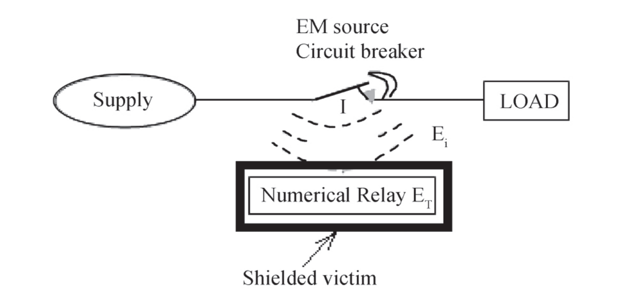

FIG. 1 GENERATION OF EMI DISTURBANCES THROUGH CIRCUIT BREAKER OPERATION

The disturbance levels are function of the following parameters: the type of CB (e.g. air, vacuum, and SF6), the type of load (e.g. capacitive, inductive

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and resistive), the load current, on which part of the current and/or voltage sine wave, the CB is closed or opened.

The more severe disturbances are generated when the CB operates inside the red zones as shown in Figure 2. In these conditions, dv/dt and di/dt are large and the electromagnetic field (electrical and/or magnetic) radiation is also large. These disturbances are coupled by the air and on all the cables located near the MV CB. [1].

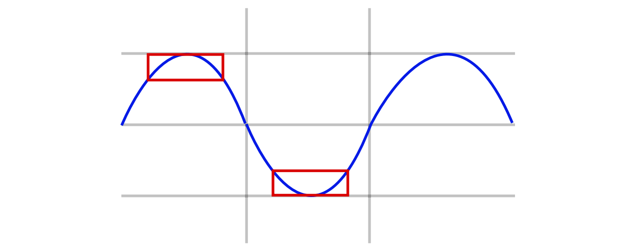


FIG. 2 VOLTAGE DISTURBANCE AT PEAK OF THE WAVE

Major malfunctions caused by EMI indicate the sluggish performance associated with some electronic devices and digital devices behaving erratically when power switchgears are switched on or off. EMI is a wave which propagates from source to victim that can be reduced by effective shielding and installation of ferrite cores in addition to basic methods of grounding and filtering.

In general, all types of CB are enclosed in a metal housing. The restriking phenomenon in the contactor gap causes extremely high-frequency overvoltages with natural frequency between 10 and 100 MHz; this induces an overvoltage up to several kV in the metal housing of CB. The EMI radiated from the CB can be reduced by earthing the housing of the CB. This provides some degree of shielding to low-voltage wiring. The high-frequency disturbances due to isolator operation have been reduced by damping resistor significantly [2].

The electromagnetic fields decrease with the distance. In case of short distance between CB and electronic devices, a shielded enclosure is highly recommended. Enclosures are used to shield a broad range of electronic items. However, the effectiveness of such shielding is reduced due to holes, seams and cable penetration which cannot be avoided [3]. Ferrite core clamps are also used to reduce the conducted disturbances on the cable bundles going to the electronic devices. In this paper, a unique and cost-effective solution with GI sheet shielding and ferrite core installation is implemented to avoid the risk of electronic equipment malfunction in the vicinity of MV switchgear.

2.0 PROBLEM DEFINITION

The 6.6 kV LG make vacuum CBs (VCB) were mounted in a two-tier fashion Korean panel. The control wiring was done on the VCB cabinet door. The numerical relay was fixed in such a way that they directly face the VCB front when the panel door is closed as shown in Figure 3.

