A diagnostic method for microgrids and distributed generation based on the parameter state estimate

Francesco Muzi

Abstract**—** The great increase in the diffusion of microgrids and Distributed Generation (DG) requires a substantial evolution of dedicated supervision and control systems, in order to assure high levels of flexibility, automation and reliability. With special reference to the operation of these systems, the paper describes a diagnostic methodology based on the circuit theory, properly adapted to compute the state of the grid parameters. Subsequently the changes in these parameters are used for diagnostic purposes, achieving effective, timely, and economical scheduled maintenance of the monitored microgrid. The described method is successful in detecting a number of anomalies, even though the paper is especially targeted at diagnosing high impedance faults. The simulation results obtained from a study example showed high accuracy in the network parameter estimation.

Keywords**—** Power systems diagnostics, microgrids and distributed generation, maintenance.

I. INTRODUCTION

DISTRIBUTION grids active in the presence of distributed generation require the development of new technologies in a number of fields, namely:

- Interconnection devices and linked control logic.
- Protection systems.
- Forecasting systems.
- Telecommunication systems.
- On-line voltage control.
- Load management techniques.
- Real-time management of power flows in strongly interconnected structures.
- Emergency management.
- Monitoring and diagnostics of the distribution system.

In this scenario, state observation techniques can be effectively used for suitable real-time diagnostics and a consequent improvement in the reliability and efficiency of electrical systems [9], [10].

In order to identify the state of a network establishing the conditions of all its components the basic circuit theory approaches [11], [12], were adopted, evaluating network impedances (parameters) instead of electrical quantities (voltages and currents) that were assumed as unknowns. In this case, node voltages must be measured in a number of network nodes in real time [1], [2].

The measurement systems were applied only to some nodes of the networks (named “accessible nodes” in the following). 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). Unfortunately, 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 algorithm was then implemented to process the information received and compute the actual network impedances, allowing therefore to establish the actual state of the system.

The method herein illustrated was developed for mesh networks but can be used in radial networks as well. Distribution networks consist of nodes, where more branches converge, and connections between nodes (branches) established with cables and aerial lines. For line representation, it is convenient to adopt well-known simplified equivalent circuits. The presence of such derived devices as loads does not interfere with the developed method. The diagnostic procedure can be used to check normally operating power grids.

II. THE 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:

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

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

Manuscript received March 08, 2007; Revised received June 30, 2007

F. Muzi is 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).

By applying the first Kirchhoff's rule to the N independent nodes the following matrix relation will be obtained:

$$[Y]\cdot[V]=0 \tag{2}$$

The Y_{ii} ($i=1,\dots,N$) terms in the main diagonal of the *[Y]* matrix correspond to the "proper admittances" obtained from the sum of the admittances converging to the *i-th* node, which means:

$$Y_{ii}=y_{i1}+y_{i2}+\dots+y_{iN}=\sum_{k=1}^{N}y_{ik} \tag{3}$$

where $i=1,\dots,N$.

The Y_{ij} terms, (with $i=1,\dots,N$ and $j=1,\dots,N$), are defined as "mutual admittances". A generic mutual admittance corresponds to the total admittance between nodes i and j with changed sign, that is:

$$Y_{ij}=-y_{ij} \tag{4}$$

Of course, if there are no admittances between nodes i and j, the mutual admittance [2] is nil:

$$Y_{ij}=-y_{ij}=0$$

A final observation on the admittance matrix is summarized by the condition $Y_{ij}=Y_{ji}=-y_{ij}$, which means that the admittance matrix is symmetric. As a consequence, a drastic simplification in the computation occurs when mutual terms are nil.

As regards the proposed method, in order to compute the value of all unknown admittances (or impedances) it is important to establish the g number of tests to be performed. Let us define the following conditions:

$$l=\frac{N\cdot(N-1)}{2} \text{ (maximum network branches);} \tag{5}$$

np = number of accessible nodes (where node voltages are measured);

g = number of tests performed;

N-np = number of non-accessible nodes. (6)

After performing g tests, the number of unknowns will be:

$$\textit{no. of unknowns}=l+g\cdot(N-np). \tag{7}$$

After g tests the number of the obtained equations is:

$$\textit{no. of equations}=g\cdot N. \tag{8}$$

With g tests, the equations system exhibits linearly independent solutions if:

$$\textit{no. of equations}=\textit{no. of unknowns}. \tag{9}$$

This means that relations (7) and (8) must be equal, therefore:

$$\begin{aligned}&l+g\cdot(N-np)=gN\\&l-g\cdot np=-gN+gN\\&l=g\cdot np\\&g=\frac{l}{np}\end{aligned} \tag{10}$$

By substituting relation (5) in the last of the (10) equations, the following equation can be written:

$$g=\frac{N(N-1)}{2}\cdot\frac{1}{np} \tag{11}$$

In relation (11) g is the number of tests necessary to characterize a network with N independent nodes, np peripheral measurement points and all nodes connected with l maximum number of branches.

