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Verification of the Reactive Power Requirements in Wind Farms

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***Abstract*—Reactive power must be measured and watched to verify accomplishment of Spanish grid code requirements in wind farms. However, no definition of reactive power is established in that code. Thus, two reactive power formulations are compared in this paper applied to wind farm generators in presence of transient disturbances such as voltage dips. First reactive power formulation is based on Emanuel's approach, included in the IEEE Standard 1459-2000. Second reactive power formulation has recently been established by Czarnecki. Both formulations express reactive power decomposed into the reactive power due to the reactances and the reactive power caused by the unbalances. This decomposition allows for a better knowledge of wind farms working and to verify the accomplishment of code grids established in several countries.**

Index Terms—*Power measurement; reactive power; standards; wind energy; wind power generation.*

I. INTRODUCTION

WIND power has became the most important renewable energy source in many countries. At the beginning of 2008, wind power installed in Germany was 22.5 GW, which is the largest wind energy user in the world. Wind power installed in Spain was 15.5 GW and previsions indicate wind power installed in Spain will reach 20 GW at last of 2010. Because of the importance of wind energy in electric power generation, stability of the electric network can be affected by any failure in wind farms, caused by a transitory perturbation, as a voltage dip, for example. Thus, governments established recently new grid code requirements, which forbid disconnection of wind farms when voltage fells bellow of 80% or 90% of its rated value. Wind power generators must win these perturbations and they must restore RMS-values and frequency of voltage network. For that, Spanish grid code [16], establishes requirements for consumptions of reactive currents and powers in presence of any sudden voltage disturbance. However, Spanish grid code does not specify which the reactive power definition is and thus several reactive power formulations could be used at this moment for accomplishing grid code requirements. In our opinion, two reactive power formulations are the most adequate for measuring this quantity: Emanuel's positive-sequence fundamental-frequency reactive power [6,7,13,14] and Czarnecki's CPC reactive power [3,4,5]. First power definition has been included in the IEEE Standard 1459-2000 [15] and can be separated into two components: the reactive power due to the load reactances and the reactive power caused by the unbalances. Czarnecki's reactive power is the traditionally well-known reactive power. Also, this quantity can be separated into the reactive power due to the reactances and the reactive power caused by the unbalances. Reactive phenomenon caused by the unbalances was first characterized in [9] and formulated in [10] for Emanuel's fundamental-frequency positive-sequence reactive power. This phenomenon can hold the same or different character (inductive or capacitive) that reactive phenomenon caused by the load reactances and, thus, they can add or compensate their effects. That is true for Emanuel's and Czarnecki's approaches, and so they can explain reactive phenomena rather than other reactive formulations [2,11,12].

In this paper, the two above indicated reactive approaches are applied to analyze actual wind farms at Castilla-La Mancha Community and to verify the accomplishment of the new Spanish grid code requirements [16] in presence of two-phase and three-phase voltage dips.

Values of Czarnecki's reactive powers obtained from these registered data are greater than those based on Emanuel's formulations [8,9,10] and, thus, first approach is more restrictive in the measuring of the reactive phenomena. However, both approaches are able to analyze the reactive phenomena in wind farms, since their reactive powers explain (with a certain scale) the same power system behavior.

II. SPANISH GRID CODE REQUIREMENTS

New Spanish grid code [16] establishes that wind farms and all their components must support without disconnection voltage dips presents at the electric network interconnection point, originated by three-phase, two-phase and single-phase to ground faults. In the same time, Spanish grid code determinates limits of reactive power consumptions:

- Power consumptions are not allowed during the fault and the posterior recovery period. However, it is admitted some reactive power consumptions during the 150 ms after the beginning of the fault and the

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150 ms after the fault clearance (Fig. 1).

- Reactive power consumptions must not be greater than the 60% of the wind farm power rated in each network voltage period (20 ms), for three-phase faults, or the 40% for single and two-phase faults (Fig.1).

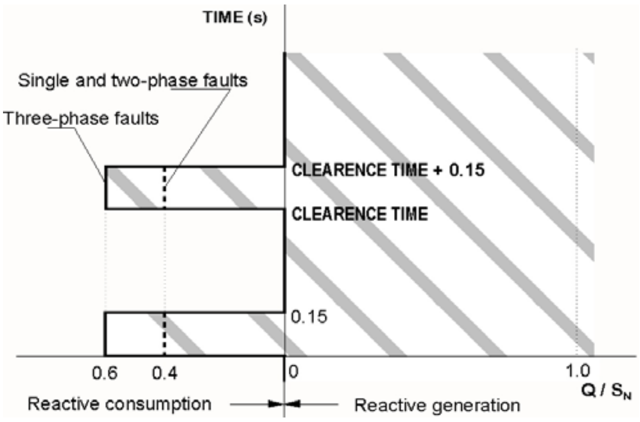

Fig.1. Limits of the reactive power consumptions in wind farms during a voltage dip established by the Spanish grid code.

