A real-time monitoring and diagnostic procedure for electrical distribution networks

Francesco Muzi, and Luigi Passacantando

***Abstract*—** A monitoring and diagnostic approach based on the circuit theory is presented. The proposed procedure allows a continuous control of all network branch admittances, including conductances associated to insulation levels between phases and phase-to-ground. The detection of possible anomalies can be suitably used to activate proper protection or maintenance procedures. The monitoring process allows to prevent sudden, large-scale supply interruptions which might give rise to very serious problems in the operation of secondary networks. In addition, corrective maintenance of an electrical system can be usefully scheduled subdividing the network into different zones in order to achieve both considerable maintenance savings and remarkable quality improvements in distribution services. Finally, the possibility to promptly eliminate small anomalies can avoid more serious damages involving large network areas. An extensive simulation work was performed to test the proposed algorithm and results, mainly concerning the diagnosis of insulation between phases, are reported and discussed.

***Keywords*—** Protection of distribution systems, prediction of electric network state, power systems diagnostics and maintenance.

I. Introduction

DISTRIBUTION systems are getting more and more complex in order to satisfy the increasing quality demands from customers. As a matter of fact, the management of complex systems, under either normal operation or critical conditions, requires more and more improvements in monitoring, control and diagnostic systems.

This necessary evolution started from early protection systems of electromechanical type, moved to electronic systems and then to the present, mainly digital systems, where both electronic hardware and specific software are used. Therefore today the new challenges to be faced concern hardware improvement but also a constant development of new, applicative, powerful software [1], [2], [9], [10], [11].

Manuscript received February 18, 2008.

F. Muzi and L. Passacantando are with the Department of Electrical Engineering and Computer Science, University of L'Aquila, Piazzale Pontieri, 1, 67100 L'Aquila, Italy (phone: +39-0862-434425; fax: +39-0862-434403; e-mail: muzi@ing.univaq.it).

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 the circuit theory network parameters (impedances and admittances) are usually assumed to be known quantities. This happen also in power flows computation where voltages and currents are calculated for all network nodes and branches, starting from the knowledge of external constraints (powers and voltages) and network admittances. The approach here proposed acts in the opposite way, since network parameters are assumed as the unknowns and some measured node-voltages and branch currents are assumed as the known quantities. The specific implemented algorithm allows a continuous computation of all network parameters, that is to say all branch admittances, phase-to-ground conductances and admittances between phases.

II. 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:

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

Let us suppose to stimulate the network with a current source of known amplitude (I_s) and frequency placed between the k node (k=$1, 2,\ldots N$) 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:

$$\begin{vmatrix} \sum I_1 \\ \sum I_2 \\ \ldots \\ \sum I_N \end{vmatrix} = 0 \qquad (2)$$

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

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

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

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

In the following, a method based on the (4) matrix equation is implemented that allows the computation of all the admittances present in the $[Y]$ matrix and also the unknown node voltages at the non-accessible nodes that correspond to a number of terms of the $[V]$ vector.

The basic concept behind the proposed method consists of stimulating the network with suitable signals, which have different frequency from the power frequency, at a certain node, while at the same time measuring the node voltages (voltage between node and ground) at a number of network nodes, also named accessible nodes. In order to obtain at each measurement cycle (test) n linear equations independent from the previous cycle but also from the n equation of the subsequent cycle, both the stimulated node and monitored nodes are changed without changing the number of the monitored nodes.

In order to better explain the method, a simple example based on the 4-node network shown in Fig. 1 is presented. Fig. 1 shows also the electrical quantities of the first measurement cycle.

After the application of the first Kirchhoff rule to each node of the network as shown in Fig. 1, the following relations will be obtained:

$$\begin{cases} node\ 1\ I_S^{'} = I_1^{'} + I_4^{'} \\ node\ 2\ I_1^{'} = I_2^{'} + I_{V1}^{'} \\ node\ 3\ I_3^{'} + I_2^{'} = I_{V3}^{'} \\ node\ 4\ I_4^{'} = I_{out}^{'} + I_3^{'} \end{cases} \qquad (5)$$

