European Association for the
Development of Renewable Energies, Environment
and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality
(ICREPQ'12)
Santiago de Compostela (Spain), 28th to 30th March, 2012

Modeling of equivalent grids through vulnerability studies for analysis of power systems with wind producers

C.B.M. Oliveira[1], J.T.de Oliveira[1] and M.F.de Medeiros Jr.[2]

[1] Department of Computing and Automation Engineering
UFRN, Federal University of Rio Grande do Norte
Campus Universitário – Mirassol, Natal (Brazil)
Phone/Fax number:+0055 84 3215-3732, e-mail: **clovisbosco@yahoo.com.br**, **jtavares@ct.ufrn.br**.

[2] Department of Electrical Engineering
UFRN, Federal University of Rio Grande do Norte
Campus Universitário – Mirassol, Natal (Brazil)
Phone/Fax number:+0055 84 3215-3732, e-mail: **firmino@dca.ufrn.br** .

Key words

Wind farm, power systems, network equivalents, load flow.

1. Introduction

Initiatives investment in sustainable solutions in energy supply at low environmental and social costs stimulated the insertion of technologies based on renewable energy. Among the propositions, wind farms have demonstrated ability to meet expectations. The Technology Platform for Wind Energy in Europe shows that 25% of energy demand in Europe, or a total of 300 GW will be supplied by wind by 2030 [1].

These facts are strong indications to pay attention to good market prospects of wind generation for the next year which, in turn, open doors to this research area. However, in order to make technically possible the integration of wind power with conventional sources of energy prior studies of the behavior of the system against disturbances are required, by means of models and efficient computational tools that allow both to systematize the relationship between different agents.

The principle of the process of system analysis, conducted by producer, is based on technical data provided by the concessionaire. This work aims to propose a simplified model for networks that allows the user agent requesting connection, requires knowledge only of internal network data, ie, the network portion of interest for analysis of steady-state voltage variations caused by connection. Thus, within the context of the studies required in the analysis of the impacts of stress caused by an independent producer, the investigation can be carried out without the need for information on the external network [2].

The model proposed to simplify network identifies the internal network, external network and the buses from the boundary, from a vulnerability study of the network, considering unknown the injected powers at the boundary nodes, i.e., modeling them as slack buses. The models for network simplification are implemented in the Newton-Raphson power flow algorithm and a hybrid alternative is achieved, using and Gauss Seidel Z_{bus} and Power Summation load flow methods. This way, it is intended to provide resources to assist in the systematization of the relations between the accessed company and the producer.

The set of methods proposed in this paper aims to present solutions to problems that involve directly accessed industry and producers. Both parties have responsibilities regarding the secure connection of new power injections. In Brazil, these responsibilities are defined by the National System Operator, ensuring the supply of consumers with quality services in accordance with legislation [3]. At first, attributed to the accessed company is the duty to supply information about your internal network, including the equivalent external to the producer can do basic required studies. Adding value to this concept, the model for simplified network being enough to the producer, allows the company to provide data only of its internal network, through a vulnerability study, standardizing the first contact between the involved agents.

2. Equivalent Grid

Studies directed to assess the electrical behavior before changes in operating state of power systems require appropriate mathematical modeling. In general, is represented in detail only the interest portion of the system, adopting techniques to reduce network. Methods for calculation of equivalent external seek to represent, on a limited, part of the system under review, to allow studies in detail only the network of interest, internal network in Fig. 1, minimizing computational costs and simplifying the analysis of the case study [4],[5],[6] and [7].

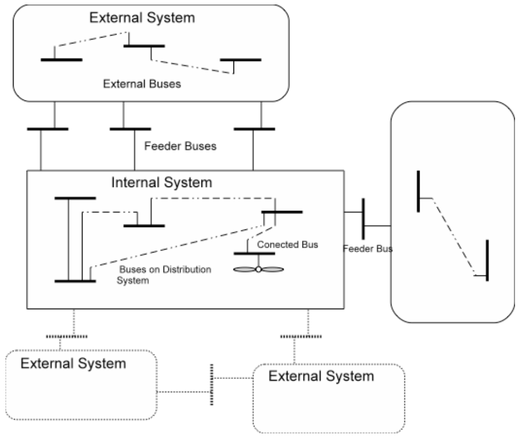

Fig. 1. Power System with distribution grid and feeder buses detached.

Among the techniques for calculation of equivalent external, can be found in the literature several methods such as REI or the method of linearization. However, the most widely tested and recognized correspond to the Ward method and its variants. The methods of Ward eliminate the buses on the external network, by applying Gauss elimination, and differ from each other by treatment equivalent power injections at boundary buses.