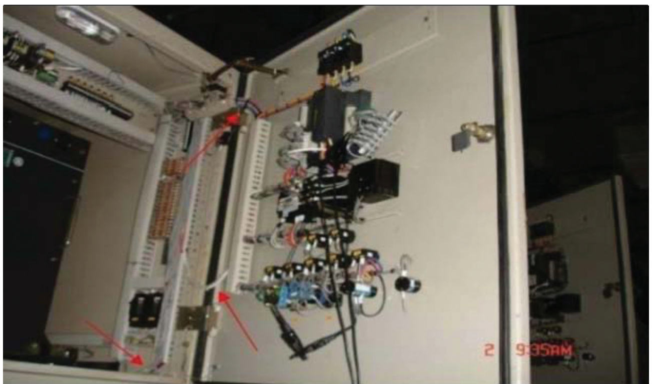


FIG. 3 RELAY MOUNTING ON VCB CABINET DOOR

While switching ON the VCB using trip and close switch, numerical relays malfunction. Owing to the malfunctioning of numerical relays, plant production was affected. These in turn raised questions about reliable power availability for an operating plant. Hence, investigation is carried out and during investigations the following points were observed.

(a) Malfunctioning of electronic equipment during VCB open and close operations.

(b) No problem found in 110 VDC bus (auxiliary Power Supply of numerical relay).

(c) Earthing conditions are not found according to the IEC standard: MV panels installation, panel internal apparatus and communication cables.

EMI measurement was done using a field meter and CRO. The data was used to investigate the probable electromagnetic compatibility (EMC) on numerical relays, digital meters of Transformer Feeders during operation of MV CB.

3.0 EMI MEASUREMENTS AND ANALYSIS

The goal of these measurements was to investigate all possible sources of disturbances and installation issues.

3.1 Measuring Devices Used

(a) Oscilloscope Tektronix TDS 3052B (500 MHz bandwidth)

(b) Current measurement system Tektronix TCPA300 (DC–100 MHz)−Current probe (150 A) Tektronix TCP303 (DC–15 Hz)

(c) Current probe (30 A) Tektronix TCP312 (DC–100 MHz)−50 Hz leakage current clamp MEGGER 00E

(d) Fieldmeter Maschek ESM-100 (5 Hz–400 kHz)

(e) Fieldmeter PMM 8053A + Field probe 100 kHz-3 GHz

(f) Multi-meter ITC 760

All measurements are done according to the standard Industrial EMC test level (IEC 61000-4-3).

3.2 Different Measurements Taken on 2 MVA Transformer Feeder

3.2.1 Measurement of EMI

Electromagnetic field measurements were carried out during VCB opening and closing. The disturbances are higher during VCB closing (two times higher). The following results are found during closing operation of the CB.

The loop antenna of field meter was placed close to the cabling bundles and relay located on the door. The target was to catch the EMI with this loop, the electromagnetic (EM) disturbances radiated during the VCB closing.

- The electromagnetic fields measured inside the panel at the top level of the VCB are:

  Low frequency (50 Hz): 0.8 A/m and 80 V/m.

  High frequency (10–100 MHz): 2.4 V/m up to 4.5 V/m.

  Hence, these levels are correct (no low-frequency issue).

- The electromagnetic fields measured inside the panel in front of the VCB are:

  Low frequency value (50 Hz): 1.5 A/m and 246 V/m.

  Hence, these levels are correct (no low frequency issue).

  High frequency (10–100 MHz): 16 A/m and 13.2 V/m peak one time (6.8 V/m peak continues)

- The electromagnetic fields measured on door I/O cablings in front of the numerical relay are:

  Low frequency (50 Hz): not measured as found satisfactory in above measurements.

  High frequency (10–100 MHz): 7.1 A/m and 13.1 V/m peak one time.

3.2.2 Measurement of Radiated EMI Effects

During normal relay operation, current transformer and voltage transformers are used to sense the faulty conditions and relay gives output according to the desired protection functions. Relay output O1 trips the circuit breaker according to the control scheme. The CRO probes were connected across the Relay output O1 and its 110 VDC circuit was disconnected from terminals 1 (110 V MCB S1 kept off), so as to measure the effects of EMI on relay potential-free contact O1 separately during closing operation of circuit breaker as shown in Figure 4.

