Interference currents in 380 and 150 KV substations

INTERFERENCE CURRENTS IN 380 AND 150 KV SUBSTATIONS

A.P.J. van Deursen, P.C.T. van der Laan

High Voltage Group, Eindhoven University of Technology
POB 513, Eindhoven, NL 5600 MB The Netherlands

Introduction.

We discuss the interference in high-voltage (HV) substations which results from switching operations, from an (inadvertent) breakdown or from a direct or nearby lightning stroke. In case of switching operations the initial power level of the disturbance is of the order of V^2/Z_0, where V can be the amplitude of the phase voltage, and where Z_0 is the characteristic impedance of the HV circuit. A ns-fast rising wavefront runs through the HV circuit; after reflections in or near the substation high frequency (hf) waves are resulting. One expects that the disturbances will be more severe for higher voltages or lower impedances Z_0 (in closed gas insulated substations (GIS), about 75 Ω, versus open air substations, about 300 Ω).

The approach generally followed to solve the interference problem is to characterize the EM-environment, in agreement with the IEC definition of EMC. At various locations one measures the intensity of the E-field [see e.g. 1] and/or the B-field. Some comments on this approach:

- The EM-environment can be strongly influenced; by metal properly shaped and connected one can create an excellent "micro climate" for leads and equipment. The overall EM-environment is less important.
- Even if E- and B-fields are known at a large number of places in the substation, one cannot easily utilize that information for a (network) calculation [2], where all fields are lumped.
  In spite of the fast variations in both E and B, network calculations are commonly being used, as demonstrated by the term 'transient ground potential rise'. This 'potential' is invariably large, of the order of 1 p.u. for switching operations, and MV's for lightning; we will comment on it later.
- The approach based on E- and B-fields tends to overemphasize shielding, provided by metal housings and cubicles thought of as Faraday cages.

As an alternative approach one may characterize the interference by the common mode (CM) currents measured in the leads where they enter the electronic equipment. Interference couples in via the transferimpedance Z_t along the lead, or, often more important, via the Z_t at the point of entrance. Note that the leads are large antennas, current can also be induced by fields far away from the equipment. The prescriptions for obtaining a good EMC then immediately follow:

- one knows where to measure the CM currents, close to the equipment at the point where the leads enter;
- one knows the important parameters, the CM current waveform and peaklevel, and the local Z_t; many tricks are available to reduce Z_t.

By decreasing Z_t one brings the interference voltages -differential mode (DM) at the input of the equipment- down to acceptable levels. Far voltages between different points in the substation are less important for the protection of equipment, network 'potentials' are meaningless.

Based on this view we developed an EMC cabinet described earlier [3]. A careful layout minimizes the transferimpedance for the external CM currents with respect to the electronics inside the cabinet. Such an EMC cabinet allows us to use standard digital measuring equipment, such as Nicolet 4094 oscilloscopes, in HV substations [4] and with lightning surge generators [5].

Note the similarity between the above approach and the current injection testing of e.g. TV-sets, proposed earlier by Bersier [6]. Numerous examples prove that current injection testing is often more fruitful than testing with fields. Even rules of thumb exist relating the immunity for CM current injection to the immunity for an external field: 10 mA per V/m [7].

The IEC 801/4 standard also deals with immunity of equipment for disturbances transported by leads. A fast rising current is injected in all leads. No currents are measured, only the voltage at the testgenerator is specified. Only electrical leads are taken into account. However, other conducting connections (water, oil or gas) can carry a substantial interference current to the equipment as well.

Experimental data.

Measurements have been carried out in two substations, one for 150 kV and one for 380 kV. The incentive for the investigations were real problems in both substations. We will show the validity of the Z_t approach. The determination of all interference currents would be an impossible task, but also unnecessary. The Z_t approach tells us which currents are important.

In both stations we simulated real switching events by injecting appropriately chosen pulsed currents into the HV circuit. We used a capacitor discharge, 0.5 μF/20 kV, coupled via a step up transformer to one HV phase. The advantage of this system is the reproducible current waveform and level. As a check we used the disconnect switch to generate the interference current. For both injection and actual switching the amplitude of the current in the HV circuit is of the same magnitude.

The data were recorded with digital equipment, placed in an EMC cabinet. We measured the distribution of interference currents over all conductors connected to the HV transformer in the 150 kV substation; in the 380 kV substation we investigated all leads to several control cabins in the HV field.