3. Equivalent Grid Proposed

The equivalent network models incorporate electrical characteristics based on operating states and data pre-established network of external network, ie, an analysis of the impact of stress in some buses, caused by the connection of independent producers, requires information from all the system, even though through equivalent. In addition, it should be noted that the principle of these models are based on equivalent external networks that may have its status changed or its topology, and thus need update its equivalent. Through simplification technique for network proposes to define a preliminary assessment of the impacts of tension provoked by the injection of power, only with data from internal and boundary bus, or only the data of interest to the buses. Thus, in analyzing the impacts of stress promoted by an independent producer, an investigation will be possible without the need for information on the external network.

The proposal involves three steps: construction of matrix Z_{bus}, classification and modeling of the buses, external grid modeling and computing load flow with multislack grid.

A. Construction of Matrix Z_{bus}

The main simplifications necessary to establish the basis of a method for short circuit calculation consist in synchronous machines modeling by a f.e.m. behind a reactance, and loads representation by constant current. Alternatively, depending on the model applicable to the loads, these can be represented by impedances. Thus, the system becomes linear and the superposition principal can be applied to determine voltages and currents after the short circuit, according to scheme of Fig. 2 scheme.

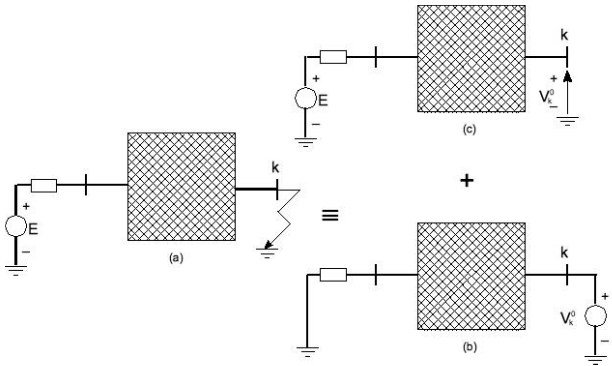

Fig. 2. Scheme of the superposition principal to determine the voltages and currents after short-circuit.

The relationship between voltages and currents for the grid of Fig. 1c, is given by:

$$\begin{bmatrix} I_1 \\ \cdots \\ -I_k^f \\ \cdots \\ I_n \end{bmatrix} = \begin{bmatrix} & & \\ & Y & \\ & & \end{bmatrix} \begin{bmatrix} \Delta V_1 \\ \cdots \\ -\Delta V_k^0 \\ \cdots \\ \Delta V_n \end{bmatrix} \tag{1}$$

If the current sources representative of loads are considered turned off, results in (2).

$$I_i = \begin{cases} 0, i \neq k \\ -I_k^f, i = k \end{cases} \tag{2}$$

Dividing all the *n* equations by $-I_k^f$ and inverting the *Y* bus matrix, one obtains:

$$\begin{bmatrix} -\Delta V_1 / I_k^f \\ \vdots \\ V_k^0 / I_k^f \\ \vdots \\ -\Delta V_n / I_k^f \end{bmatrix} = \begin{bmatrix} Z_{11} & \cdots & Z_{1k} & \cdots & Z_{1n} \\ Z_{21} & \cdots & Z_{2k} & \cdots & Z_{2n} \\ \vdots & & \vdots & & \vdots \\ Z_{k1} & \cdots & & \cdots & Z_{kn} \\ \vdots & & \vdots & & \vdots \\ Z_{n1} & \cdots & & \cdots & Z_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \end{bmatrix} \tag{3}$$

Thus, by equations (4) determine the elements of Z_{bus} matrix.

$$\begin{aligned} Z_{ik} &= -\frac{\Delta V_i}{I_k^f}, \forall i \neq k \\ Z_{kk} &= \frac{\Delta V_i}{I_k^f}, \forall i = k \end{aligned} \tag{4}$$

Thus, by Equations (4) determine the elements of Z_{bus} matrix from vulnerability data of grid, composed of voltage variation from three-phase short-circuit and the short circuit currents in buses *k*.