Owing to EMI, overvoltages seen on relay output terminals, the voltage measured is more than 40 V peak to peak (here it cannot be seen due to improper scale factor) and same is observed 78 V using multimeter.

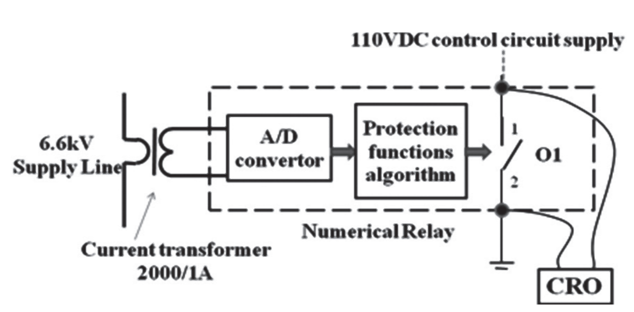
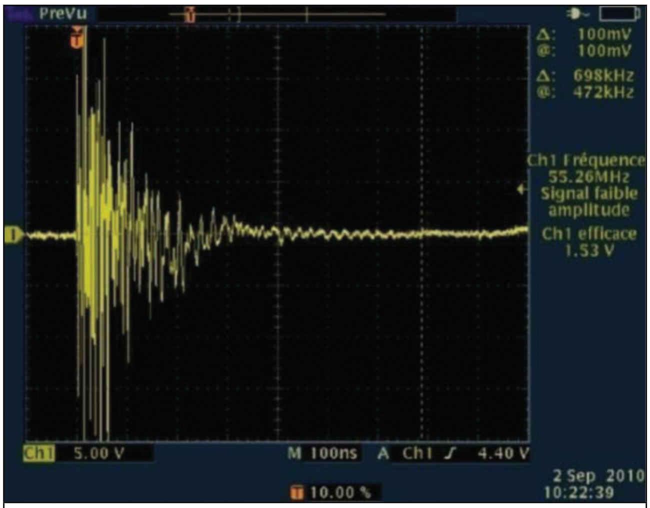


FIG. 4 HF DISTURBANCES MEASURES AT RELAY OUTPUT TERMINALS

This high voltage of equivalent frequencies between 10 and 100 MHz disturbs electronic devices.



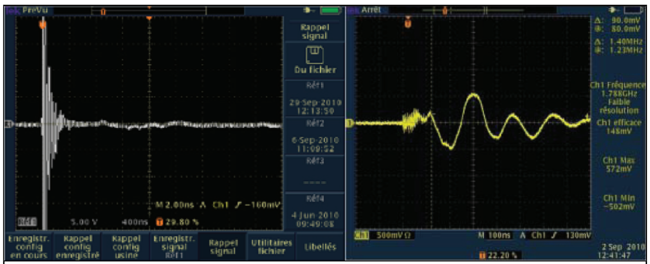
5 V/div

FIG. 5 DISTURBANCES ON THE RELAY INPUT/OUTPUT TERMINAL

During the VCB closing, a huge high-frequency electromagnetic (electric and magnetic) field is radiated as shown in Figure 5. Owing to the small distance between the VCB and electronic devices (numerical relay and PM), this EM field has adverse effects on the devices.

3.2.3 Measurement of Conducted EMI Effects

Common mode current measurements were carried out on the numerical relay incoming communication cables. The HF disturbing current levels are up to 16–20 Amp peak-to-peak is measured on CRO as shown in figure 6 (A) and (B). These levels are very huge and could disturb the electronic equipments.



(A) (B)

2.5 A/div

FIG. 6 (A) HF DISTURBANCE CURRENT ON I/O CABLINGS DURING VCB CLOSING (OFF TO ON).
(B) HF DISTURBANCE CURRENT ON I/O CABLINGS DURING VCB CLOSING (ON TO OFF).

