TRANSIENT BEHAVIOUR OF AN URBAN MEDIUM VOLTAGE CABLE NETWORK

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Abstract - Interruptions in a cable network caused by earth faults and short circuits generate fast transients spreading out and stressing various nodes. Using the EMTP a prelooking power system checking and planing was investigated on the base of an actual urban 20 kV network. Parameters are the the exactness of the generated network, the fault distance, the arc resistance and the network configuration. Peak values, relaxation time and other waveform characteristics were discussed.

1. Introduction

In the last ten years more and more modern medium voltage distribution systems use Polyethylene (PE) or cross-linked Plolyethylene (XLPE) cables to provide substations and consumers with electrical energy. These type of cables as well used in urban as in rural areas are known for their high service reliability. Nevertheless there are interruptions of supply mainly caused by earth faults and short circuits. Local statistics show that about 60% to 70% of these faults base on mechanical damages of cables for example caused by digging works. But also short circuits initiallized by water trees are a well known problem in this field.

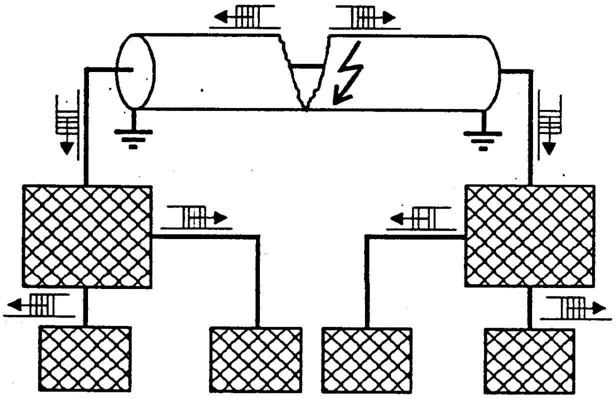

Fig.1 Schematic of a network with one fault

Fast transients, generated by the short voltage collapse, spread out in the network and may lead to a local stress (Fig.1). Therefore it is important to verify these transients, closely connected to the question of the exactness of the model network and the fault distance. In addition it must be taken in account that the fault simulation itself and the network configuration in general influences the results essentially.

The aim of the whole work on this field is a prelooking power system checking and planing by using the EMTP (Electro Magnetic Transient Program) based on a number of detail investigations. The origin was a topic case of a damage in an urban medium voltage cable network years ago and the assumption of a possible relation between this fault and a critical stress in the network nodes.

For the evaluation of the voltage stress in a power system the actual amplitudes as well as the frequency content in the network nodes are important. Including higher frequencies of some kilohertz this transients can damage voltage and current transformers. An other essential parameter is the relaxation time of the transient oscillations, which gives the extent for the stress duration.

2. Measurements of a simulated earth fault

Basic investigations on this subject deal with the local simulation of an earth fault (Fig.2) by doing measurements in a simple test setup. The aim of this part of investigations is to get knowledge of the transient behaviour at the location of the fault, especially the parameter for the voltage collapsing time. The simplicity of the setup allows a correlation to the travelling wave theory and can be checked with the EMTP.

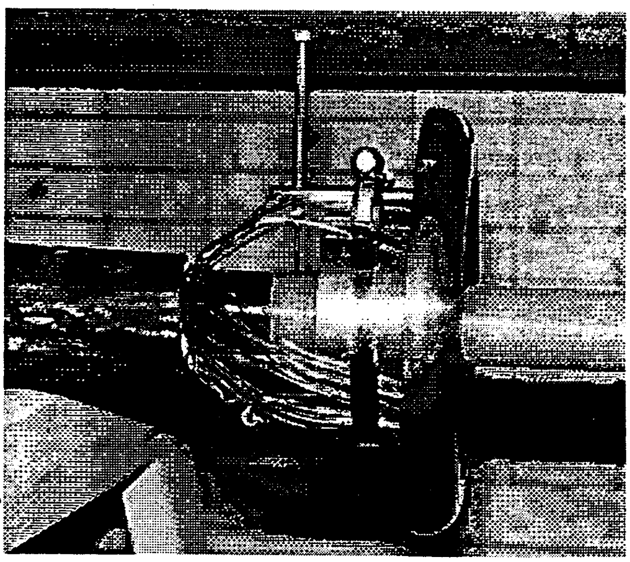

Fig.2 Local stress of the insulation by a needle

At the end of a 45 m single phase medium voltage cable the insulation was reduced by pressing a needle into the dielectric material (PE) between inner conductor and screen. The remaining insulation of about 0,5 mm was stressed by rising the voltage until the breakdown was initialized. A proved measuring technique is adapted and used in the test setup expecting very short voltage collapsing times in the range of less than 100 ns.