B. Classification and Modeling of Buses

Initially, the buses are defined eliminated, and eliminated non-border buses through analysis of voltage variations caused by short circuit in the connection bus and the rated power of producer through the parameter β (complex number), defined in this work. After this step, mount the new matrix Z_{bus} and compute the net current buses not eliminated. Table I show the criteria for classification buses.

$$\beta = \Delta V_{CC} \cdot \frac{P_{CC}}{P_{wind}} \tag{5}$$

Table I. – Classification buses by β parameters

[Situation]	[Buses classification]
$\beta\% \geq X\%$	Non-eliminated
$\beta\% \geq X\%$ and connection with one or more Non-eliminated Buses	Boundary / Non-eliminated
$\beta\% < X\%$ and without connection of Non-eliminated Buses	Eliminated

Models to the buses of the border as buses slack, since they contribute to the energy balance in the internal network, however despite the process of classification of the same buses restrict only those that have small changes in voltage, phases can not be considered constant or irrelevant variations. It is proposed to reduce the errors produced by this feature by adding the phases of pre-fault voltages at buses boundary phases of the parameter β, as it represents the changes in the short-circuit, considered a severe contingency.

C. Elimination of External Grid

Elements of matrix Z_{bus} represent the equivalent impedance seen by the buses and lines of systems, and the superposition principle the voltages correspond to sum of the contributions provided by each injection power at system. So, keep the same values of current net in the simple elimination of the elements related to the eliminated buses cause variations in the voltages on non-eliminated buses, including the boundary buses. The described technique above searches to attribute the contributions of the energetic balance on internal grid in the bounder buses.

Thus, to assess the impacts of produced by the connection of wind power producers is necessary to identify and include contributions in the injection power from the external network through the data base case, ie, without the independent producer. Thus, the matrix Equation (6) represents a system with the internal network I buses, boundary buses B and external buses E.

$$\begin{bmatrix} V_I \\ \vdots \\ V_B \\ \vdots \\ V_E \end{bmatrix} = \begin{bmatrix} Z_{II} & \cdots & Z_{IB} & \cdots & Z_{IE} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{BI} & \cdots & Z_{BB} & \cdots & Z_{BE} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{EI} & \cdots & Z_{EB} & \cdots & Z_{EE} \end{bmatrix} \begin{bmatrix} I_I \\ \vdots \\ I_B \\ \vdots \\ I_E \end{bmatrix} \tag{6}$$

Observing only equations from internal grid buses and bounder buses, it has obtained:

$$\begin{bmatrix} V_I \\ \vdots \\ V_B \end{bmatrix} = \begin{bmatrix} Z_{II} & \cdots & Z_{IB} & \cdots & Z_{IE} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{BI} & \cdots & Z_{BB} & \cdots & Z_{FE} \end{bmatrix} \begin{bmatrix} I_I \\ \vdots \\ I_B \\ \vdots \\ I_E \end{bmatrix} \tag{7}$$

Multiplying the Z_{bus} array elements of external grid to the current vector, it has obtained the vector ΔV.

$$\begin{bmatrix} V_I \\ \vdots \\ V_B \end{bmatrix} = \begin{bmatrix} Z_{II} & \cdots & Z_{IB} \\ \vdots & \ddots & \vdots \\ Z_{BI} & \cdots & Z_{BB} \end{bmatrix} \cdot \begin{bmatrix} I_I \\ \vdots \\ I_B \end{bmatrix} + \begin{bmatrix} \Delta V_I \\ \vdots \\ \Delta V_B \end{bmatrix} \tag{8}$$

$$\Delta V_I = Z_{IB+1} \cdot I_{B+1} + \cdots + Z_{IE} \cdot I_E \tag{9}$$

$$\Delta V_B = Z_{BB+1} \cdot I_{B+1} + \cdots + Z_{BE} \cdot I_E$$

Thus, from Equation (9) the ΔV are the contributions of the eliminated buses for the case base, without the necessity of the data of the external grid. This approach allows that the voltage in the bounder buses are kept in the same values of the case base.

D. Computing Load Flow with Multislack Grid

In the proposed procedure search to simplify analysis of the impacts caused by connection of producer by techniques to simplification of grid through multi-slack load flow. So, it is necessary adapt the method de Gauss-Seidel to this objective.