The standardized Industrial EMC test level (IEC 61000-4-3) is 10 V/m. Hence, all the electrical fields higher than 10 V/m could disturb the Numerical Relays.

3.3 No Earthing Conditions are Found According IEC Standard

The only economic method of dividing the currents in the earthing system to maintain satisfactory equipotential characteristics is to bond the earth networks together. Bonding earth networks contributes to the equipotential state of the earthing system, but is not a substitute for protective conductors. In order to satisfy the legal requirements for personal safety, identified protective conductors with sufficient cross-section must be retained between each item of equipment and the earthing terminal. In addition, with the possible exception of buildings with a steel structure, multiple lightning rods downconductors or the surge protection network must be taken right down to the earthing connection.

The earthing conditions were found as per requirement. However, there is a need to shorten (<25 mm) earthing connections of all the electronic cards, low-voltage meter and numerical relays.

3.4 Results and Analysis

During the above measurement, the following observations were made.

(a) The numerical relay malfunctioned (hanging, restarting) at every closing of VCB at 24 A load as well as 2 A load (no load). The VCB is located at the 6.9 kV side of the transformer.

(b) The level of disturbances (more than 20 A high-frequency transients) measured were very large.

(c) When the cubicle door on which the Numerical relay and Power Meter are installed, it opens. These disturbances have a poor effect on these devices [4]. To minimize the EM fields when the door is closed, a shield has to be put on the electronic devices.

(d) The noise levels induced are very large in the input/output (I/O) cables. This is due to the I/O wires coming from the VCB compartment to the door. To minimize such coupling and to reduce the disturbing current levels, it is recommended to use ferrite clamps.

(e) The cubicles earthing and bonding connections do not comply with EMC rules. The earthing and bonding connections have to be improved to minimize EMI and EMC effects.

(f) From the above results, it is shown that the EM fields (electric and magnetic) radiated by the VCB are the primary source of disturbance. The coupling effect on the cables is the secondary source of disturbance.

4.0 SUPPRESSION OF EMI

Electromagnetic energy is created by the current flowing through a conductor causing an electromagnetic field that has to be generated. Electromagnetic waves have two basic components: a magnetic field (H) and an electric field (E). These two fields are perpendicular to each other and the direction of the wave is at right angle to the plane which incorporates these two fields. The relative magnitude of the magnetic field (H) in relation to the electric field (E) depends upon the distance to the source. The ratio of these two fields is defined as the wave impedance (ZW).

High-frequency disturbances called EMI are considerably reduced by means of effective shielding and installation of ferrite core. This results in a reliable operation of numerical relays and digital meters.

4.1 Shielding

Shielding can be described as a conductive or ferromagnetic material which either reflects, absorbs or carries electromagnetic interference to ground. Rigid magnetic shielding is divided into two fundamental types based upon the magnetic properties of the materials: flux-entrapment shields and lossy shields. A flux entrapment shield is constructed with highly permeable, specially annealed ferromagnetic mu metal alloy composed of 80 % nickel and 20 % iron, which either surrounds (cylinder or rectangular box) or separates (‘U’ shaped or flat-plate) the victims from the magnetic source [5].

Lossy shielding depends on the eddy current losses that occur within highly conductive materials (copper, aluminum and other metals), and low permeable materials that are also conductive such as iron, steel and silicon–iron. When a conductive material is subjected to a time-varying magnetic field, currents are induced within the material that flow in closed circular paths, perpendicular to the inducing field. According to Lenzs Law, these eddy-currents oppose changes in the inducing field, hence the magnetic fields produced by the circulating eddy currents attempt to cancel the larger external fields near the conductive surface, thereby generating a shielding effect.

It is often very effective to shield the victim with multiple layers. These layers can be composed of low-permeable/conductive materials than highly conductive aluminum/copper/iron plates, and lastly highly permeable metal sheets. However, this kind of shielding is very expensive [6].

