A Real-time Prediction Procedure of the State of an Electrical Distribution System

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Abstract: – An innovative digital procedure for real-time prediction of the state of an electrical distribution system is described. The method can promptly identify any change in the impedance values of distribution networks. When changes are slow, diagnostic processes will be carried out, whereas when very quick changes occur protection processes will be activated. The diagnostic process can be usefully adopted to schedule effective, economic maintenance. The proposed method is able to detect a number of anomalies, even though this paper is especially targeted at the check of phase-to-phase insulation levels.

Key-Words: Protection of distribution systems, Prediction of electric network state, Power systems diagnostics and maintenance.

1 Introduction

Diagnostics and protection can be considered as unique aspects of the same problem and can be better separated taking into account the change rapidity in a number of parameters in the monitored system [3], [4], [5], [6], [7]. A sensitive parameter that may be usefully observed to control a network insulation level is a resistance (or a conductance).

In order to identify a network state, that is to establish the conditions of all its components, the classical approach of the basic circuit theory is adopted in this paper, assuming as unknowns the network impedances (parameters) instead of the electrical quantities (voltages and currents). In this case, node voltages must be measured in a number of network nodes in real time [1], [2]. The measurement systems are applied only to some nodes of the networks (named "accessible nodes" in the following). In these conditions, with reference to real systems, unknowns are usually more than known quantities. The measured electrical quantities are those linked to particular stimuli applied to the network that do not affect the 50 Hz power frequency (and the related harmonics). The equations obtained with only one stimulation (named "test" in the following) are not usually enough to compute all the unknowns in the problem. Stimulations must therefore be repeated a number of times until the number of linear independent equations obtained is equal to the number of unknowns. An implemented algorithm processes the information received and computes the actual network impedances allowing therefore to establish the actual state of the system.

2 The basic mathematical model

Let us consider a mesh network with $n=N+1$ nodes. The l number of maximum possible connections between all N independent nodes is:

$$l \leq \frac{N \cdot (N-1)}{2} \tag{1}$$

Let us suppose to stimulate the network with a current source of known amplitude and frequency placed between the k node ($k=1, 2,.... N$) and the $N+1$ node (ground). By applying the first Kirchhoff's rule to the N independent nodes the following matrix relation will be obtained:

$$\begin{vmatrix} \sum I_1 \\ \sum I_2 \\ \dots \\ \sum I_N \end{vmatrix} = 0 \tag{2}$$

The (2) matrix relation requires that the sum of incoming and outgoing currents at each of the N independent nodes must be zero. In the extended form relations (2) can be written as:

$$\begin{vmatrix} Y_{11} & . & . & . & Y_{1N} \\ : & Y_{22} & & & : \\ : & & . & & : \\ : & & & . & : \\ Y_{N1} & . & . & . & Y_{NN} \end{vmatrix} \cdot \begin{vmatrix} V_1 \\ V_2 \\ : \\ : \\ V_N \end{vmatrix} = 0 \qquad (3)$$

The (3) matrix relation can be written in compact form as:

$$[Y]\cdot[V] = 0 \qquad (4)$$

In the following, relation (4) will be used to compute both node voltages and network admittances.

3 Detection of phase-to-phase anomalies

For simplicity reasons, the examined three-phase network is represented by only the two phases involved in the anomaly, namely a phase-to-phase insulation level reduction. In the following, three main case-studies are analyzed:

1) Localization of a fault on a resistive three-phase network.

2) Localization of a fault on a resistive-inductive three-phase network.

3) Ascertaining the presence of a fault in a resistive three-phase network with the FFT (Fast Fourier Transform).

The tool used to simulate the different case-studies was the Simulink of the MatLab code.

A. Resistive network

The test network examined is shown in Fig. 1 with the r-phase sub-network to the left and to the right the s-phase sub-network (similar to the r-phase sub-network).

The phase-to-phase fault is simulated by means of the R_{rs} resistance inserted between the node 4 (1.4 in the figure) of the r-phase and the node 4 (2.4 in the figure) of the s-phase. The R_{rs} resistance is the parameter sensitive to the insulation level between phases. This parameter was supposed to be very high (i.e. 1MΩ) under normal conditions, and very low in case of a fault (i.e. 1Ω).