The measurement results are shown in Fig.3 and correspond very good to an EMTP simulation of the test setup. The average voltage collapsing time is measured with 75 ns, the propagation rate of 1,74 E8 m/s agrees to the length of the test cable. The high frequency oscillations superimposing the collapsing time (Fig.3a,b) are caused by the high voltage measurement circuit and can be removed by mathematical filters (Fig.3c). The relaxation time of the setup takes 22μs (Fig.3d). Using the reflection coefficient at the fault and the attenuation of the cable the arc resistance can be estimated with 1,3 ohm.

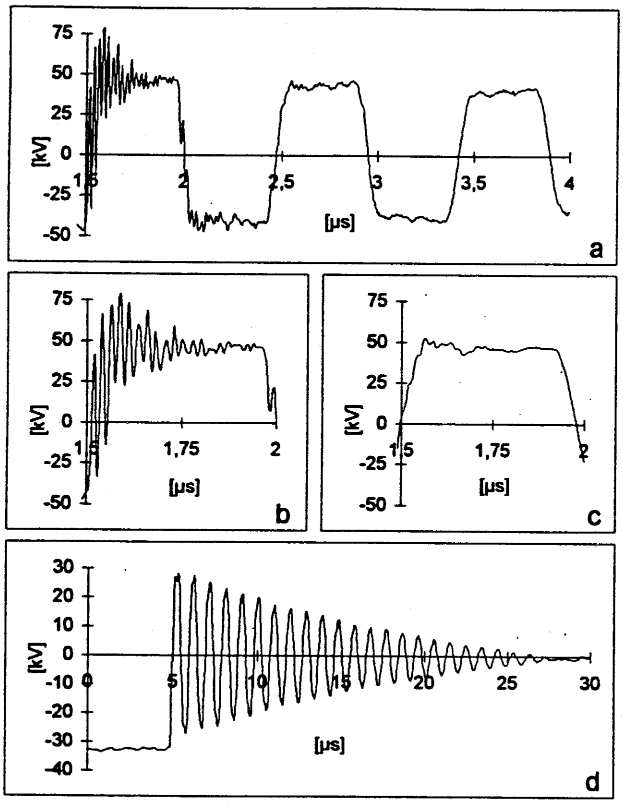

Fig.3 Measurement results of voltage collapse

3. Urban network of a 20 kV power system

For the numerical simulations the structure of a part of the working 20 kV power system run by the Graz Utility "Die Grazer Stadtwerke AG - Strom" is taken (Fig.4). In difference to the actual supply system all oil-paper-insulated cables were replaced by polyethylene cables for the following calculations. This rapid voltage collapse mentioned above leads to a stronger stress in the network components and so to a more interesting situation in case of a fault.

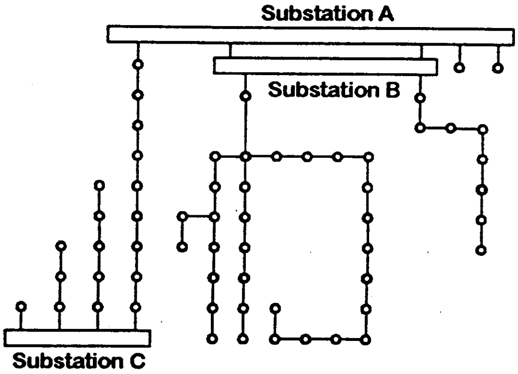

Fig.4 Schematic structure of 20 kV urban power system

This network part consists of 3 indoor switching substations (A, B, C) including 4 busbar sections (open-type) with 5 incomming supply transformers and 89 local step-down substations for the regional supply. The whole network length is 25982 m and consists of 65 cable segments with varying length between 1708 m and 59 m. In average the busbar length is about 14 m each. 21 voltage or current transformers are situated in this network part.