4.1.1 Shielding Effectiveness

While designing shielding, its effectiveness is a very important factor to be considered. Shielding effectiveness is typically measured as an attenuation of the electromagnetic signal after a shield is introduced. Thus, attenuation is a measure of the reduction in the intensity of the electromagnetic field and is normally reported in decibels (dB). This value is actually the ratio of the field strength without the shield (Ei or Hi) to the field strength with the shield (Et or Ht) and is given mathematically as follows: [7]

$$dB = 20\log\frac{Ei}{Et} = 20\log\frac{Hi}{Ht} \quad (1)$$

(electric field or magnetic field)

A conducting plate of infinite extent, having thickness t, provides shielding effectiveness between an interfering source and a victim in terms of three different EM mechanisms: (i) through reflection on the air/conducting material boundary; (ii) absorption; and (iii) multiple internal reflections. The contribution from multiple reflections is usually negligible, hence only reflection and absorption losses contribute to shielding effectiveness. The total shielding effectiveness is then obtained from the addition of both.

$$S.E(dB)=R(dB)+A(dB) \quad (2)$$

Where R(dB) is the attenuation due to the reflection of power at the interfaces; A(dB) is the attenuation due to power converted to heat as the wave propagates through the material.

Shielding effectiveness has been calculated from web-based calculator for determining the plane-wave shielding effectiveness of various materials using SE Calculator [8] and are shown in Table 1.

Although GI sheet is providing lesser attenuation due to the reflection of power at the interfaces (R) and the attenuation due to power converted to heat as the wave propagate through the material (A), it has been selected as shielding material as EMI effect is considerably reduced.

From measurement results, a reduction in the intensity of the electromagnetic field dB in this case is,

$$dB = 20\log\frac{Ei}{Et} = 20\log\frac{13.2}{6.8} = 5.76 \quad (3)$$

As attenuation is a logarithmic value, every 10 dB gain in attenuation will provide 10 times more shielding effectiveness.

TABLE 1

CALCULATIONS OF SE FOR DIFFERENT MATERIAL WITH 1 MM SHIELDING SHEET

Type of material	**Conductivity (σ) (S/m)**	**Shielding frequency (MHz)**	**R(dB)**	**A(dB)**	**SE(dB)**
Copper	5.80×107	100	78	106	184
Aluminum	3.78×107	100	76	85	161
Gold	4.52×107	100	77	93	170
GI sheet (zinc)	1.69×107	100	73	57	130

Initially, it was decided to suppress EMI using metallic screen shielding of source (MV circuit breaker). Results were not much efficient, as there are very long slots and gaps around the GI screen. Hence, the shielding effectiveness to suppress the radiation was very weak. Then, finally, it was decided to shield the victim (numerical relay) using metallic shielding box.

4.1.2 Proto Type Metallic Shielded Box

A galvanized iron (GI) sheet (around 1 mm thickness) was used to design a shielded box/ cover. This GI box has been placed on the panel door and connected to the earth. The box was held in place using wires on the door (Figure 7).

After closing the door, the malfunctioning of the relays was not observed during the entire test. However, the digital meter malfunctioned once during the entire test. Thus, the effect on radiated EMI was reduced considerably by using the GI box. However, the malfunctioning of the meter can be eliminated by using a well-designed seamless shielding box.

Owing to high prices of copper, silver, gold and aluminum, GI has been choosen for large quantities in terms of cost and to meet technical requirements also.

FIG. 7 PROTO TYPE METALLIC SHIELDED BOX OF GI SHEET

The attenuation of magnetic and electric fields for metal sheet with thickness from 0.8 up to 1 mm is a factor 4 at 50 Hz and more than 200 for frequencies >1 kHz [9].

The goal was to design a box/cover with good contacts on the door frame and on the entire box/cover periphery. In this case the screening effectiveness will be high. Hence, gaps were not allowed to boost up shielding effectiveness. Some openings will be provided on the box flange for the wiring bundles (with protection to the bundles from the sharpened edges using gaskets).