Intermediate values identify the insulation level of the system, which can also point to a degradation in case the R_{rs} resistance values are insufficient to guaranty the necessary safety conditions. With proper network stimulation and a post-processing procedure using voltages associated to stimuli (measured at the accessible nodes), changes affecting any component can be detected, as well as any phase-to-phase faults.

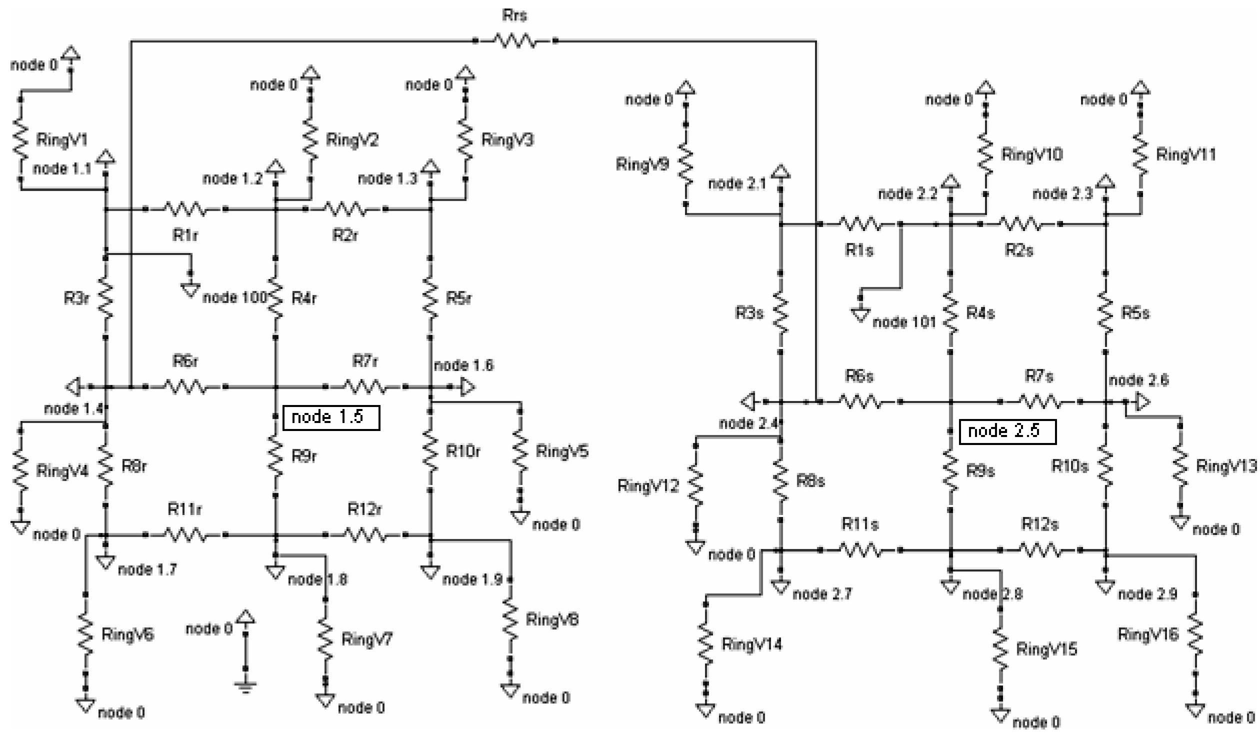

Fig. 1. Resistive test network; r-phase and s-phase are connected by the R_{rs} fault resistance.