III. REACTIVE POWER FORMULATIONS

Figure 2 shows a three-phase, three-wire wind power system. Reactive powers can be expressed by the two following approaches:

A. Reactive Powers Based on Emanuel’s Approach

It was seen in [1,10] that fundamental-frequency positive-sequence reactive power can be expressed as:

$$\begin{aligned}\overline{Q}_+ &= 3\overline{V}_{AB+}\cdot\overline{I}^*_{r+} = \\ &= j\,3\,[\pm B_+ + \delta_U Y_i\, sin(\alpha_+ - \alpha_- + \alpha_i)]\cdot V_+^2 = \\ &= \overline{Q}_{r+} + \overline{Q}_{u+}\end{aligned} \qquad (1)$$

This power holds two components: the traditionally known *reactive power due to the reactive loads* [3]

$$\overline{Q}_{r+} = 3\overline{V}_{AB+}\cdot\overline{I}^*_{rr+} = \pm\, j\,3\,B_+V_+^2 \qquad (2)$$

and the *reactive power due to the unbalances* [3]

$$\overline{Q}_{u+} = 3\overline{V}_{AB+}\cdot\overline{I}^*_{ur+} = j\,3\,[\delta_U Y_i\, sin(\alpha_+ - \alpha_- + \alpha_i)]\cdot V_+^2 \qquad (3)$$

where $\overline{V}_{AB+} = V_+\,|\,\alpha_+$, $\overline{V}_{AB-} = V_-\,|\,\alpha_-$ are positive- and negative-sequence line voltages, respectively; $\overline{I}_{r+}$ is the positive-sequence line reactive current; $\overline{I}_{rr+}$ is the reactive current due to the reactances and $\overline{I}_{ur+}$ is the reactive current due to the unbalances and (*) indicates the conjugate of those complex quantities. The positive susceptance of the load:

$$B_+ = \tfrac{1}{3}\left(\sum_{z=AB,BC,CA} B_z\right) \qquad (4)$$

and

$$\overline{Y}_i = \tfrac{1}{3}(\overline{Y}_{AB} + a^2\overline{Y}_{BC} + a\overline{Y}_{CA}) = Y_i\,|\,-\alpha_i \qquad (5)$$

being $a = 1_{|\,120^\circ}$,and

$$\overline{\delta}_U = \frac{\overline{V}_-}{\overline{V}_+} = \delta_U\,|\,\alpha_- - \alpha_+ \qquad (6)$$

is the unbalance line-voltage degree.

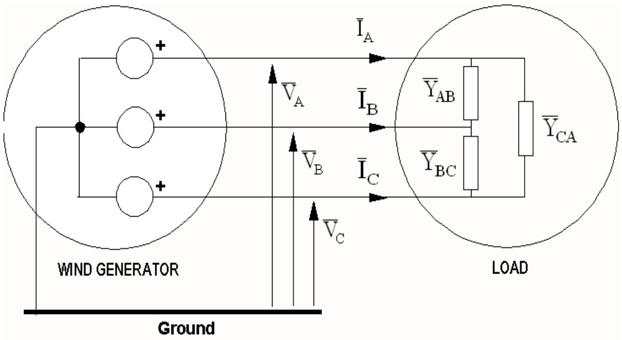

Fig. 2. Electric circuit of a wind power generator and its load.

B. Czarnecki’s Reactive Power

Traditional reactive power (Q) is decomposed by Czarnecki [4,5] into the reactive power at a symmetrically supply voltage (Q_s) and the reactive power due to unbalances at supplies and loads (Q_d):

$$\begin{aligned}&Q = V\cdot I_r = -B_b\cdot V^2 = -(B_e + B_d)\cdot V^2 = Q_s + Q_d \\ &Q_s = -B_e\cdot V^2 \\ &Q_d = -B_d\cdot V^2\end{aligned} \qquad (7)$$

where:

$$V = \sqrt{V_A^2 + V_B^2 + V_C^2} \qquad (8)$$

and B_b, B_e, B_d are the imaginary part of the following admittances [2], respectively:

$$\begin{aligned}\overline{Y}_b &= \frac{\overline{S}^*}{V^2} = 2\,\overline{Y}_e - \frac{3}{V^2}(\overline{Y}_{BC}V_A^2 + \overline{Y}_{CA}V_B^2 + \overline{Y}_{AB}V_C^2) \\ \overline{Y}_e &= \overline{Y}_{AB} + \overline{Y}_{BC} + \overline{Y}_{CA} \\ \overline{Y}_d &= \overline{Y}_e - \frac{3}{V^2}(\overline{Y}_{BC}V_A^2 + \overline{Y}_{CA}V_B^2 + \overline{Y}_{AB}V_C^2)\end{aligned} \qquad (9)$$

being $\overline{S}^* = P - jQ$ the conjugate of the complex power of the three-phase load.