From all the above consideration, shielding encloser design specifications are as shown in Table 2.

TABLE 2	
SHIELDING DESIGN SPECIFICATION	
Distance between EM source and victim (mm)	240
Type of material	Galvanized iron
No. of layers	one
Shielding box size (mm)	435×435×110
Conductivity σ (s/m)	1.69×10^{7}
Resistivity δ (Ω m)	5.90×10^{-8}
Thickness of the material	1 mm

The shielded box which was installed to cover the devices installed on the door as shown in Figure 8. Owing to the shielding box, the Numerical relay and Power meter were not affected during the open-to-close VCB operations.

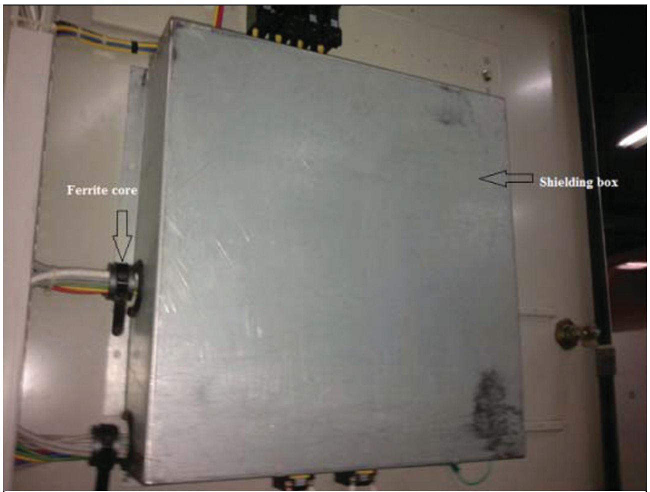


FIG. 8 GI SHEET SHIELDING AND FERRITE CORE IMPLEMENTATION

To minimize the influence of external disturbances on the bundle holes, it has been decided to use ferrite clamps on the cabling bundles near the holes but outside the box/cover.

4.2 Use of Ferrites

Basic construction of ferrite core is shown in Figure 9; generally it can be seen with electronic devices. Ferrite beads are used (in a way similar to inductors) as a passive low-pass filter.

FIG. 9 BASIC CONSTRUCTION OF FERRITE CORE

Figure 10 represents Series equivalent circuit of ferrite suppression core where loss free inductor (Ls) is in series with equivalent loss resistor (Rs). The geometry and electromagnetic properties of coiled wire over the ferrite bead result in a high resistive impedance (resistance) for high-frequency signals, attenuating high-frequency EMI/RFI electronic noise. The energy is either reflected back up the cable or absorbed resistively within the ferrite core and dissipated as low-level heat [10]. If phase and null both conductors pass through the ferrite hole, the net current is theoretically zero and no saturation occurs.

The permeability of the ferrite core is a complex parameter, where real component represents reactive portion and imaginary component represents the losses. These may be expressed in series components (μs′, μs′) and parallel components (μ_p', μ_p'')

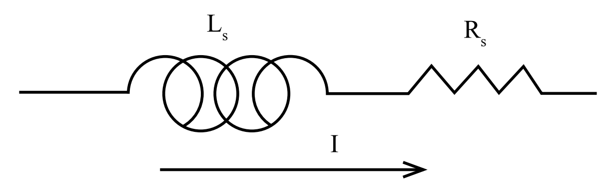


FIG. 10 SERIES EQUIVALENT CIRCUIT OF FERRITE SUPPRESSION CORE

Vectorial representation of the ferrite core circuit is shown in Figure 11. Following equations relate the series impedance and complex permeability.