With reference to the network in Fig. 1, the proposed method was first tested considering the system to be in normal condition (R_{rs}=1MΩ). Network branch admittances, voltages and fault resistance are reported in the following vector supplied by the simulator:

```
xr =

  1.0e+003 *

  Columns 1 through 4

   0.00100000000000   0.00100000000012   0.00099999999999   0.00099999999989

  Columns 5 through 8

   0.00100000000020   0.00100000000003   0.00099999999983   0.00099999999999

  Columns 9 through 12

   0.00099999999985   0.00100000000003   0.00100000000006   0.00099999999988

  Columns 13 through 15

   0.12499685689607   1.25003143103926   0.00000000100000
```

The above *xr* vector reports the values of the 12 branch admittances in the first 12 columns, and in the next two columns the voltages at “non accessible” nodes (1.5 and 2.5 in Fig. 1) computed using two different stimulation tests. In the last column of the vector the value of the R_{rs} resistance is reported assuming the system in normal conditions (R_{rs} =1 MΩ, that means G_{rs} = 1 μS).

Now let us suppose to have a phase-to-phase fault caused by an R_{rs} resistance of 1 Ω. After a first simulation similarly to the previous case, the voltage values computed for the non-accessible nodes are assumed to be acquired by a measurement system and supplied to the implemented procedure based on relation (4).

The obtained results are reported in the next vector:

```
xr =

  1.0e+003 *

  Columns 1 through 4

   0.00100000000154   0.00099999999201   0.00099999999466   0.00100000001497

  Columns 5 through 8

   0.00099999998530   0.00099999998575   0.00099999999803   0.00099999999902

  Columns 9 through 12

   0.00099999998418   0.00100000000210   0.00100000000497   0.00099999999025

  Columns 13 through 15

   0.12498958911046   1.25010410889731   0.00100000050967
```

The 13th column shows the computed fault resistance, which actually corresponds to the real fault resistance 1Ω (G=1S). The simulation results show that the fault was correctly localized.

B. Resistive-inductive network

The tests reported in section *A* were repeated for the resistive-inductive network shown in Fig. 2.

In this case, the values of a few significant branch admittances of the network and the R_{rs} fault resistance (R15r) are reported in the following vector:

```
L10r = 0.00100000007264
R11r = 1.00000005270631
L11r = 9.999999867484073e-004
R12r = 1.00000005378393
L12r = 0.00100000001492
R15r = 9.959455834229010e+005
```