The PNEM 150 kV substation Den Bosch noord.
This station does not have a grounding grid under the switchyard. We present the interference current distribution around the HV transformer in Fig. 1. The values shown are the peak currents. The arrows indicate the main direction of the current. The algebraic sum of the values presented is not zero. Of course Kirchhoff's current law is valid for the actual currents but then one should take the instantaneous values.

We injected 250 A (at about 440 kHz) in the middle HV phase, close to the circuit breaker, about 20 m from the transformer. Every conductor carried some part of the injected current, whether intended (e.g. grounding pins, GP in Fig. 1, 40 %) or not (e.g. fire extinguisher pipe, 30%). Several other grounding situations have been investigated too:

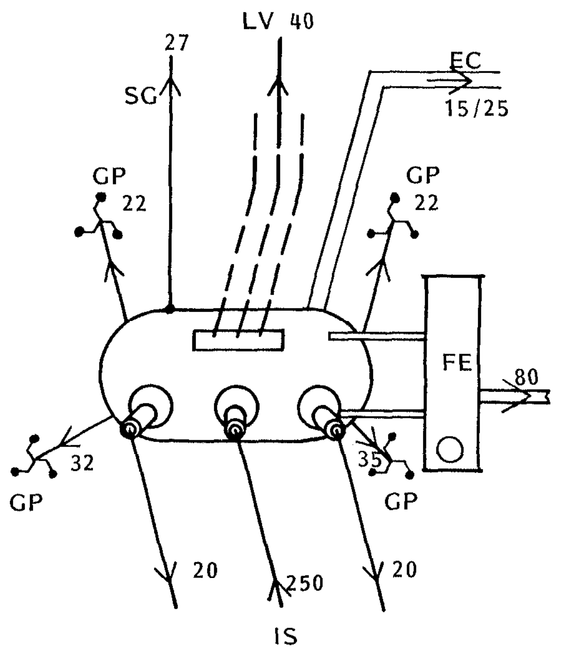

Fig. 1. Interference currents around the 150/10 kV transformer. The current was injected at the middle HV bushing (IS). The values given are the peak currents in amperes. Only the connections with the larger currents are shown. The four sets of grounding pins (GP) carry only 40 percent of the injected current; the 50 Hz safety ground (SG) about 10 percent. A large fraction is taken away by the unintended path via the fire extinguisher (FE). The experimental conduit or shielded cable (EC) carries 25 A (resp. 15 A) to the control room.

- no grounding pins at all
- additional copper foil (200 x 0.1 mm) between the transformer base and the groundconnection at the injection point; this simulates a grounding grid under switchyard.

Between the transformer and the control room a number of local EMC grounding structures have been tested, a.o. a shielded cable, a steel conduit and a shielded cable in the conduit (see Table 1 later in this paper). In all grounding situations of the transformer about 20 to 40 A flows through those EMC grounding structures towards the control room.

The SEP 380 kV station Geertruidenberg.
This substation was built in 1969; the secondary equipment is not based on microelectronics. A rectangular grounding grid (meshes of 5 x 15 m) is present about 80 cm below the surface. Each section of primary equipment, belonging to a HV line or a transformer, has its own (brick) control cabin with secondary equipment, placed nearby in the HV switchyard. Shielded cables are used throughout for control and power. The shields are connected to ground locally at both ends. In the control cabin a single copper rail collects the current of all shields; this rail is connected to the grounding grid under the cabin. The secondary equipment is placed in open metal racks (no Faraday cages).