4. Model network simplification

Starting with a complete and in detail modeled transient power network this chapter shows a step by step reduction of network modeling.

Equal to all networks are the charging unit and the switching unit (time-varying resistance), which simulates the time behaviour of the fault.
For the simulation of the voltage collapse the whole network is charged to the peak value of the steady-state condition. This is possible because transient waves may be superimposed to this conditions. The presented results refer to the 100% value (1 p.u.).

Based on the actual urban power system of chapter 3 a complete transient network (Network A) for the EMTP with one fault location (Fault) was generated. Therefore all busbars had to be analysed in detail to determine average surge impedances and representative transient network elements (e.g. overcurrent relays). The so converted network consists of 357 nodes, 281 linear Pi-elements representing the busbars, 14489 elements of distributed lines representing the cable segments (28 ohm, 1,74 E8 m/s) and 7 non linear elements for lightning arrestors (Fig.5a and Fig.6a).
At the first step (Network B) all "little" stations (step-down substations) are reduced to their impuls capacitance conected to the cables, Pi-elements are removed at this stations (Fig.6b). A typical average value for the impulse capacitance is 2,3 nF/station.

Additionally in the second step (Network C) at all indoor switching substations (Substation A, B, C) the used Pi-elements are replaced by distributed lines (Fig.5b). For their surge impedance an average value of 210 ohm with 2,99 E8 m/s is taken. Busbars with an actual length < 0,8 m are neglected at all.

Finally for Network D all substation are reduced to their representative impulse capacitance without distributed lines in the stations (Fig.5c and Fig.6b). The remaining network consists of distributed lines only for the cables, all transformes combined in one impulse capacitance at each substation (Substation A 1,9 nF, Substation B 1,7 nF and 0,13 nF, Substation C 3,1 nF).

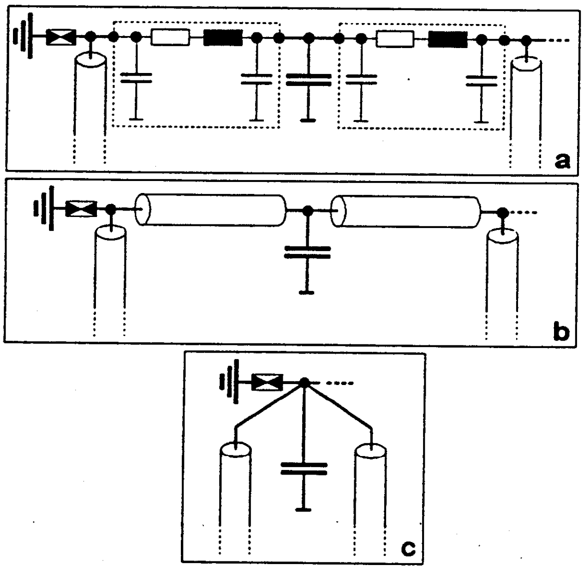

Fig.5 Schematic of the network reduction in the swiching substations

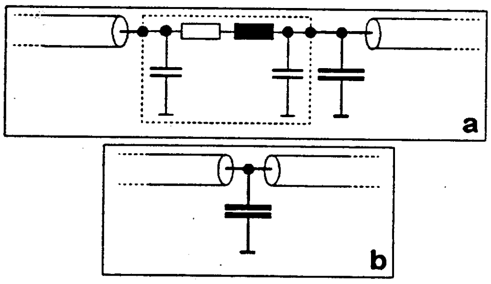

Fig.6 Schematic of the network reduction in the step-down substations

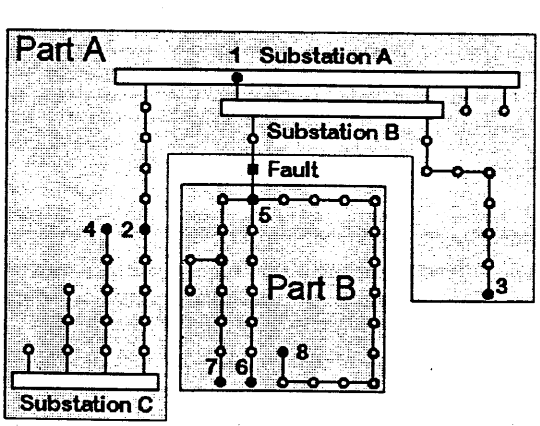

Fig.7 Schematic network (Part A and B with 8 nodes)