$$Z = R_S + j\omega L_S \quad (4)$$

$$Z = R_S + j\omega L_0 \mu s' \quad (5)$$

$$Z = j\omega L_0 \mu s' \, [(R_S/jL_0) + \mu s] \quad (6)$$

$$Z = j\omega L_0 (\mu s' - j\mu s'') \quad (7)$$

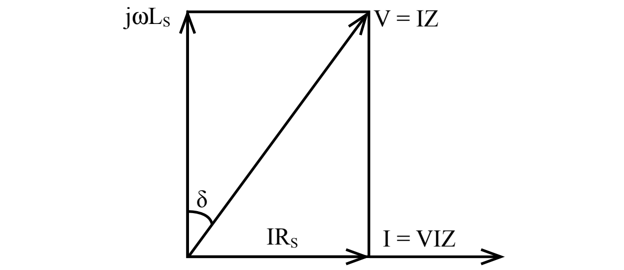


FIG. 11 VECTORIAL REPRESENTATION OF FERRITE SUPPRESSION CORE

$$R_s = \omega L_0 \mu s'' \quad (8)$$

$$L_s = \omega L_0 \mu s'' \quad (9)$$

$$\text{Tan}\delta = \frac{R_S}{\omega L_S} \quad (10)$$

$$\text{Tan}\delta = \frac{\mu s''}{\mu s'} \quad (11)$$

$$L_0 = \frac{4\pi N^2 10^{-9}}{C_1} \quad (12)$$

where L_0 is the air core inductance and C_1 is the core factor.

The impedance of the ferrite core is depends on intrinsic material type and no. of turns (N) wound on core [11] (Table 3).

4.2.1 Ferrite Core Selection

Conducted EMI can occur over a wide range of frequencies from as low as 1 MHz to several GHz. To protect the circuit from such wide range of frequencies, different types of materials are used to manufacture ferrite cores [12].

TABLE 3

ATTENUATION PROPERTIES OF DIFFERENT TYPES OF FERRITE CORE

Type of waves	Application	Permeability	Curie temp
Universal wideband	1 MHz – 1 GHz, 250 MHz peak	3350	>175
Low - frequency	1 MHz – 60MHz, 30 MHz peak	4800	>200
High - frequency	1 MHz – 1.2 GHz, 700 MHz peak	3650	>225
Microwave	2.45 MHz peak	2700	>510

Toroidal cores are majorly used in suppression application, when dimensions are in inches. L_0 for a toroidal core is given by

$$L_0 = 1.17N^2H10^{-8} \log\frac{OD}{ID} \quad (13)$$

where H is height, OD is outer diameter and ID is inner diameter as shown in Figure 12. The height of the core is a very important factor out of the three dimensions. This is because doubling the height will double the volume and hence impedance, whereas doubling OD and ID will increases impedance only by 40 %.

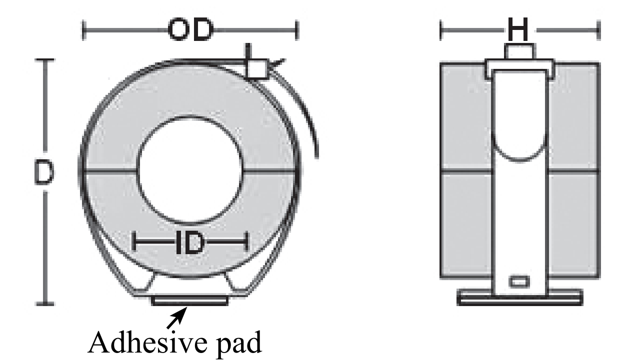


FIG. 12 UNIVERSAL WIDE BAND TYPE FERRITE CORE

The most common application of a ferrite is as a sleeve over a cable to reduce interference currents on that cable. They are available in a large variety of shapes and sizes, from a small bead to fit on a single wire to larger size to fit on cable bundles. They are even available to fit on flat cables and inside multipin connectors.

4.2.2 Use of Ferrite Core on the Control Cable Bunch

A particularly useful type is the split tube in plastic 'clip-on' housing. It is easy to retro fit to a cable (and to remove when they are found not to do much).