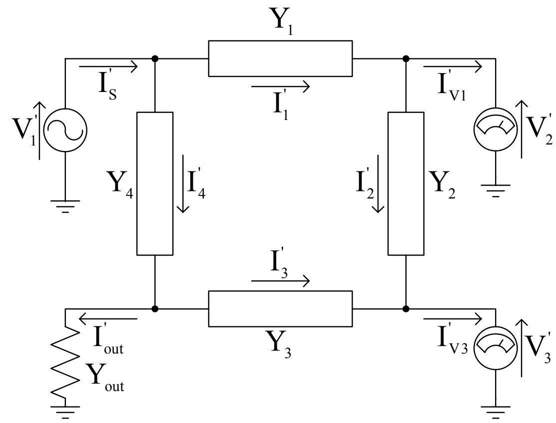

Fig. 1 first network stimulation

Equations (5) can be written in the explicit form as follows:

$$\begin{cases} I_S^{'} = \left(V_1^{'} - V_2^{'}\right) \cdot Y_1 + \left(V_1^{'} - V_4^{'}\right) \cdot Y_4 \\ \left(V_1^{'} - V_2^{'}\right) \cdot Y_1 = \left(V_2^{'} - V_3^{'}\right) \cdot Y_2 + V_1^{'} \cdot Y_{V1} \\ \left(V_4^{'} - V_3^{'}\right) \cdot Y_3 + \left(V_2^{'} - V_3^{'}\right) \cdot Y_2 = V_3^{'} \cdot Y_{V3} \\ \left(V_1^{'} - V_4^{'}\right) \cdot Y_4 = V_4^{'} \cdot Y_{out} + \left(V_4^{'} - V_3^{'}\right) \cdot Y_3 \end{cases} \qquad (6)$$

The $Y_{V1,V3}$ admittances of the (6) system are the internal admittances of the voltage sensors (which are known) and contribute to close the stimulus current circuit. Y_{out} allows to close the circuit of the stimulus current. The apexes above the voltage and currents refer to the first stimulation.

The (6) equation system can be written in the compact form as:

$$[Y] \cdot [V^{'}] + [I_S^{'}] = 0 \qquad (7)$$

In Fig. 1, the stimulated node is node 1 while the monitored nodes are 2 and 3 ($V_2^{'}, V_3^{'}$); the unknowns are Y_1, Y_2, Y_3, Y_4' and $V_4^{'}$. The quantity $V_1^{'}$, which is the voltage of the stimulated node, is assumed as known. The column vector $[I_S^{'}]$ is composed of zero values with the exception of the value corresponding to the stimulated node (namely, where $I_S^{'}$ is applied). System (7) exhibits 4 equations and 5 unknowns (Y_1, …,Y_4 and $V_4^{'}$) , therefore it does not admit one single solution. For this reason, a second stimulation is required where both stimulated and monitored nodes are changed, as shown in Fig. 2.

The subsequent application of the first Kirchhoff rule supplies the following relations:

$$\begin{cases} node\ 1\ I_1^{"} + I_4^{"} = I_{V1}^{"} \\ node\ 2\ I_2^{"} = I_1^{"} + I_{out}^{"} \\ node\ 3\ I_S^{"} = I_2^{"} + I_3^{"} \\ node\ 4\ I_3^{"} = I_4^{"} + I_{V4}^{"} \end{cases} \qquad (8)$$

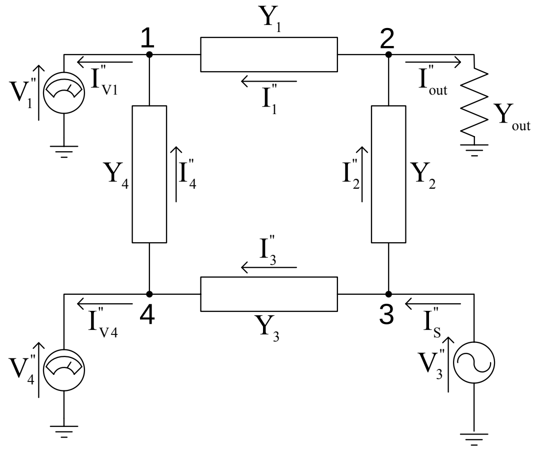

Fig. 2 second network stimulation

Equations (8) can be also written as:

$$\begin{cases} \left(V_2^{"} - V_1^{"}\right) \cdot Y_1 + \left(V_4^{"} - V_1^{"}\right) \cdot Y_4 = V_1^{"} \cdot Y_{V1} \\ \left(V_3^{"} - V_2^{"}\right) \cdot Y_2 = \left(V_2^{"} - V_1^{"}\right) \cdot Y_1 + V_2^{"} \cdot Y_{out} \\ I_S^{"} = \left(V_3^{"} - V_2^{"}\right) \cdot Y_2 + \left(V_3^{"} - V_4^{"}\right) \cdot Y_3 \\ \left(V_3^{"} - V_4^{"}\right) \cdot Y_3 = \left(V_4^{"} - V_1^{"}\right) \cdot Y_4 + V_4^{"} \cdot Y_{V4} \end{cases} \tag{9}$$