The schematic network divided into two parts (A, B) by the fault node is shown in Fig.7. Two representative network nodes (Node 1, Node 8) in each part are chosen to show the difference in their oscillation freqencies as well as the influence of the reduction steps (Fig.8).

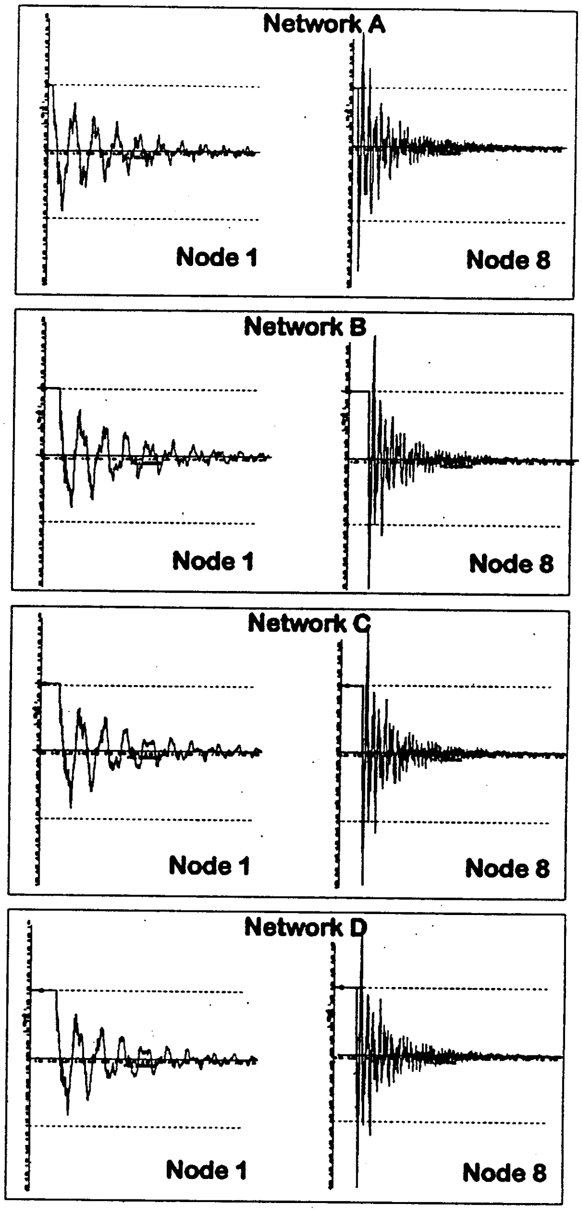

Fig.8 Calculation results of the model network simplification (Node 1, Node 8)

Characteristic parameters of all networks are shown in Fig.9. "U" represents the maximum/minimum peak after the voltage collapse, "Δt" defines the voltage collapsing time (100% to 0%), "τ" the relaxation time and "f" the dominant frequency of the damped oscillation.

Amplitude and relaxation time versus fault distance for the model network simplifications (A, B, C, D) are shown in Fig.10.

An increasing of the node distance to the fault location causes an increasing of the peak to peak values and also an icreasing of the relaxation time. Network nodes far away from the fault are stressed higher than nodes close to the fault.

