An equivalent circuit for earth-fault transient analysis in resonant-grounded distribution power networks

P. FERRACCI, M. MEUNIER
Ecole Supérieure d'Electricité
Service E.E.I.
Plateau de Moulon
91192 Gif-sur-Yvette Cedex

L. BERTHET
Electricité de France - Direction des Etudes et Recherches
Service Etudes de Réseaux
1 avenue du Général de Gaulle - B.P. 408
92141 Clamart Cedex

ABSTRACT:

Lengths of underground cable in rural distribution power networks are increasing. Overvoltage levels caused by ground-fault currents could reach the benchmark values (potential rises of MV network earthing ...). Grounding of the MV neutral by a compensation reactance (tuned to the capacitive earth-fault current of the system) allows a better control of the overvoltage values.

In mixed, compensated distribution networks, restriking faults are the most common type of permanent line-to-ground faults.

The amplitude of the 50 Hz component is very small compared to the amplitude of transient components. Thereby, protection devices on MV feeders need to operate using the transient state.

This paper presents a simple model based on an equivalent circuit to study transients (in the frequency range from 0 to 1 kHz) caused by the occurence of an earthfault in underground or mixed compensated distribution power networks, either loaded or unloaded.

This circuit requires few parameters of the network.

The major advantage of this single-phase circuit is to provide an efficient and easy calculation of any zero sequence currents and voltages of the network.

The model is validated by comparison with EMTP simulations and with recorded faults in a real distribution network (20 kV, 50Hz) of Electricité De France.

The knowledge acquired on earth-fault transient in compensated networks will enable to get more precise equipment specification. Validation tests of equipments are also concerned.

KEYWORDS:

Distribution network-Transient-equivalent circuit-earth fault-Resonant-grounding

1. THE NEED FOR A MODEL IN THE RANGE OF 0 - 1 KHZ:

To be able to improve the quality of supply for the customers [10], [12] and to improve the integration of networks to the environment [13], lengths of underground cable in distribution networks are increasing. Because of the high capacitive earth fault current of underground cables (compared to overhead lines), ground fault current causes overvoltages, the levels of which could reach the benchmark values (potential rises of MV networks earthing and surrounding earth electrodes by coupling).

To better control these overvoltages values reached during earth faults and to improve the quality of supply, earthing of mixed distribution networks neutral using a compensation reactance is currently tested in some HV/MV substations in France [7], [9], [11].

In mixed, compensated distribution networks, restriking faults are the most common type of permanent earth faults [8]. The duration of the fault is generally smaller than a period of the power supply and the amplitude of the 50 Hz component is very small compared to the amplitude of transient components. Thereby, protection devices selecting the faulty feeder need to operate using the transient state caused by the occurence of the ground fault [6], [8], [11].

Traditional methods to solve transient problems are Transient Network Analyser and digital methods such as EMTP. Such methods allow detailed formulation of the physical situation and require the knowledge of a lot of data. These methods don't provide expertise in an easy way.

Some transient problems in apparently complicated networks can be efficiently solved by simple models. Their simplicity often provides a better physical understanding of the phenomena.

Simple equivalent circuits have been proposed in the literature [1], [2], [3], [4], [5] to study earth fault transients in MV networks. They deal with particular and simple configurations (solid phase to ground fault - fault on the busbar - ungrounded neutral).

This paper presents a simple model based on an equivalent circuit to study transients (in the frequency range from 0 to 1000 Hz) caused by the occurence of an earthfault in underground or mixed compensated distribution networks, either loaded or unloaded.

We are particularly concerned with zero sequence currents and voltages of the network.

2. MODELING:

Consider Fig. 1, which shows a schematic three-phase representation of a distribution network. This type of network have a radial structure.

The network can be divided as follows:

- a high voltage line
- a HV/MV transformer or a three phase zig-zag coil if necessary
- a neutral impedance
- a faulty feeder
- some healthy feeders
- a three-phase capacitor bank (isolated from ground) for power factor improvement, connected or not.