IV. EXPERIMENTAL APPLICATIONS

Reactive power formulations expressed in the before section have been applied on data registered in actual wind turbines in presence of two-phase and three-phase voltage dips. Results are showed in this section.

A. Two-phase voltage dip

Figure 3 shows one registered two-phase voltage dip involving the A and B-phases of the wind generator. Reactive powers obtained with Emanuel´s based approach (Fig. 4) and Czarnecki´s reactive powers (Fig. 5), are supplied (negative sign) to the electric network during the fault. Thus Spanish grid code requirements are verified, because wind farm was not disconnected and it continued supplying reactive power to the electric network.

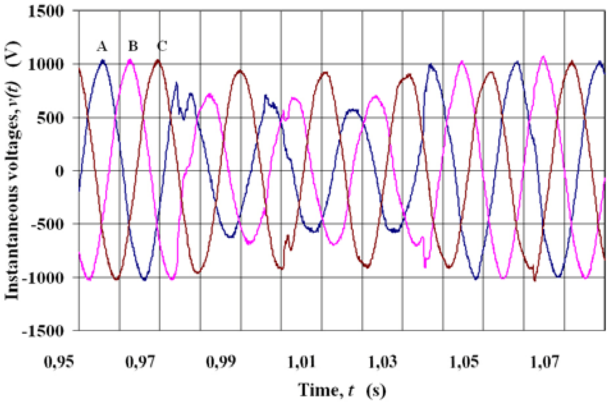

Fig. 3. Two-phase voltage dip.

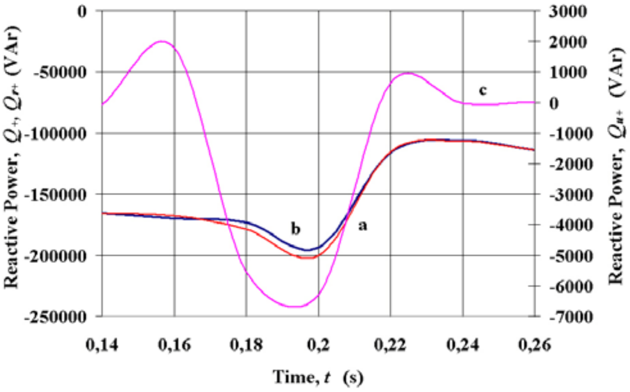

Fig. 4. Emanuel´s reactive powers: a) positive-sequence fundamental-frequency reactive power, Q_+ ; b) reactive power due to the reactances, Q_{r+} ; c) reactive power due to the unbalances, Q_{u+} .

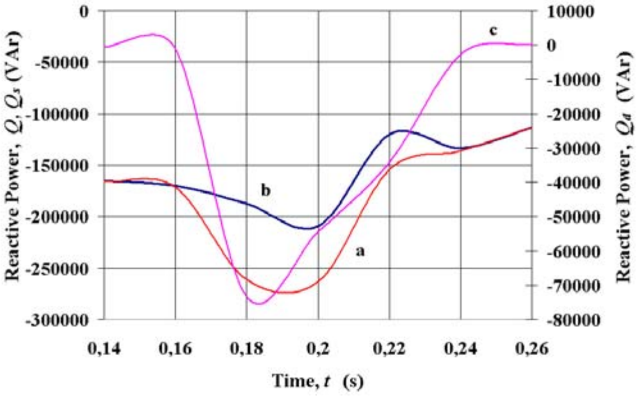

Fig. 5. Czarnecki´s reactive powers: a) reactive power (Q); b) reactive power with balanced voltages (Q_s); c) reactive power caused by unbalanced voltages (Q_d).

Comparing Fig. 4 and 5, it can be observed that evolution of the reactive powers obtained with both approaches is very similar in this registered voltage dip. Values of Czarnecki’s reactive powers are greater than Emanuel’s based reactive powers, due to the negative sequence effects. Thus, that approach is more restrictive than last mentioned approach.

B. Three-phase voltage dip

Another registered transitory fault was the three-phase balanced voltage dip showed in Fig. 6.