The load flow Gauss-Seidel Z_{bus} traditionally considers a single slack bus isolating its current injection during the iterative process. In the present study proposes, after the classification of buses, the boundary buses are defined as slack buses [8], where yours voltage and phases will remain equal to the pre-fault voltage and phases. Equation (10) consider a simplified grid with only the non-eliminated buses.

$$\begin{bmatrix} V_S \\ V_I \end{bmatrix} = \begin{bmatrix} Z_{SS} & Z_{SI} \\ Z_{IS} & Z_{II} \end{bmatrix} \begin{bmatrix} I_S \\ I_I \end{bmatrix} \tag{10}$$

After the manipulation of matrix equations above have the equations 11 and 12 that allow the calculation of voltages and powers in a multi-slack.

$$[V_m]=[Z_{mS}]\cdot[Z_{SS}]^{-1}\cdot\{[V_S]-[Z_{Sl}]\cdot[I_l]\}$$
$$+[Z_{ll}]\cdot[I_l]+\begin{Bmatrix}[Z_{ll}]\\ -[Z_{mS}]\cdot[Z_{SS}]^{-1}\cdot[Z_{Sm}]\end{Bmatrix}\cdot I_m \qquad (11)$$

$$S_m=\left\{[Z_{mm}]-[Z_{mS}]^{-1}\cdot[Z_{SS}]\cdot[Z_{Sm}]\right\}^{-1}\cdot V_m^*$$
$$\cdot\begin{Bmatrix}\begin{Bmatrix}[V_m]\\ -[Z_{mS}]\cdot[Z_{SS}]^{-1}\end{Bmatrix}\cdot\begin{Bmatrix}[V_S]\\ -[Z_{Sl}]\cdot[I_l]_{for\, l\neq m}\end{Bmatrix}\\ -[Z_{ml}]\cdot[I_l]_{for\, i\neq m}\end{Bmatrix} \qquad (12)$$

4. Simulations and Results

The proposed algorithms were tested using a grid of IEEE composed by 98 buses. In order to give a better idea of the impacts on the grid, all buses were modeled as PQ.

The wind farm is composed by 210 wind generators, producing an equivalent rated power of 142.56 MW, equally distributed in 22 buses, composing a radial system. The wind farm connection is assured by two parallel transformers with ratings of 34.5/69 kV and 69/230 kV, interconnected by underground cables, as shown in Fig. 3. The steady-state behavior of synchronous generators and doubly fed induction generators can be equally modeled, as PQ buses, once in both cases the active power is constant and the reactive power is controlled. However, the converters power of the DFIG just have 30% of the generator power, restricting the limits of the reactive power generation in about 30% of synchronous generator power.

A. Results of Grid Simplification

This section shows the efficiency evaluation of the proposed model for simplification of grid. IEEE98 grid was delimited in three differents situations allowing simplification at 60, 23 and 12 buses with 7, 9 and 6 slack buses through the criterion of section IV-A. This assessment is based on comparison with the results obtained by grid equivalent method, through the ward extended method. The results of the voltage (pu) of grid simulated are presented in Figures 4, 5 and 6, with the summary table of average and maximum voltage in Table II.

The results indicate the high degree of efficiency of the model to simplification grid, because the average percentage errors between the maximum and simplified grid and complete the network were small compared with the results obtained using the equivalent grid with errors that reached percentages greater than 8%.

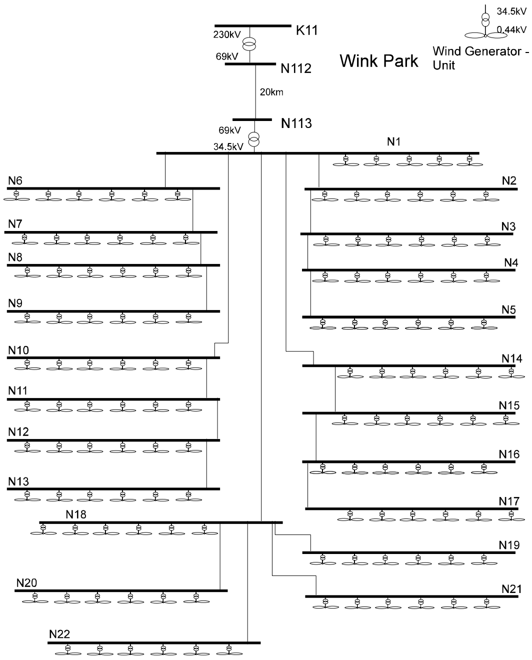

Fig. 3. Wind farm grid.