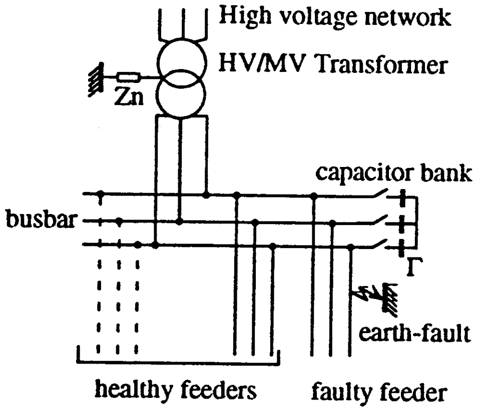

Fig. 1: schematic representation of a distribution network

The components of the system will be treated as concentrated constants, without seriously impairing the accuracy of the calculation in the frequency range from 0 to about 1000 Hz.
As a consequence, the model can't represent very fast transient phenomena. They would necessitate a distributed representation. In particular, an earth fault initiates two incident waves travelling from the point of fault. They are reflected and refracted at every network discontinuties. Therefore, the model doesn't modelize the discharge of the faulty phase-ground capacitance of the faulty feeder through the arc.

The paper focusses on the modeling of the different components mentioned above.

2.1. HV/MV transformer and HV supply:

Two cases of grounding can be found: by means of the neutral of the HV/MV transformer or a three phase zig-zag coil creating an artificial neutral point.
These components seen from the busbar can be represented by an equivalent circuit.

2.1.1. neutral of the HV/MV transformer:

The equivalent circuit is shown in Fig. 2.

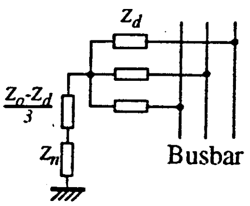

Fig. 2: high voltage network and transformer referred to the secondary winding

Where Z_o and Z_d are operational impedances.
By definition:

$$Z_d = L.s + L_{da}.s = L_d.s \text{ and } Z_o = L_o.s$$

Where s is the Laplace operator.
L is the leakage inductance of the transformer referred to the secondary winding.
L_o is the zero sequence inductance of the transformer referred to the secondary winding.
L_{da} is the short circuit inductance of the high voltage network referred to the secondary winding.
Usually L_{da} is small compared to L and therefore can be neglected.

2.1.2. three phase zig-zag coil:

Since the zero sequence impedance of the HV/MV transformer referred from the secondary winding is infinite the equivalent circuit is shown in Fig. 3.

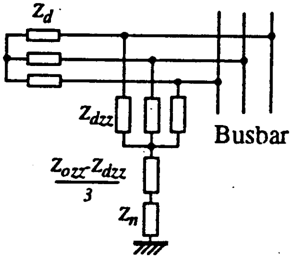

Fig. 3: high voltage network and transformer referred to the secondary winding and zig-zag type device

Where Z_d , Z_o , Z_{dzz} and Z_{ozz} are operational impedances.
By definition:
$Z_d = L.s + L_{da}.s = L_d.s$, $Z_{dzz} = L_{dzz}.s$ and $Z_{ozz} = L_{ozz}.s$
L, L_o and L_{da} are defined as mentioned above. However, in this case L_o is infinite.
L_{dzz} is the positive sequence inductance of the three phase zig-zag coil.
L_{ozz} is the zero sequence inductance of the three phase zig-zag coil.
Since in practice L is extremely small compared to L_{dzz}, the circuit of Fig. 3 can be reduced to the circuit of Fig. 4.

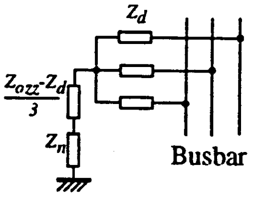

Fig. 4: high voltage network and transformer referred to the secondary winding and three phase zig-zag coil (equivalent circuit)

Circuits of Fig. 2 and Fig. 4 have the same layout. This provides the opportunity to establish a model adequate for the two cases of grounding.

2.2. the neutral impedance Z_n is represented by a parallel R_n, L_n circuit where L_n is tuned to the zero sequence capacitance of the MV network. Usually, $(Z_{ozz} - Z_d)/3$ can be neglected compared to Z_n.

2.3. healthy feeders:
Each feeder is constituted by underground cables and overhead lines sections.

Underground and overhead lines sections between two derivations are represented by a three phase π circuit (with concentrated constants).
In distribution networks, lengths of the sections are short compared to the wave length of the highest frequency being considered.

The most used cable configurations in distribution networks tend to be three shielded single phase cables and shielded triplexed cables. The serial and shunt zero sequence parameters used are the manufacturer's power-frequency positive sequence values.
At the highest frequency (1kHz) of interest, the skin effect can be neglected in stranded conductors.