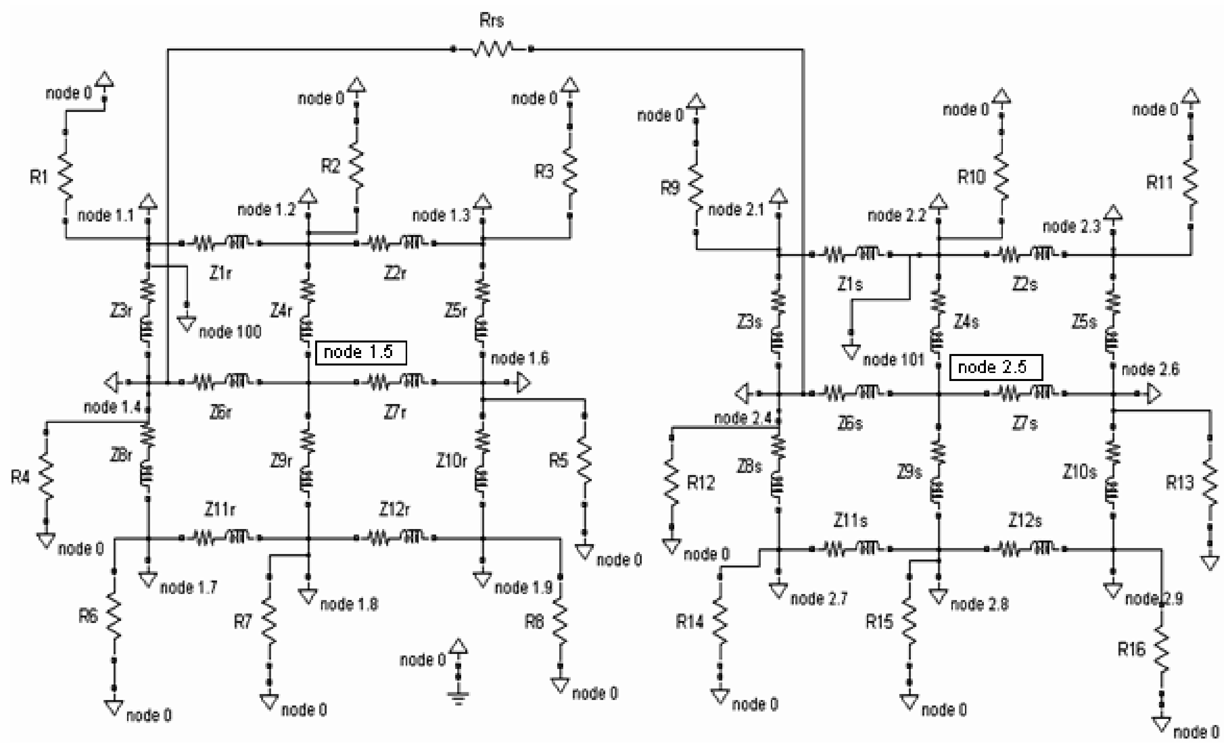

Fig. 2. Resistive-inductive test network with r-phase and s-phase connected by the R_{rs} fault resistance.

The model implemented in the above case is more complicated than the former one since a phasor representation in the complex space is to be used. Moreover, in this case the subsequent computed voltages of non-accessible nodes are assumed to be acquired by a measurement system and supplied to the implemented procedure based on relation (4). The obtained results are reported in the next vector:

```
R12r = 1.00000001542055

L12r = 0.00100000002763

R15r = 1.00005941183832
```

The final value shows that also in this case the fault resistance is correctly estimated and localized.

C. A resistive network analyzed with the FFT

This last simulation was performed to test whether the procedure was able to ascertain the presence of a phase-to-phase fault in a three-phase network independently from the fault location. The procedure uses the FFT applied to the stimulus-signal spectra present in each single-phase network associated to the three-phase system. In order to verify this capability, two current stimuli with different frequencies are injected respectively into the r-phase and s-phase. The network analyzed is shown in Fig.1; the frequencies of the stimuli (signals) are 20 Hz and 40 Hz respectively. In this case a qualitative analysis is adopted because only the presence of a fault was to be ascertained. In the former simulation performed, a value of 1MΩ was assumed for the R_{rs} resistance (normal condition) while in the latter simulation a value of 1Ω was assumed for the same R_{rs} resistance (fault condition). Simulation results reported in Figs. 3 and 4 show that in the former case only the 20Hz signal is present in the r-phase sub-network, while in the latter case both 20 and 40Hz signals are present in the same sub-network.

Figs. 3 and 4 show that the insulation level between phases in a distribution network can be easily established if stimuli simultaneously injected into each single-phase of the three-phase system have different frequencies from each other.