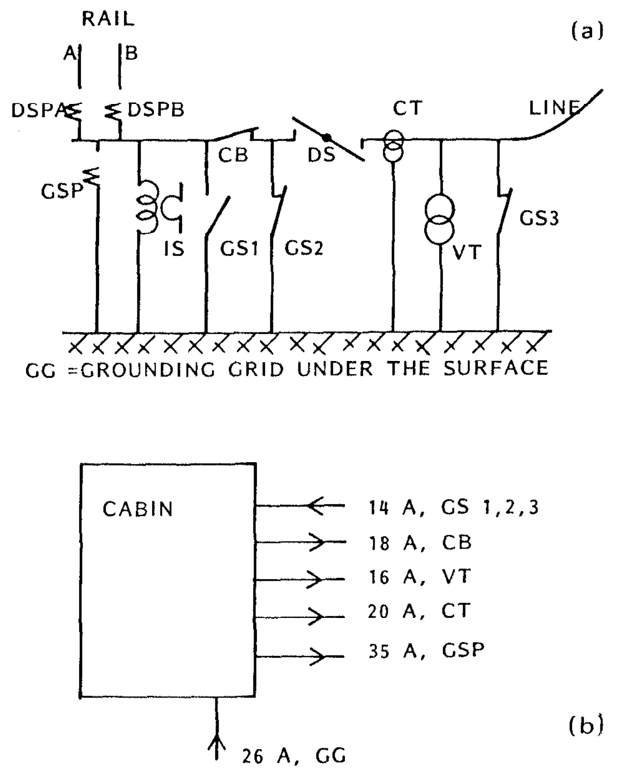

Fig. 2. (a) HV circuit with current injection source (IS). The current is injected in one phase only. The circuit breaker (CB) was closed, the disconnect switch to the line (DS) and to the rails (DSPA and DSPB, Pantograph type) were open. The position of the grounding switches (GSP and GS1,2,3) is indicated. The control cables to the current and voltage transformers (CT and VT) carried a large CM current, even with the DS opened. The grounding grid (GG) consisted of rectangular copper meshes.
(b) The larger currents measured at the cabin entrance with the injection testing.

Four cabins have been investigated. For a typical one, serving a HV line, Fig. 2 shows the primary circuit during injection measurements. The injected current is 375 A at predominantly 325 kHz. Several control cables, out of a total of about eighty, carry a considerable current up to 40 A peak value; only those are shown in Fig. 2, with the main direction presented by the arrow. Again the algebraic sum is not zero. One observes that the connection to the grounding grid is just one of the current carrying leads; it acts certainly not as a current sink.

The initial rate of rise of the injected current is of the order of 10^{10} A/s. For the disconnect switch current (which was not measured) one can expect values of the order 10^{11} A/s [8]. A typical value for the initial rate of rise of the current measured at the cabin (GSP in Fig. 2) is of the order 4 10^7 A/s with injected current and 2 10^8 A/s for some other cables during disconnector switching. In the latter case the waveform contains mainly frequencies up to 3 MHz; an example is given in Fig.3.

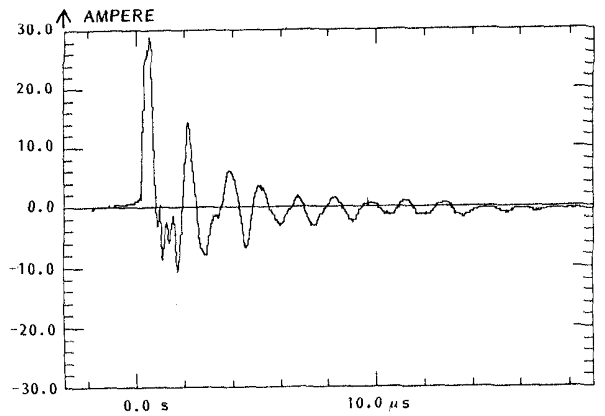

Fig. 3. The waveform of the CM current on the cables controlling the disconnect switches DSPA and DSPB (see Fig. 2) during operation of DSPB.

Discussion.

In both substations the CM current, flowing on the shields of the control cables, is of the same magnitude, up to 40 A. In the 150 kV substation this current kept the same peak value within a factor two, regardless of the grounding situation at the transformer. In the 380 kV substation some part of the "primary" hf current flows through the grounding grid. This primary current causes the flow of CM interference currents along the control cables; at high frequencies mainly via an inductive coupling.

Any protection scheme must be able to deal with these currents. At three places the CM current may generate a harmful DM voltage for the equipment, at the beginning of the cable near the primary equipment, along the length of the cable and at the end of the cable close to the secondary equipment. At all three cases the local Z_t is the important parameter.

At the equipment a low value for Z_t is obtained by an EMC cabinet (Fig. 4). Such a cabinet provides a clear path for CM currents from all leads connected to the equipment. All conductors run through the backpanel of

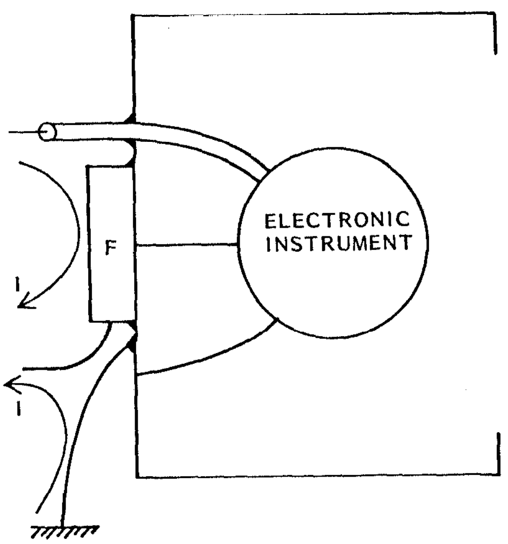

Fig. 4. An EMC cabinet diverts the CM currents (I) to improve the combined transferimpedance of cabinet and the electronic instruments within. The filter (F) is used for the power leads.