III. THE ALGORITHM IMPLEMENTED

Based on the above method, a diagnostic algorithm as shown Fig. 1 was implemented. The algorithm is based on MATLAB features and tools.

A correct application of the method requires the following preliminary information:

- The technical characteristics of all network components including lines and distributed generators.

- All operational data of the main relays installed for different kinds of faults.

- Data coming from a continuous measurement process performed on a number of the network nodes.

- Synchronization of the performed measurements.

In order to detect the anomaly location, computed network parameters are compared with the corresponding values of a table that was provided by off line calculations assuming the network is in optimal operating conditions.

The proposed diagnostic process allows to identify the network state when the characteristics of the parameters do not reveal changes during time intervals shorter than the information acquisition process; in addition, also the characteristics of the channels connecting sources and sensors must remain in the same state detected at the time of the previous calibration procedure. Occasionally during the monitoring phase network configuration can change suddenly, as with circuit breakers during open/close operations. The diagnosis can however be performed also in this situation, supposing the apparatus to be bi-stable (or, more generally, multi-stable). These cases will require, of course, more complex mathematical models.

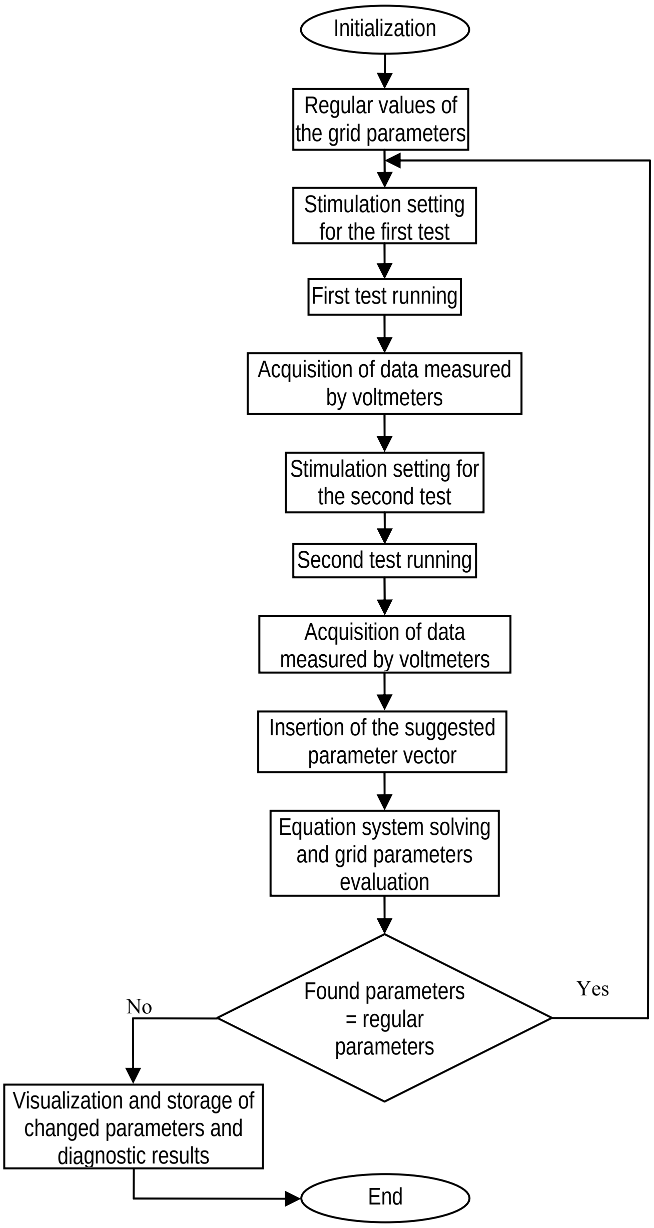

Fig. 1 the microgrid diagnostic algorithm implemented

IV. METHOD VALIDATION

In order to validate the method, the Simulink tool of the MATLAB code [8] was used, which allowed a virtual cabling of the network starting from the single components and then feeding the test network and acquiring node voltages at all points. In addition, numerical results can be downloaded into the MATLAB Work-Space where all possible off-line computations can be implemented using the data supplied by the simulation process.

A. Detection of a Phase-to-Ground Insulation Reduction

The method was first applied to test the case-study network built with the MATLAB code shown in Fig. 2.

The network impedances were assumed to be of an ohmic-inductive nature.