From the line geometry, the wire type, the earth resitivity and the frequency, the impedance matrix is calculated by using Carson Formulae.
The earth conductivity varies from place to place and also depends on weather conditions. The widely used value of 100 Ω.m is assumed.
The parameters are nearly constant in the frequency range from 0 to 1000 Hz. They are calculated at power-frequency (50 Hz).
A balanced behaviour of overhead lines can be assumed in distribution networks.

Loads (MV/LV substations ...) are assumed to be passive. They are represented by a balanced star connected, parallel R, L circuit, isolated from ground. The R, L impedance is calculated from the frequency-power characteristics (apparent power and power factor).

A healthy feeder is represented by the total capacitance and the total load of the feeder. This requires that the serial impedances can be neglected compared to the shunt impedances.

The circuit of Fig. 5 shows all the healthy feeders seen from the busbar.

Where:
C_o' is the zero sequence capacity of the healthy part of the network.
C_d' is the positive sequence capacity of the healthy part of the network.
The R_c' , L_c' circuit models the total load of the healthy part of the network.

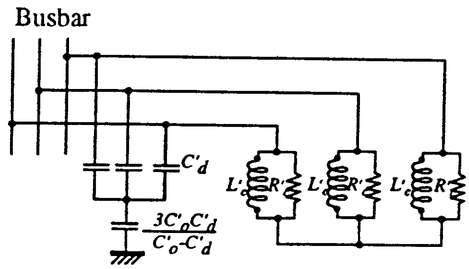

Fig. 5: healthy feeders seen from the busbar

In case of mixed or underground networks, C_o' and C_d' are nearly equal.
Neglecting the contribution of the load current to the transient of the residual current (irs), all the healthy feeders can be modeled as shown in Fig. 6 (loads are assumed isolated from ground). Therefore, the load is taken back on the busbar.

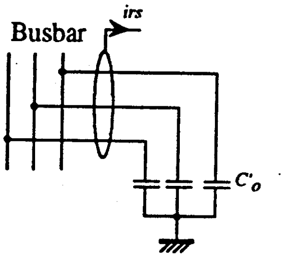

Fig. 6: healthy feeders seen from the busbar (simplified circuit)

2.4. the faulty feeder:
A constant resistance (R_{def}) models the arc resistance and the MV earth electrode concerned by the fault path.

Neglecting the contribution of the load current to the transient of the residual current (ird), the faulty feeder can be modeled as shown in Fig. 7

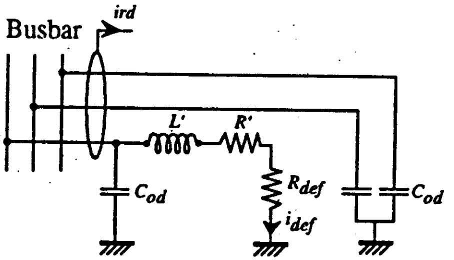

Fig.7: modeling of the faulty feeder

R' and L' are the resistive and reactive part of the self serial impedance of the lines between the fault point and the busbar.
By definition: $L'.s + R' = \left(Z_{o\,fb}(s) + 2.Z_{d\,fb}(s)\right)/3$
Where $Z_{o\,fb}(s)$ and $Z_{d\,fb}(s)$ are the zero and positive serial impedances of the lines between the fault and the busbar.
Notice that L' is an information about the distance between the fault point and the busbar.

Since the circuit is linear, the principle of superposition is applied to simulate the fault.
Let V_f be the voltage between the fault point and the ground in the network when there is no fault.
The source voltage V_f in serie with R_{def} is injected accross the faulty phase and earth, at the fault point with inverse polarity. Note that the system has all initial conditions equal to zero.