the cabinet, close to each other. All shields of cables are connected circumferentially to the backpanel. When filtering is necessary, eg for the power leads, the filter is properly bonded to the backpanel. An extra ground lead, when present, is also connected there. By this layout the coupling between the external CM currents and the internal circuits is kept low. All panels of the cabinet form a single well conducting metal surface. Often the door panel can be left open, or even be omitted. For other applications with less intense interference, the backpanel alone can be sufficient.

The Z_t of the cable can be reduced by a proper choice of the outer conductor, such as a folded foil. The cables in both substations are multiwire 2.5 mm² copper; the outer conductor is a relatively open structure of steel wires, primarily for mechanical protection of the wires. The Z_t of this cable is remarkably slow function of frequency (Fig. 5).

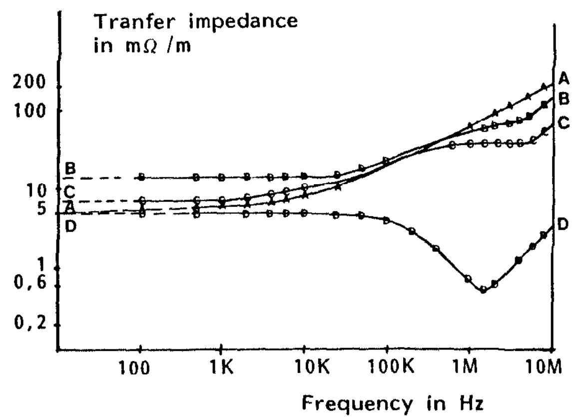

Fig. 5. The transferimpedance Z_t measured for several cables types with coarsely woven steel outer conductor, (A) Draka type Vulta mb, 37 x 2.5 mm², (B) Jobarcoflex ground cable, (C) Jobarcoflex ground cable type YKO, with a copper strand against the inside of the braided outer conductor. The results for the coaxial cable RG 214 (D) are given for comparison.

A conduit provides an additional protection for the cable, as discussed by van Houten [3]. The cable is laid inside the conduit. With the conduit properly connected at both ends, the conduit carries the CM current instead of the cable shield. In many cases steel conduits are preferred over copper or aluminum, firstly because at low frequencies the Z_t decreases faster due to the skin effect. Secondly, at high frequencies the CM currents at the outside are damped strongly by dissipation in the skin. In Table 1 we recall some of the results, published earlier [9], obtained in the 150 kV substation. A 23 m long cable was connected between the HV transformer and the control room. With the cable in a steel conduit (6 x 6 cm, 1mm wall), a DM interference voltage of less than 1 V is obtained at the end of the cable. Of course one also has to deal with the current carried to the equipment by the conduit. An EMC cabinet serves this goal. In addition one may also reduce the CM current arriving at the equipment by many extra connections of the (outside of the) conduit to other grounded metal, e.g. the grounding grid [10]. These extra connections provide an earlier return path for the CM current.

EMC aspects are often neglected in the cable layout. Routing the cable along existing large grounded metal structures, such as construction elements, reduces the CM current induced in the cable. Preferably one should install cables in the corner of e.g. H-shaped beams, simulating a conduit.

Conclusions

The primary sources of interference for electronic equipment are the common mode currents carried to the equipment by the electrical leads, but also by conductors like water pipes or other metal structures. Guided by the transferimpedance concept one designs local protection structures, EMC cabinets for equipment and conduits for cables.

	I_{cm}(A)	I_{lp}(A)	U_{dm}(V)
a) no protection			2300
b) shielded cable	15		20
c) cond. & sh. cable	25	0.4	≈ 1

Table 1. A comparison of several protection schemes for leads tested in the 150 kV substation; all numbers are peak values, taken from Table 1 in [9].

a) The voltage U_{dm} measured in the control room between the local ground and the end of a 23m long unshielded lead connected at the other end to the top of the HV transformer.
b) The CM current I_{cm} through the shield of the cable connected to the local ground at the top of the transformer; I_{cm} is measured at the end of the cable in the controlroom; the U_{dm} is due to the Z_t of the cable.
c) The CM current I_{cm} through a conduit (EC in Fig. 1) between the transformer base and the control room with the shielded cable in the conduit; the current I_{lp} in the ground loop formed by the inside of the conduit and the shield of the cable; the U_{dm} is again due to the Z_t of the cable.