Table II. – Classification buses by β parameters

[Systems] IEEE	**[Average Error %] [Maximum Error %] Simplif. (multi-slack) I Reduc.**
1ª Situation	0.14 I 0.89 0.35 I 2.83
2ª Situation	0.15 I 2.71 0.41 I 8.62
3ª Situation	0.42 I 2.12 1.07 I 6.92

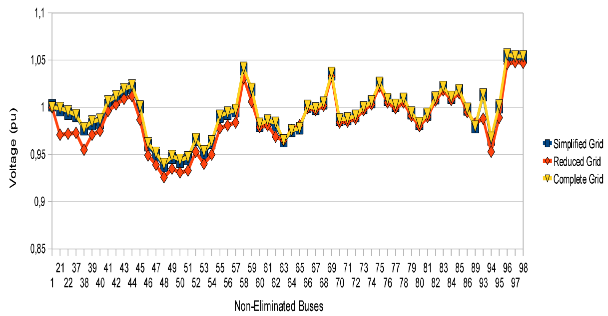

Fig. 4. Results of simulation to complete, reduced and simplified (multi-slack and optimal methods) for 1ª situation.

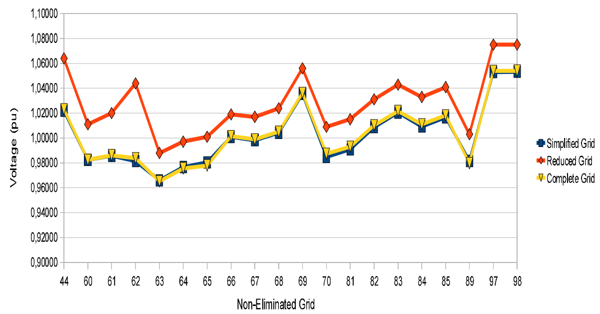

Fig. 5. Results of simulation to complete, reduced and simplified (multi-slack and optimal methods) for 2a situation.

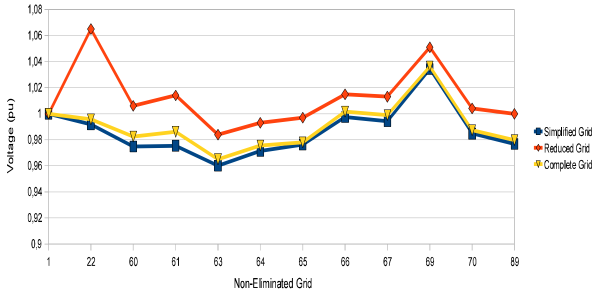

Fig. 6. Results of simulation to complete, reduced and simplified (multi-slack and optimal methods) for 3ª situation.

5. Conclusion

On review of the methods for calculation of equivalent grid, there was efficiency and maturity of the theme, being used by several companies in their analysis, with convergence (agreement) in the use of the Ward method and its variations, in particular the Extended Ward method. Nevertheless in all techniques of off-line application is necessary knowledge of data on the external network. Thus emerged the proposition of the grid simplifying model with multi-slack for boundary buses, where the results suggest an alternative that allows pre-analysis of the impacts of voltage impacts caused by the connection of independent producers, modeling the internal circuit with all its buses, ie, the proposed method to simplify the grid has as its main feature only the need of data for analysis to the internal grid from the impacts caused by the connection of independent producers, showing, among the three methods tested, lowest voltage error compared to the exact calculation with complete network.

References

[1] TPWind, European Technology Platform for Wind Energy. (July). Strategic Research Agenda - Market Deployment Strategy - for 2008 to 2030. Tech. rept. TPWind, 2008.

[2] Ortiz, M., Ríos, J., Acosta, M. Wind Generation and Power System Interaction Analysis using Probabilistic Techniques. Renewable Energy and Power Quality Journal, No.6, March 2008.

[3] ONS, Operador Nacional do Sistema. 2009a. Submódulo 23.3 - Diretrizes e Critérios para Estudos Elétricos, in Portuguese, 2011.

[4] Monticelli, A., Deckmann, S., Garcia, A., & Stott, B. 1979. Real-Time External Equivalents for Static Security Analysis. IEEE Trans. Power App. Syst., PAS-98(March/April), 498–508.

[5] Rahim, A.H.M.A., & Al-Ramadhan, A.J. Dynamic equivalent of external power system and its parameter estimation through artificial neural networks. Electrical Power and Energy Systems, 24(February), 113–120, 2002.

[6] Srivani, J., & Swarup, K.S. Power system static security assessment and evaluation using external system equivalents. Electrical Power and Energy Systems, 30(June), 83–92, 2008.

[7] Pavie, Ivica, Hebel, Zdravko, & Delimar, Marko. Power System Equivalent based on an Artificial Neural Network. Proceedings of the 23rd International Conference on Information Technology Interfaces, 19–22, 2001.

[8] Dimitrovski, A., & Tomsovic, K. Slack bus treatment in load flow solutions with uncertain nodal powers. Electrical Power and Energy Systems, 27(November), 614–619, 2005.