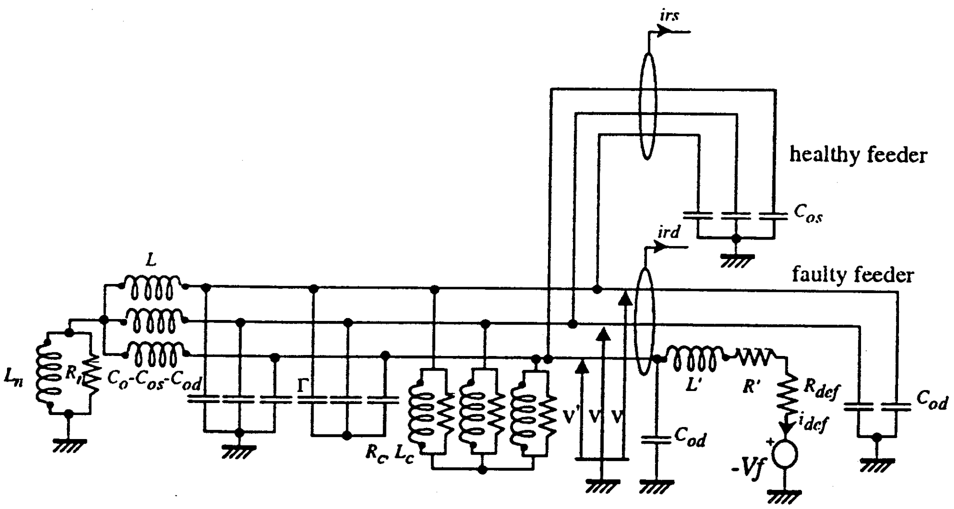

Fig. 8: equivalent circuit

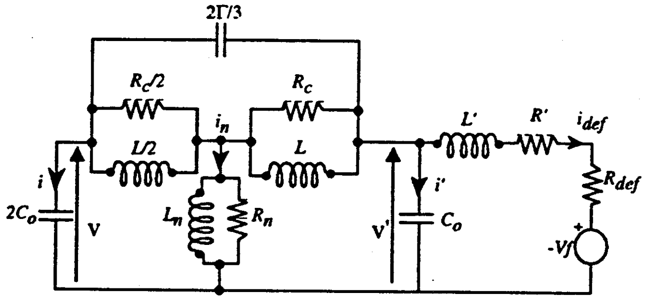

Fig. 9: reduced equivalent circuit

A direct approach without using any systems of components such as symmetrical components or Clarke's components is preferred. It allows a better understanding of the physical behaviour of the system.

The network is represented by the equivalent circuit of Fig. 8.

Where:

- C_o is the zero sequence capacitance of the MV network.

C_{od} is the zero sequence capacitance of the faulty feeder.

C_{os} is the zero sequence capacitance of the studied healthy feeder

The parallel R_c, L_c circuit is the total load (MV/LV substations...) of the MV network (faulty and healthy feeders).

Since the circuit is symmetric, the model of Fig. 8 can be reduced to the simplified equivalent circuit shown in Fig. 9 (a delta-star transformation is used, L_c appears in parallel with L and is neglected with respect to L and an impedance appears in serie with Z_n and is neglected with respect to Z_n).

This circuit shows that the fault current (i_{def}) is the sum of three currents:

-i: the charging current of phase to ground capacitances of the healthy phases

-i': the discharging current of the phase to ground capacitance of the faulty phase

-i_n: the current in the neutral impedance.

3. VALIDATION OF THE MODEL:

The circuit of Fig. 9 allows us to calculate the zero sequence currents and voltage seen from the busbar.
From Fig.8, the operational expressions of i_{rs}, i_{rd} and V_o (the zero sequence voltage on the busbar) are determined as follows:

$$\boxed{\begin{aligned}&I_{rd}(s)=I_{def}(s)+2.C_{od}.s.V(s)+C_{od}.s.V'(s)\\&I_{rs}(s)=C_{os}.s.V'(s)+2.C_{os}.s.V(s)=3.C_{os}.s.V_o(s)\\&V_o(s)=\left(2.V(s)+V'(s)\right)/3\end{aligned}}$$

These expressions assume a steady-state before the fault occurs.

The transient current through the neutral impedance can also be calculated for equipment specification.
The transient voltage to ground of the faultless phases are obtained by superposing the unfaulted network values to v (Fig. 8).
The transient voltage to ground of the faulty phase is also obtained by superposing the unfaulted network value to v' (Fig. 8).
The model is validated by comparison with recorded faults in a network of Electricité de France.
A comparison with measured data of the first ignition of a restriking earth-fault in a rural distribution (20 kV, 50Hz) network of Electricité de France is presented here after.
This network is fitted with equipments for transient measurements. And sufficient informations about both the fault and the network are available to use recorded data for model validation.

A Yd, 63 kV/21 kV,36 MVA, 17 % transformer feeds the busbar to which nine feeders are connected.
A parallel R_n, L_n circuit has been placed between the neutral point of a three phase zig-zag coil and the earth. L_n is tuned to the capacitive current of the network (280 A) and R_n allows an active current to ground equal to 18 A.