Numerical results were used to check the validity of the proposed model supposing the network to be in all three possible states (good, weak, faulted). Namely, the simulation results demonstrated that the diagnostic procedure can reveal any changes in the value of phase-to-ground and phase-to-phase admittances.

In order to eliminate repetitions, the performed validation procedure is better explained (step by step) in the following, more complex example.

B. Detection of a Phase-to-Phase Insulation Reduction

The study case concerns the localization of an anomaly in the resistive-inductive three-phase network shown in Fig. 3. For simplicity reasons, this network is represented by the only two phases involved in the insulation change, with the r-phase sub-network to the left and the s-phase sub-network to the right, with the two sub-networks being of course similar to each other. The phase-to-phase insulation reduction is simulated by means of the R_{rs} resistance inserted between node 4 (1.4 in the figure) of the r-phase and 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 a fault case (i.e. 1Ω).

Intermediate values identify the insulation level reduction of the system, which can also point to a degradation whenever R_{rs} resistance values are insufficient to guarantee the required insulation conditions.

With proper network stimulation and a post-processing procedure using voltages associated to stimuli as measured at accessible nodes, changes affecting any component can be detected, as well as any phase-to-phase faults.

With reference to the network in Fig. 3, the proposed method was preliminarily tested considering the system to be in normal condition (R_{rs}=1MΩ).

Afterwards, a phase-to-phase fault caused by an R_{rs} resistance of 1Ω was supposed to occur. After a first simulation similarly to the previous case, the voltage values computed for the non-accessible nodes were assumed to be acquired by a measurement system and supplied to the implemented procedure based on relation (2). In order to obtain a solution, two different stimulation tests were performed.

Also in this case the obtained simulation results demonstrated that the insulation level reduction was correctly identified.

Simulations can obviously be performed by means of different software, either commercial or from the open source world. Among these, the most powerful and complete are LabVIEW of National Instruments and MATLAB of MathWorks. The former allows a very efficient management of the signal acquisition procedure, whereas the latter supplies further analysis tools. In case also a signal acquisition procedure must be performed, the MATLAB code requires the toolbox Instrument Control. In any case, both software codes are programmable by the user to implement original data analysis algorithms. In this paper, the MATLAB code was adopted.

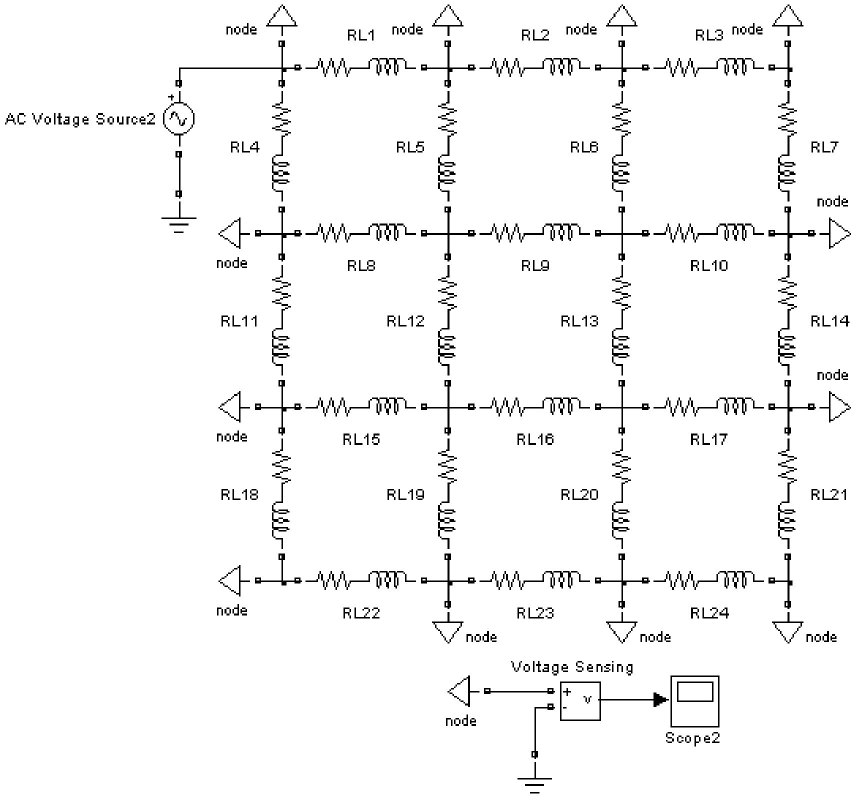

Fig. 2 model of the test network built with the MATLAB code in order to validate the procedure during a phase-to-ground insulation level change