Moreover, in system (9) $Y_{V1,\ V4}$ correspond (to the internal admittances of the voltage sensors, which also means they are known.
In the compact form, system (9) can be written as:

$$[Y] \cdot [V^{"}] + [I_S^{"}] = 0 \tag{10}$$

Also in this case the column vector $[I_S^{"}]$ is composed of zero values except for the position corresponding to the stimulated node.
The unknowns of system (10) are $V_2^{"}$ and the four admittances Y_1, …, Y_4, which are assumed to be unchanged from those of the previous stimulation. The $V_3^{"}$ stimulated-node voltage is a known quantity. $V_{1,4}^{"}$ voltages are also known since they are measured. If systems (7) and (10) are merged together, the following equation system is obtained:

$$\begin{cases} I_S^{'} = \left(V_1^{'} - V_2^{'}\right) \cdot Y_1 + \left(V_1^{'} - V_4^{'}\right) \cdot Y_4 \\ \left(V_1^{'} - V_2^{'}\right) \cdot Y_1 = \left(V_2^{'} - V_3^{'}\right) \cdot Y_2 + V_1^{'} \cdot Y_{v1} \\ \left(V_4^{'} - V_3^{'}\right) \cdot Y_3 + \left(V_2^{'} - V_3^{'}\right) \cdot Y_2 = V_3^{'} \cdot Y_{V3} \\ \left(V_1^{'} - V_4^{'}\right) \cdot Y_4 = V_4^{'} \cdot Y_{out} + \left(V_4^{'} - V_3^{'}\right) \cdot Y_3 \\ \left(V_2^{"} - V_1^{"}\right) \cdot Y_1 + \left(V_4^{"} - V_1^{"}\right) \cdot Y_4 = V_1^{"} \cdot Y_{V1} \\ \left(V_3^{"} - V_2^{"}\right) \cdot Y_2 = \left(V_2^{"} - V_1^{"}\right) \cdot Y_1 + V_2^{"} \cdot Y_{out} \\ I_S^{"} = \left(V_3^{"} - V_2^{"}\right) \cdot Y_2 + \left(V_3^{"} - V_4^{"}\right) \cdot Y_3 \\ \left(V_3^{"} - V_4^{"}\right) \cdot Y_3 = \left(V_4^{"} - V_1^{"}\right) \cdot Y_4 + V_4^{"} \cdot Y_{V4} \end{cases} \tag{11}$$

In compact form, system (11) can be written as:

$$\begin{cases} [Y] \cdot [V^{'}] + [I_S^{'}] = 0 \\ [Y] \cdot [V^{"}] + [I_S^{"}] = 0 \end{cases} \tag{12}$$

And finally:

$$[Y] \cdot [V] + [I_S] = 0 \tag{13}$$

System (13) exhibits 8 equations and 6 unknowns (Y_1, …, Y_4, $V_4^{'}$ and $V_2^{"}$); therefore, by eliminating the redundant linearly dependent equations, it admits a single solution.
In the following the method is generalized to a network with N+1 nodes.
Let us consider the (3) matrix system assuming that all elements of the $[Y]$ matrix are unknown. In general also *r* elements of the $[V]$ vector are unknown, with $r < m$ where *m* is the total number of unknowns.
If different stimulations (tests) are performed in a network with *N* nodes plus the ground node, the number of equations and the number of unknowns increase in accordance to TABLE I.

TABLE I
THE NUMBER OF EQUATIONS AND UNKNOWNS VS. THE NUMBER OF PERFORMED TESTS

n° test	n° equations.	n° Y unknowns	n° V unknowns
1	N	$N \cdot N$	R
2	N	0	R
3	N	0	R
P_{th}	N	0	R
Total P	$N \cdot P$	$N \cdot N$	$P \cdot r$