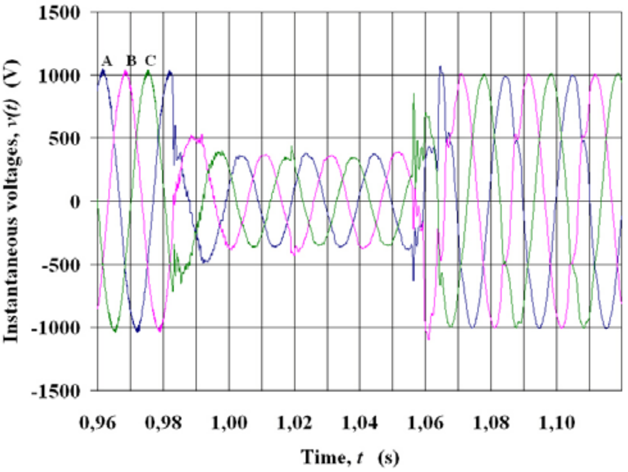

Fig. 6. Three-phase voltage dip.

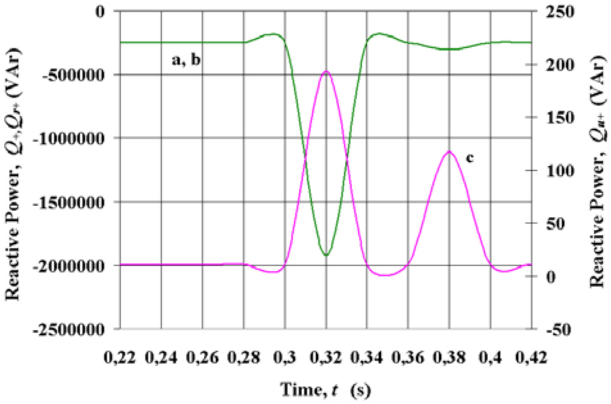

Fig. 7. Emanuel´s reactive powers: a) positive-sequence fundamental-frequency reactive power, Q_+ ; b) reactive power due to the reactances, Q_{r+} ; c) reactive power due to the unbalances, Q_{u+} .

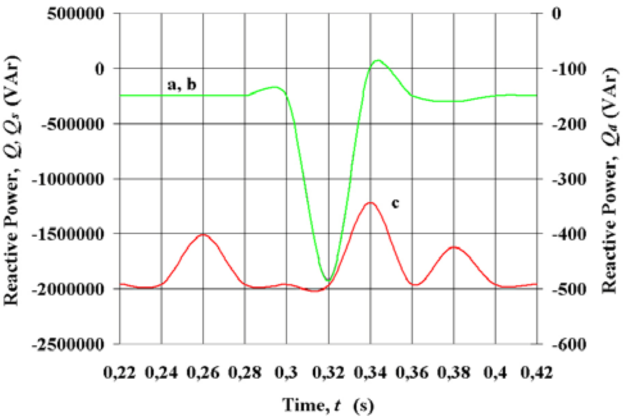

Fig.8. Czarnecki´s reactive powers: a) reactive power (Q); b) reactive power with balanced voltages (Q_s); c) reactive power caused by unbalanced voltages (Q_d).

It is appreciated in Figs. 7 and 8 that Emanuel¡s based and Czarnecki's reactive powers hold similar evolution during the disturbance. Also, it is observed that reactive powers caused by the unbalances are less than those measured in the two-phase voltage dip. Values of reactive powers due to the load reactances are very great in front of the reactive powers caused by the unbalances, which are very little in the three-phase voltage dip. All the above mentioned demonstrates that reactive powers caused by the unbalances are related directly with the supply unbalances and these reactive quantities are zero when voltages are balanced.

V. CONCLUSIONS

Two definitions of reactive power have been used in this paper to analyze wind farm working in presence of voltage dips. First reactive power formulations are obtained from Emanuel's fundamental-frequency positive-sequence reactive power, included in the IEEE standard 1459-2000. Second reactive power was established recently by L.S. Czarnecki. Both theories decomposed reactive power into two components: a) reactive power with balanced voltages (or due to the reactances), and b) reactive power due to the unbalances. This last reactive power exits when there are unbalances at supplies and loads, in the same time, or when there are certain symmetry at the power system. Reactive power caused by the unbalances can have the same or opposite character (inductive or capacitive) that reactive power due to the load reactances. This last property can be used for establishing procedures to maintain the supply of reactive power and to recover wind farm generation in presence of voltage dips, since reactive power due to the unbalances can maintain and, inclusive, can increase total reactive power being added to the reactive power due to the load reactances. Czarnecki's reactive powers are greater than Emanuel's based reactive powers and they can be used for more restrictive conditions; however, both approaches can be applied to verify the accomplishment of grid code requirements at wind farms, since evolution of reactive powers during the voltage disturbances are very similar.

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