A Cable Bundle Clamp with Universal Mounting Strap with a universal wide band type ferrite core was used on the control cable bunch to reduce the conducted EMI as shown in Figure 13.

FIG. 13 FERRITE CORE INSTALLED ON CABLE BUNCH

With reference to the suitability for an application, there are two rules of thumb:

(1) Where you have a choice of shape, longer is better than fatter.

(2) Maximum impedance demands the maximum material density.

Considering all the factors finally selected ferrite core specifications are as shown in Table 4 with a view to reduce the EMI and fixing arrangement on cable bunch size.

TABLE 4

FERRITE CORE SPECIFICATION

Cable bunch size (mm)	23
Height H (mm)	24
Outer diameter OD (mm)	38
Inner diameter ID (mm)	25
Frequency band	1 MHz – 1.2 GHz
Permeability	3650

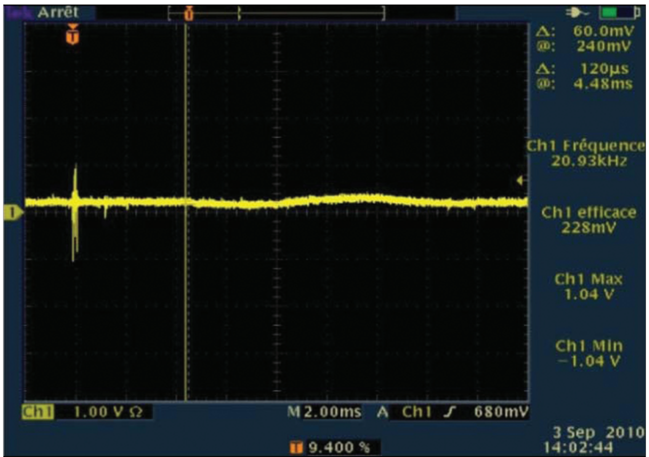
4.3 Proper Earthing of Electronic Module

All earthing connections that were greater than 25 mm were removed and reworked so that the new earthing wire length was less than 25 mm. The number of earthing points was reduced so as to minimize the ground loops.

5.0 RESULTS

After fixing shielding box around the relays and digital meters (shielding of victim) and installation of ferrite cores on the cable bunch, some common mode current measurements were carried out on the numerical relay incoming communication cables to ensure the EMI suppression. During the VCB closing, a huge high-frequency electromagnetic (electric and magnetic) field is radiated. This EM field could not affect the Relay and Meter working due to the shielding of electronic devices (numerical relay and digital meter).

The HF disturbing current levels measured are up to 1 A peak-to-peak. These levels are very low and could not disturb the electronic devices as shown in Figure 14.



1 A/div

FIG. 14 EFFECT ON RELAY OUTPUT WIRES DURING VCB CLOSE COMMAND GIVEN

Electromagnetic field measurements were carried out during VCB opening and closing. The disturbances were observed to be lower during VCB closing. The results during VCB closing inside the shielding box are as below.

The electromagnetic field-measured cables in front of the numerical relay are:

Low frequency (50 Hz): not measured, as found satisfactory in above measurements.

High frequency (10–100 MHz): 6.8 V/m peak one time.

The standardized Industrial EMC test level (IEC 61000-4-3) is 10 V/m.

6.0 CONCLUSION

The study has shown that normal operation, transient events and faults in medium-voltage networks generate high-frequency disturbances which can result in malfunctioning or damage of low-voltage electronic devices.

The measurements have shown that low-voltage circuit consisting of numerical relay and digital meters were highly affected by electromagnetic fields generated during switching (on/off) operation or fault conditions in medium-voltage networks.

When the low-voltage circuits are protected using ferrite core on control cables and proper shielding of victim is done, the magnitude of the overvoltage caused by high-frequency disturbances is significantly reduced.

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