In accordance to Tab. I, the computation procedure supplies a single solution if the number of equations is equal to the number of unknowns:

$$N \cdot P = N \cdot N + P \cdot r \tag{6}$$

As a consequence, the necessary *P* tests to be performed are:

$$P = \frac{N \cdot N}{N - r} \qquad \text{with } r < N \tag{7}$$

The best condition occurs when all node voltages are measured; in this case the following relation can be obtained:

$$P = \frac{N \cdot N}{N} = N \tag{8}$$

The worst condition occurs when the non-monitored node voltages are equal to *N-1*; in this case equation (7) becomes:

$$P = \frac{N \cdot N}{N - (N - 1)} = N \cdot N \qquad (9)$$

III. THE DETECTION OF PHASE-TO-PHASE ANOMALIES

The proposed method allows the detection of a number of anomalies, among which only a reduction of the insulation level between two phases of a three-phase system is examined in the following. As shown in Fig. 3, in this case a Y_{ins} finite admittance was inserted, which is the element to be monitored in order to control the insulation level between the examined phases.

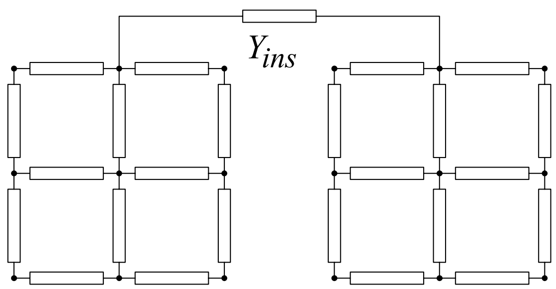

Fig. 3 a system circuit adopted to monitor the insulation level between two phases

The phase-to-phase fault (or anomaly) is simulated by means of an 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 a 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 levels 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.

The implemented computer program was developed using the MatLab's Simulink tool [8].

With reference to the network in Fig. 4, the proposed algorithm was first tested considering the system to be in normal condition (R_{rs}=1MΩ).

For simplicity reasons, in Fig. 4 a pure resistive network, which may be the case of an LV cable grid, is examined. In the same figure the r-phase sub-network is placed to the left and the s-phase sub-network to the right. Of course, the two networks are similar to each other.

Network branch admittances, voltages and fault resistances are reported in the following vector supplied by the implemented simulator.

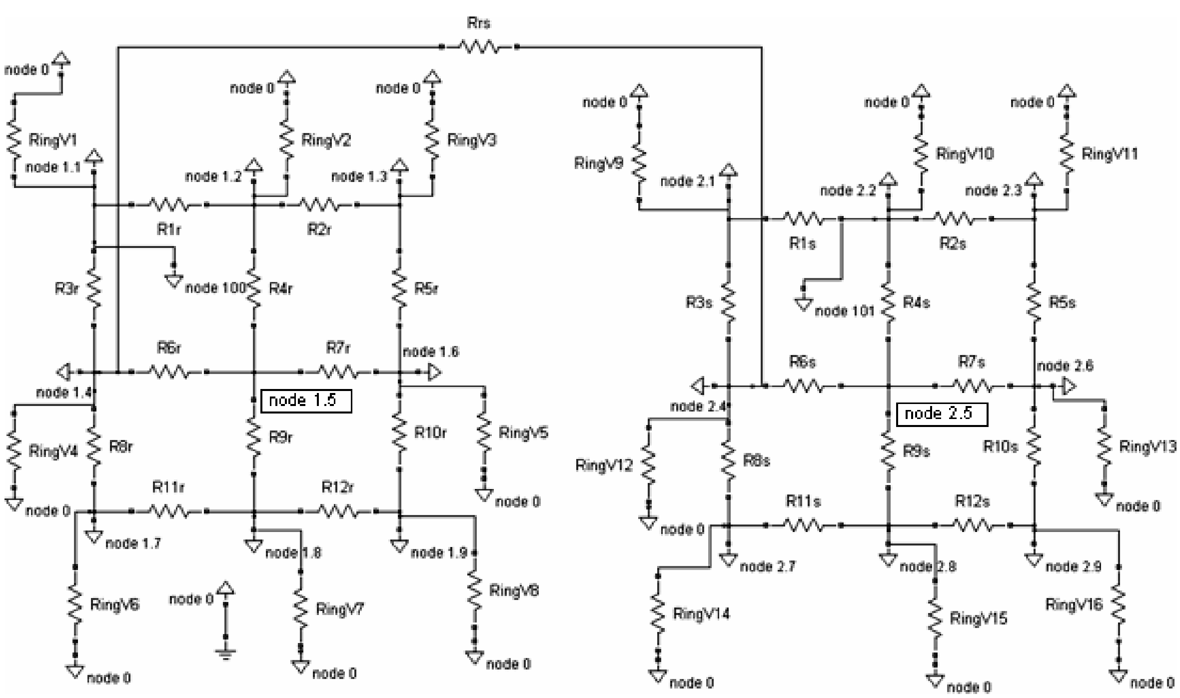

Fig 4 resistive test network; r-phase and s-phase are connected by the R_{rs} fault resistance

```
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" node 5 (1.5 and 2.5 in the figure) 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 to be in normal conditions (R_{rs} =1 MΩ = 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 performed as in 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
```

In the 15th column the computed fault resistance is reported, which actually corresponds to the real fault resistance of *1Ω=1S*. The simulation results show that the fault was correctly localized.