This approach has been extremely successful in a number of experiments. The current measurements described in this paper have been carried out with two 200 megasamples/s 4094C Nicolet digital osciloscopes. The measuring equipment was placed in an EMC cabinet directly in the 380 kV switchyard. Interference free measurements of all currents were possible.

It is generally believed that a GIS substation generates the most severe interference. This is based on the low value of the characteristic impedance Z_0 and the small distances between switchgear and control equipment. Rise times of switching wavefronts are extremely short [11]. Due to the coupling at openings of the coaxial structure these internal waves generate fast rising CM currents in external circuits. In an experimental single phase 380 kV GIS wavefronts of 3 ns rise time have been measured [12]. The measuring equipment comprised a Tektronix digitizer of 600 MHz bandwidth. This delicate instrument, at only 2 m distance from the GIS, has been protected by an EMC cabinet. The same measuring equipment has been used in real three phase GIS substations, Eindhoven West (150 kV) [13] and the Maasvlakte (380 kV) [4].

An implicit demonstration of the correctness of our protection approach is given by Meppelink [1]. In an experimental 800 kV GIS the secondary equipment is placed in Faraday cages in the immediate vicinity. Due attention is paid to the transferimpedance of all cables and connectors which seemed to be mounted on one panel of the cubicle (A in Fig. 5 of [1]). With the door of the Faraday cage opened "no disturbance at the electronics occurred", in spite of the much higher E-field strenghts in the cubicle. With the door open the cubicle still acts as an EMC cabinet and not anymore as a Faraday cage.

In both substations investigated about the same CM currents have been found to flow along cables, i.e. those connected to the secondary equipment. No special EMC attention was paid to the routing of the cable nor to the mounting at its ends. Therefore the control equipment has to withstand the interference voltages at its input.
The same protection method can be used in both substations. It is a matter of convenience and price whether several EMC cabinets are placed directly around the equipment in the cabin or controlroom; as an alternative the cabin or controlroom itself might be designed as a single large EMC cabinet.

The protection by EMC cabinets and conduits find their most critical application in HV substations and testlabs. Based on the same ideas we proposed an effective protection of transmitters against lightning [10]. As mentioned before, the notion to primarily protect against CM currents is not confined to HV work. Our ideas can also be adapted to situations with less intense interference, e.g. for consumer electronics.

Transient Ground Potential Rise, an incorrect term.

In Fig. 6 we schematically present a GIS, with a fast rising T(E)M wavefront inside the coaxial structure. At points where the coaxial envelope is interrupted, a coupling occurs with the outside world. Many publications are devoted to the voltage between e.g. the envelope and the local ground (as will be measured by voltmeter A in Fig. 6). This voltage may lead to flash over through the air. However, we are not dealing with a real potential; if so, then the two voltmeters, connected via different ways to the same two points, would give the same reading.

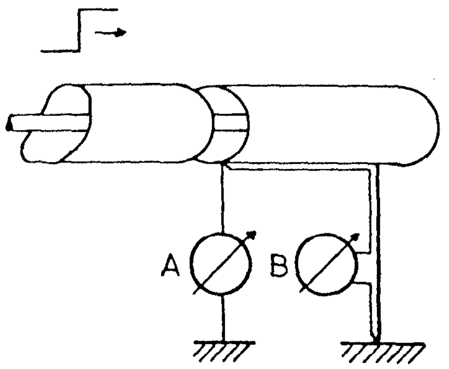

Fig. 6. Voltmeter B measures nearly zero, whereas voltmeter A measures a considerable voltage.

Voltmeter B will show the electric field component parallel to the outside of the GIS wall, integrated along the leads, $V_B = \int E.dl$. The GIS wall and the ground connection is made up of metal. The perpendicular component of the electric field will certainly be large; the parallel component will be very small, if not negligible at all. Voltmeter B will therefore show a low value. The difference between the reading of voltmeter A and B is equal to the time derivative of the magnetic flux in the loop formed by the leads of both voltmeters and ground.

It is a good practice to route cables along large metal grounded surfaces, very close to the surfaces, inside corners whenever possible. The CM currents induced in the shield are then small (cf. voltmeter B). Also extra grounding structures as conduits can be installed. Those structures carry the CM current that otherwise would flow through the shield (see eg. Table 1), thus protecting the cable and the DM circuits served by it.

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