The line natures and the wire types between the fault and the busbar is shown in Fig. 10

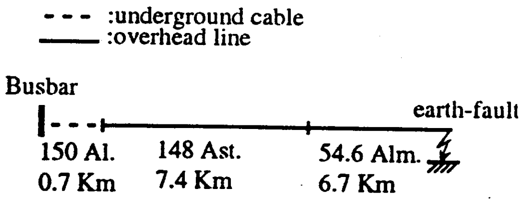

Fig.10: Lines between fault and busbar

The load (R_c , L_c) takes an apparent power of 16 MVA at a power factor of 0.9 (capacitor bank not connected)
The ground fault occurs at the peak of the faulty phase voltage to ground.
The capacitive current of the faulty feeder is 13 A. Its total length is 31.3 Km.
The capacitive current of the studied healthy feeder is 31 A. Its total length is 19.7 Km.

Figs 11 to 13 show calculated data (dashed line) and measured data (solid line). The measuring sample frequency is 1.6 kHz.

The only unknown factor is R_{def}. The most suitable value of R_{def} for the studied example is found to be 18 Ω.

Curves have been truncated where i_{rd} passes through zero (nearly the instant of arc extinguishing).

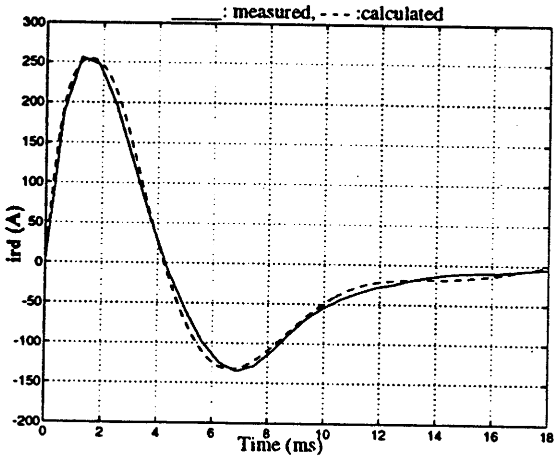

Fig. 11: residual current of the faulty feeder (ird) Comparison between measured data (solid line) and calculated data (dashed line)

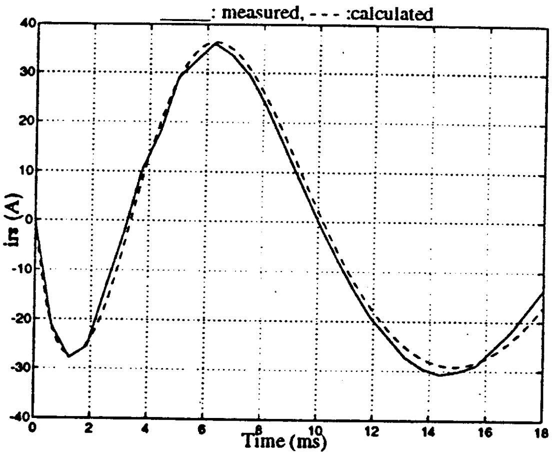

Fig. 12: residual current of a healthy feeder (irs) Comparison between measured data (solid line) and calculated data (dashed line)

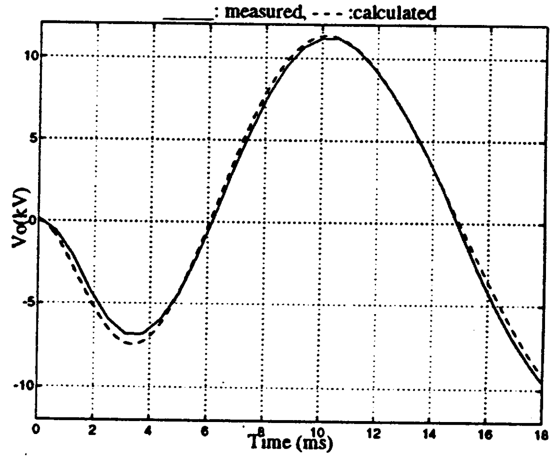

Fig. 13: zero sequence voltage at busbar (V_o) Comparison between measured data (solid line) and calculated data (dashed line)

According to the theory of linear systems, the signals contain terms of the form $A\sqrt{2}.e^{\alpha.t}.\cos(2.\pi.f.t+\varphi)$