IV. CONCLUSIONS

The presented digital procedure allows a real time monitoring of the state of each parameter in a secondary network. The method is based on the circuit theory, which was properly modified in order to evaluate the state of the different network parameters. The monitoring and diagnostic process can be usefully adopted to schedule effective, economical maintenance but also to improve security and quality in network management. Special attention was paid to the monitoring of the network insulation level both to ground and between phases. As an example, the method was applied to detect a phase-to-phase fault. The possibilities offered by the implemented algorithm and the results obtained from the simulation study are presented and investigated. The proposed diagnostic strategy can be suitably enacted from a remote supervision and control center.

REFERENCES

[1] C. Bartoletti, D. D'Amico, F. Muzi, G. Sacerdoti, "From instrument to intelligent systems," Series in Sensors and Microsystems, World Scientific Publishing - 2000 - Singapore.

[2] C. Bartoletti, F. Muzi, G. Sacerdoti, "Intelligent monitoring in electrical power systems," IMEKO 2000 16th World Congress 25-28 September 2000, Wien Austria.

[3] G. Fazio, V. Lauropoli, F. Muzi, G. Sacerdoti, "Variable-window algorithm for ultra-high-speed distance protection," IEEE Trans. on Power Delivery - Vol. n. 18, NO. 2, April 2003.

[4] F. Muzi "Preventive maintenance optimization to improve quality in electrical power systems," Ninth ISSAT Int. Conf. on Reliability and Quality in Design – August 7-9, 2003, Honolulu, Hawaii, USA.

[5] C. Bartoletti, M. Desiderio, D. Di Carlo, G. Fazio, F. Muzi, G. Sacerdoti, F. Salvatori, "Vibro-acoustic techniques to diagnose power transformers," IEEE Trans. on Power Delivery, Vol. 19, NO. 1, Jan. 2004.

[6] C. Bartoletti, G. Fazio, M. Marinelli, F. Muzi, G. Sacerdoti, "Electromagnetic and acoustic emissions to diagnose complex electrical and mechanical structures," IEEE-PES General Meeting - June 6-10, 2004, Denver, Colorado, USA.

[7] M. Cerullo, G. Fazio, M. Fabbri, F. Muzi, G. Sacerdoti, "Acoustic signal processing to diagnose transiting electric-trains," IEEE Trans. on Intelligent Transportation Systems, Vol. 6, No. 2 June 2005.

[8] Mat-lab, Rulebook, Vers. 7, 2006, The MathWorks, Inc. South Natick, MA 01760, USA.

[9] R. H. Díaz, M. T. López, "Fault location techniques for electrical distribution," Proceedings of the Conference on European Power and Energy Systems, 2005.

[10] T. S. Sidhu, M. Dadash Zadeh, M. Vijayasarathi, "Modeling and simulation of computational techniques used in numerical protective relays", Proceedings of the 18th conference on Proceedings of the 18th IASTED International Conference on Modelling and Simulation, Montreal, Canada, 2007.

[11] Y. Liao, "Fault location for single-circuit line based on bus-impedance matrix utilizing voltage measurements," IEEE Transactions on Power Delivery, Volume 22, Issue 4, Oct. 2007

F. Muzi is a professor of Power Systems at the University of L'Aquila, Italy, where he has also the scientific responsibility for the Power System Group. His main research interests concern power quality in distribution systems, power system reliability and power systems diagnostics and protection. In these fields, he authored or co-authored about 100 scientific papers. On the subject of Power Systems, he has also few patents and is a technical reviewer of a number of international journals.

L. Passacantando was born in L'Aquila, Italy, in 1983. He received is first level degree in electronic engineering from the University of L'Aquila, Italy, in 2005 with a thesis on diagnostics of electrical distribution systems. Currently, he is working on power system protection and diagnostics at the Department of Electrical Engineering and Computer Science of the University of L'Aquila.