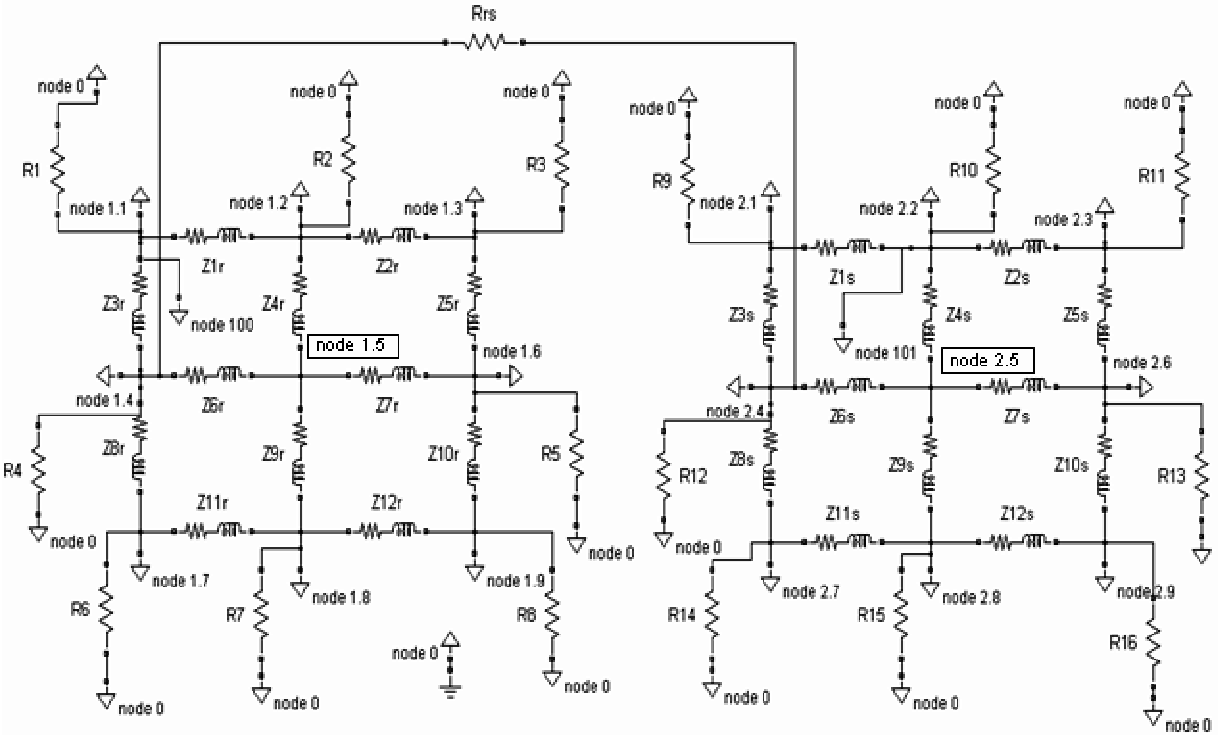

Fig. 3 resistive-inductive three-phase test network with r-phase and s-phase connected by the R_{rs} fault resistance

V CONCLUSIONS

The proposed diagnostic method for microgrids and DG offers the following advantages:

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

The method was based on the use of a properly designed stimulation, performed by applying a stimulus at one node of the network and at the same time registering the acquisitions of responses to the stimulus at a number of other nodes. For a continuous monitoring of the network, the procedure needs to be repeated permanently so as to detect any possible changes in the distribution system state. Whenever changes from the expected values are revealed in the network impedance calculations, an anomaly may be present in the system. The information is then used to forecast undesired events in the electrical monitored grid achieving therefore an effective scheduled preventive maintenance.

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] MATLAB, *Rulebook*, Vers. 7, 2006, The MathWorks, Inc. South Natick, MA 01760, USA.

[9] F. Muzi, C. Buccione, S. Mautone "A new architecture for systems supplying essential loads in the Italian High-Speed Railway (HSR)" WSEAS Transactions on Circuits and Systems, Issue 8, Volume 5, August 2006.

[10] C. Bartoletti, G. Fazio, F. Muzi, S. Ricci, G. Sacerdoti "Diagnostics of Electric Power Components: an improvement on signal discrimination," WSEAS Transactions on circuits and systems, Issue 7, Volume 4, July 2005.

[11] C. Giannì, S. Pennisi, G. Scotti, A. Trifiletti "The universal circuit simulator: a mixed- signal approach to n-port network and impedance synthesis," IEEE Transactions on circuits and systems - vol. 54, no. 10, October 2007

[12] I. Mayergoyz, W. Lawson Basic, (1996) *"Electric Circuit Theory"*, Elsevier Publishing.

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 also has a number of patents and is a technical reviewer for various international journals.