Network A					
Node	dist.	Û	Δt	τ	f
	[km]	[p.u.]	[μs]	[ms]	[kHz]
4	11,0	0,92/-1,10	54	1,61	3,1
3	6,7	0,67/-1,03	13	1,40	3,0
2	5,5	0,92/-1,07	50	1,17	3,1
1	3,1	0,73/-0,90	72	1,20	3,0
Fault	0,0	0,16/-0,14	62	0,36	2,5
5	0,6	0,70/-056	20	0,68	10,6
6	2,1	0,93/-0,85	4	0,80	10,5
7	2,2	0,90/-0,97	9	0,79	10,4
8	3,8	1,75/-1,88	2	0,79	10,5

Network B					
Node	dist.	Û	Δt	τ	f
	[km]	[p.u.]	[μs]	[ms]	[kHz]
4	11,0	1,37/-1,27	15	1,39	3,0
3	6,7	1,00/-0,97	13	1,65	2,9
2	5,5	0,82/-1,00	51	1,24	3,0
1	3,1	0,66/-0,78	57	0,96	2,9
Fault	0,0	0,18/-0,13	60	0,32	2,8
5	0,6	0,57/-0,61	19	0,43	10,0
6	2,1	0,62/-0,88	5	0,68	9,1
7	2,2	1,06/-1,06	8	0,64	9,5
8	3,8	1,85/-1,98	2	0,67	11,1

Network C					
Node	dist.	Û	Δt	τ	f
	[km]	[p.u.]	[μs]	[ms]	[kHz]
4	11,0	1,22/-1,55	14	1,13	3,0
3	6,7	0,93/-1,03	12	1,60	3,0
2	5,5	0,93/-1,12	69	1,00	2,9
1	3,1	0,65/-0,87	57	1,00	2,9
Fault	0,0	0,20/-0,10	54	0,29	2,9
5	0,6	0,61/-0,63	19	0,60	9,6
6	2,1	0,70/-0,83	4	0,80	9,1
7	2,2	1,18/-1,10	7	0,73	9,4
8	3,8	1,90/-1,98	1	0,67	10,0

Network D					
Node	dist.	Û	Δt	τ	f
	[km]	[p.u.]	[μs]	[ms]	[kHz]
4	11,0	1,20/-1,62	16	1,20	2,9
3	6,7	0,90/-0,98	12	1,53	2,9
2	5,5	0,92/-1,08	68	1,00	2,9
1	3,1	0,62/-0,84	58	1,00	2,9
Fault	0,0	0,18/-0,12	55	0,32	2,8
5	0,6	0,60/-0,64	20	0,53	10,0
6	2,1	0,73/-0,80	5	0,87	9,1
7	2,2	1,18/-1,10	7	0,80	9,4
8	3,8	1,90/-2,00	1	0,60	11,1

Fig.9 Characteristic parameters of the transients

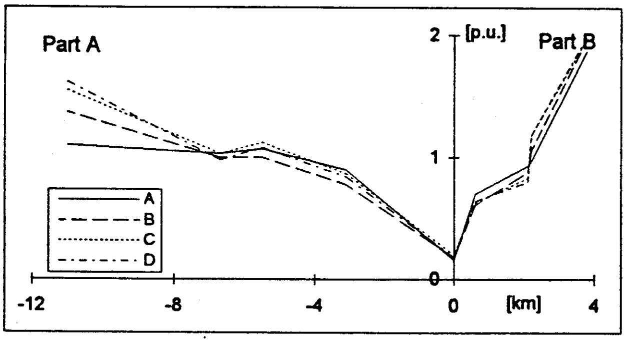

Fig.10a Amplitude versus fault distance

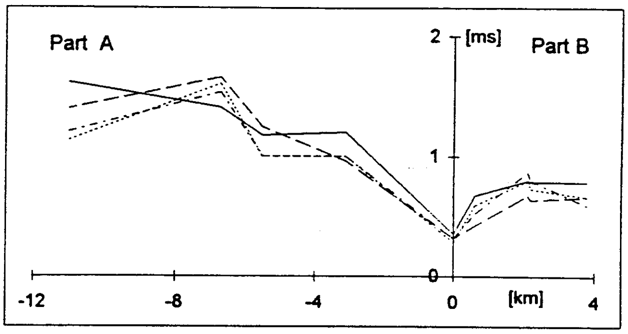

Fig.10b Relaxation time versus fault distance

Extremely different frequency behaviour of the two network parts have been discovered. Part A oscillates with a dominant frequency of about 3 kHz and Part B with a dominant frequency of about 10 kHz. Every node belonging to one part oscillates with the same frequency depending on the network structure.