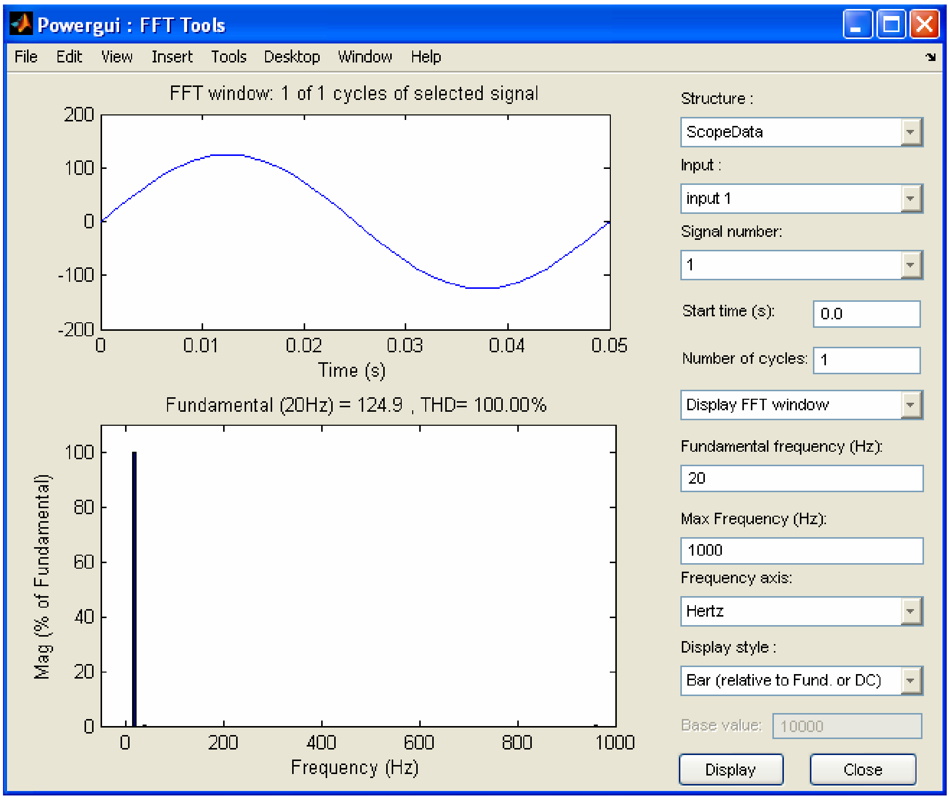

Fig. 3. In the absence of a phase-to-phase fault only a 20 Hz signal is present.

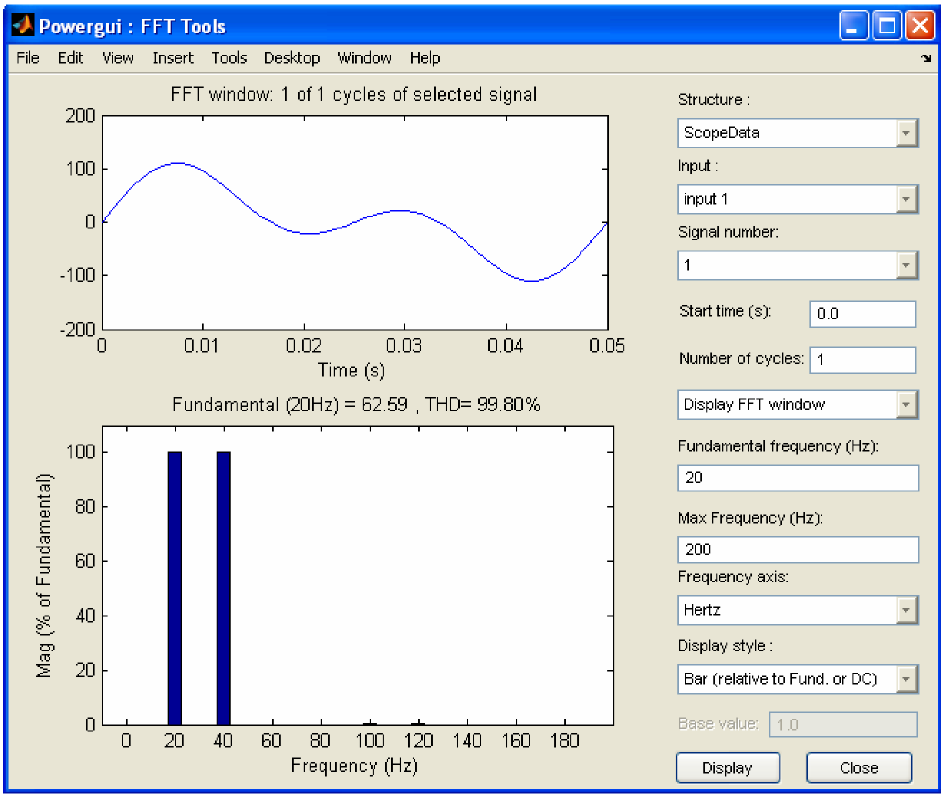

Fig. 4. In the presence of a phase-to-phase fault both 20 and 40 Hz signals are present.

4 Conclusions

The proposed method can perform both diagnostics and protection of an electrical distribution system at the same time and, if compared to other current procedures, has a number of advantages, such as:

- Real time monitoring of network branch impedances.
- An effective detection of both phase-to-ground and phase-to-phase faults.
- Optimal scheduling of network maintenance.

The research work performed outlines innovative concepts in the diagnostics and protection of electrical power systems, suggesting new capabilities that can be implemented on a centralized supervision system for monitoring electrical distribution networks.

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