Their characteristics are given by Tables 1 to 3.

f (Hz)	α (s^{-1})	A (A)	φ (rad)
50	0	17	6.0
96	-294	622	4.9
417	-833	33	4.7
0	-154	143	3.14

Table 1: transient characteristics of i_{rd}

f (Hz)	α (s^{-1})	A (A)	φ (rad)
50	0	29	4.7
96	-294	82	1.6
417	-833	3	1.5
0	-154	1.5	0

Table 2: transient characteristics of i_{rs}

f (Hz)	α (s^{-1})	A (V)	φ (rad)
50	0	11260	3.12
96	-294	14960	5.86
417	-833	142	5.9
0	-154	2534	3.14

Table 3: transient characteristics of V_o

4. CONCLUSION AND PROSPECTS:

A simple equivalent circuit to study earth-fault transient (in the frequency range from 0 to 1 KHz) in resonant-grounded distribution power networks has been presented.

The model is validated by comparison with recorded faults in a real distribution network (20 kV, 50Hz) of Electricité De France. This network is fitted with equipments for transient measurements. Sufficient informations about both the fault and the network are available to use recorded data for model validation.
It is remarkable that a quite simple model can efficiently represent transient ground faults (in the frequency range of interest) in real distribution systems which are often complex (multiple feeders, many connected cables and overhead lines, great number of loads).

Since the most important simplification is based on the assumption that the serial impedances of the lines can be neglected with respect to the shunt impedances, the tendency of decreasing average length of feeders (by multiplying HV/MV substations in French networks) is favourable to the accuracy of the model for ground fault transient analysis.

The model requires few parameters of the network.

The major advantage of the single-phase circuit is to provide an efficient and easy calculation of any zero sequence currents and voltages of the network. The transient current through the neutral impedance, the transient voltages to ground of both the faultless phases and of the faulty phase can also be obtained.

The next step should be to study the influence of model parameters on the characteristics of the transient (natural frequencies-dampings-amplitudes-phases). It is possible to try to establish analytical relations.
Informations contained in the earth-fault transient could be used to improve the reliability of protection devices and to get informations about faults in the network.
The knowledge acquired on earth-fault transient in compensated networks will enable to get more precise equipment specification. Validation tests of equipments are also concerned.

REFERENCES:

[1] H. Pundt,
Untersuchung der Ausgleichsvorgange bei Erdsschluβ in Energieversorgungsnetzen Energietechnik, 15 Jg, Heft 10, Oktober 1965.

[2] T. Lobos,
Transiente Vorgange bei Erdschlüssen in Mittelspannungsnetzen, Archiv fur Elektrotechnik 57 (1975) p. 205-214.

[3] V.P. Schwetz,
Ausgleichsstrome beim Erdscluβ im geloschten Netz Elektrizitatsswirstchaft, Jg. 79, (1980), Heft 22.

[4] E.I., Anderson,
L'amortissement des surtensions dans les réseaux M.T. pendant les défauts monopolaires, HM/71-04791 EIA/SD, July 1982.

[5] L.E. Dudarev, I.V. Voloshev,
Analysis of transients in networks with ungrounded neutral
Elektricestvo, April 1990, N°.4, p. 61.

[6] L. Berthet, O. Grob
Protection of feeder bays in rural HV/MV substations, RGE N° 1/91 - January 1991.

[7] M. Clément, D. Daniel, J. Bergeal
Developements in MV neutral control at Electricité de France, CIRED '91.

[8] J. Bergeal, L. Berthet, O. Grob,
P. Bertrand, B. Lacroix, Single-phase faults on compensated neutral medium voltage networks, CIRED '93.

[9] M. Clément, L. Berthet
How to reduce long interruptions: maintaining the supply during a MV single-phase fault,. PQA '94.

[10] C. Greiveldinger, F. Habozit, B. Hyon,
J-L Javerzac, New power quality contracts in France, PQA '94.

[11] D. Griffel, Y. Harmand, J. Bergeal, M. Clément
New technics for neutral earthing in MV networks, RGE N° 11/94, December 1994.

[12] G. Laturnus,
EDF GDF Services policy regarding power supply quality in rural distribution, RGE N°1, 1991.

[13] E. Loos,
Inserting electric network in the environment: the State/EDF protocol, RGE N°4, 1994.