5. Time step variation

In correlation to the measured fault behaviour two types of voltage collapsing models have been used. One is an "ordinary switch" in addition with a linear or non-linear resistor for the arc resistor and the other one is a "time-varying resistance".

The time-varying resistance was generated out of seven steps, until it reaches the value of the arc resistance (1,3 ohm) in a defined characteristic.

The ordinary switch results in an enormous reduction of the CPU-time, but one restriction is its dependence on the time step, which forces the lower limit of the line length. The used one closes in 70 ns.

For the actual model simulations no essential difference between these two switches have been discovered (Fig.11).

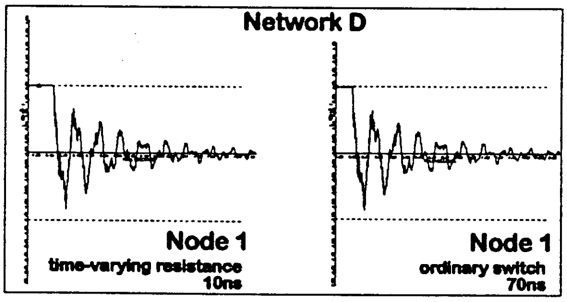

Fig.11 Calculation results of different time steps

6. Fault location variation

To get knowledge of the influence of the fault location on the transient behaviour in the network 4 earth faults are simulated. The location of the faults and calculated nodes are shown in Fig.12. Representative transients are given in Fig.13 for two nodes. The dependency of the distance between fault location and node location for 5 nodes are summerized in Fig.14 with peak values and relaxation times.

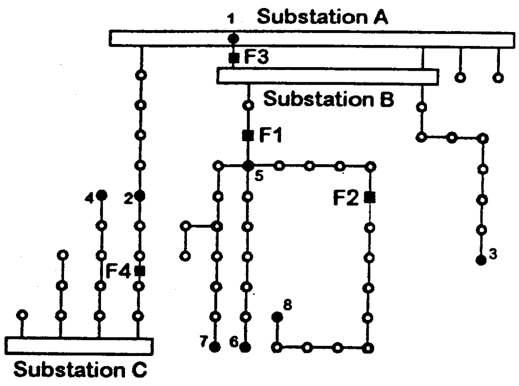

Fig.12 Schematic network with 4 fault locations

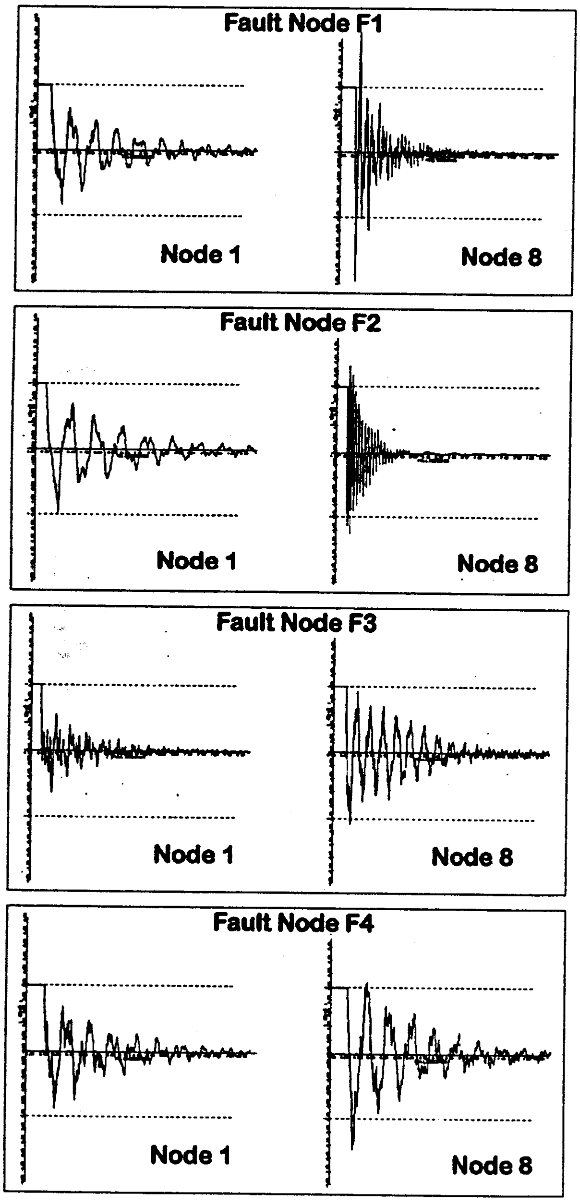

Fig.13 Calculation results of the fault location variation

A close relationship between frequency behaviour of the network part and the location of the fault can be found. In the situation "Fault Node F2" a very high frequency and a short relaxation time in "Node 8" is remarkable.

As shown in Fig.14 far away network nodes are stressed higher than node close to the fault location in general.

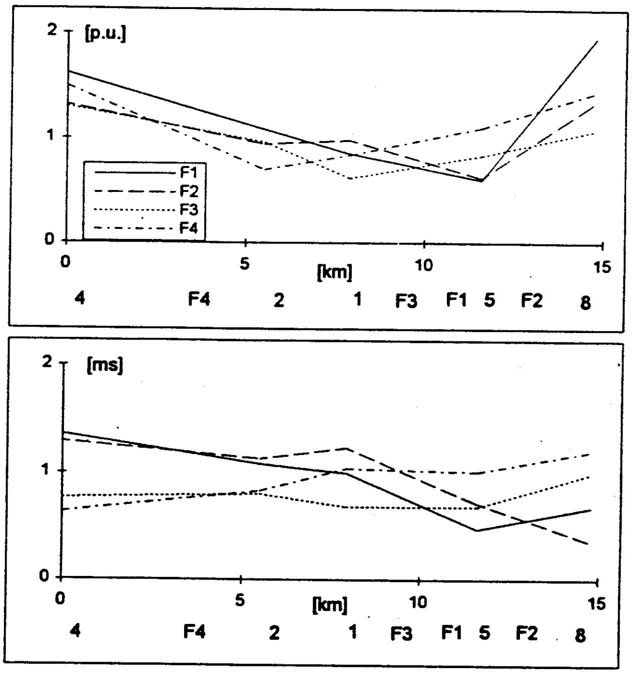

Fig.14 Amplitude and relaxation time versus node distance

7. Arc resistance variation

The local fault simulation with ist arc resistance has an essential influence to the transient behaviour of the network nodes. Therefore a variation of 4 different arc resistances (1,5, 1,0, 0,5 and 0,2 ohm) are chosen to evaluate their influence on the calculated results. The calculations are done with network D. The transient voltages are shown in Fig.15 and two representative parameters are given in Fig.16.

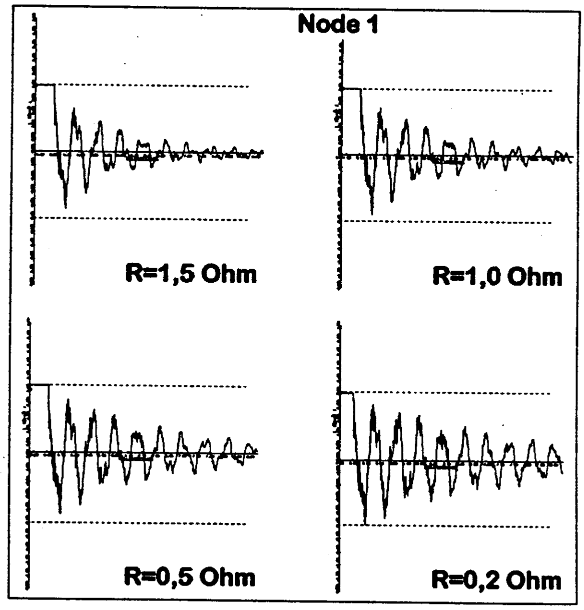

Fig.15a Calculation results of the arc resistance variation Node 1

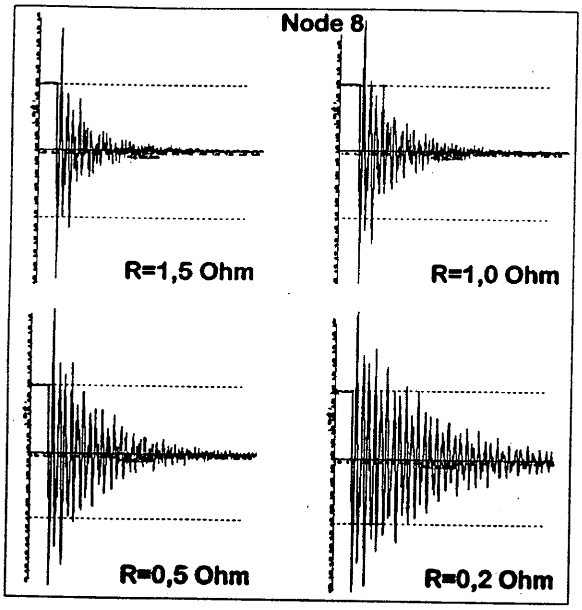

Fig.15b Calculation results of the arc resistance variation Node 8

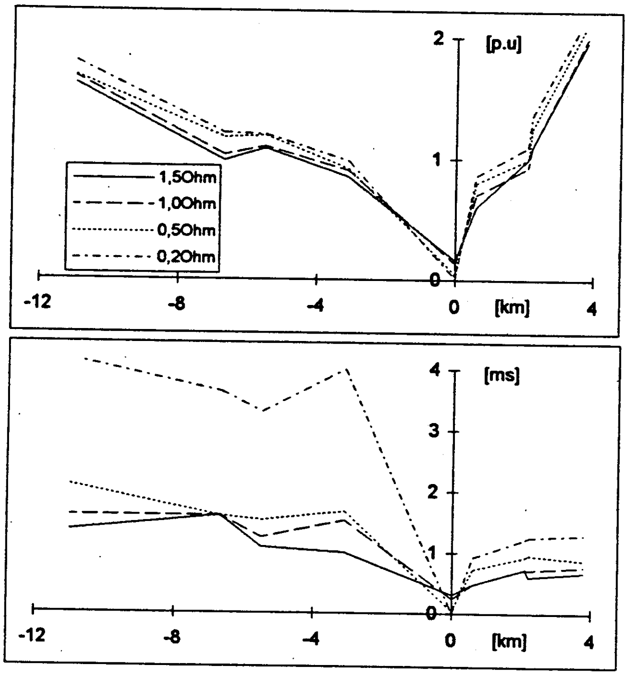

Fig.16 Amplitude and relaxation time versus arc resistance

A decreasing of the arc resistance causes an increasing of the peak to peak values in the observed nodes as well as an increasing of the relaxation times.

8. Power system variation

The circuit state is not a constant one in a working power system. Expecially an urban one has many different circuit states depending on the supply requirements. Mostly one typical circuit state will taken as representative for the evaluation of the transient behaviour in the system by simulation methodes. Therefore investigations are still going on varying the circuit state by connecting or disconnecting network branches. Also short and long branches as well as capacitive load influences the transient behaviour of the network.

9. Summary

A number of model network simplifications, fault location variations and arc resistance variations are compared to evaluate the transient behaviour in representative network nodes. Based on measurements for the voltage collapse time at the fault location many numerical calculations of an actual urban 20 kV power system are carried out. The investigations are continued varying the branches of the model network to find general characteristics for a prelooking power system checking and planing. The results of the above mentioned investigations are summerized as followed:

- Detail modeling of urban substations including all small busbars are not neccessary.
- Network configuration, cable length and load capacitance have essential influence to the calculated transients.
- An earth fault causes fast transients in all network nodes.
- The transient behaviour of the network will be divided into two parts by the fault node.
- The dependence of the transient behaviour of each part is confirmed by fault location variation.
- The arc resistance has an influence on the peak to peak values and on the relaxation times.

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