A Voltage Regulation Strategy through the Control of Reactive Power on Wind Farms

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***Abstract* — The growing demand for energy sources with low environmental impact have intensified the importance of wind farms in many countries. However, due to the operational characteristics of these complexes, which are reflected in a variability of the produced energy and the use of electronic converters, the interaction between wind power plants and connecting electrical networks is shown to be an area of strong investigative interest. In fact, among the various phenomena that exist, steady state voltage variations constitute a topic that comes under the constant attention of agencies responsible for the power systems operation. In this context, the present paper is directed towards the analysis of a strategy based on wind generation systems with synchronous machines and full converters. Using such arrangement with specific control strategy, the paper is focused at providing wind farm additional features related to voltage regulation process at the grid connection busbar. By means of computational simulations on the ATP/EMTP platform, results are presented that attest the efficiency of the proposed strategy.**

***Index Terms* — Reactive Compensation, Wind Energy, Voltage Regulation, Power Quality**

I. INTRODUCTION

The interest manifest in the use of wind energy has been a central concern for the transmission system operators. In fact, the connection of these power plants on the grid assumes the fulfilment of various requirements and procedures, which are set out in specific standards [1, 2] or even in the grid codes of each country. To meet such demands, power electronics converters play an important role on the wind energy generation systems, guaranteeing the integration of control functions that allow these systems to provide active power generation and ancillary services of voltage and frequency regulation [3]. Such conditions allow wind units to participate in an active manner on the control and stability of the power grid.

However, when considering the variability of the energy produced and the operation of the electronic converters, the integration between the wind farm and power grid still shows itself as an area of strong investigative interest. in this sense, a great number of studies and publications have been performed with a view to characterizing the effects mentioned above and corresponding mitigating actions.

In respect to wind turbines constituted of full converters [4], the use of inverter units for the compensation of reactive power is covered in [5]. These present qualitative results associated with the addition of this functionality in commercial wind turbines, yet without presenting details of the control strategy used. In [6], a control strategy philosophy is established for the back-to-back converter, which integrates a maximum power point tracker, and still allows the fixed supply of reactive power. This study considers the operational limits for an inverter, in respect to the relationship between power supply and power quality, as presented in [7]. The computational results put forward in [8] demonstrate a methodology for regulating the voltage at the coupling point via the optimized dispatch of reactive power to the wind farm. Other developments related to this theme are presented in [9-13].

In light of these facts and focused specifically on the technology for wind generation through synchronous machines and full converters, this research study aims at presenting an operational strategy for the adjustment of the reactive power flow between the wind power plant and the electrical network, while keeping in mind the voltage regulation process at the connection busbar. In order to achieve the set aims, after the presentation of the fundamental mathematics relevant to voltage variations in steady state, a control strategy is proposed that is destined to the dispatch of reactive power of the individual wind turbines. Such information is complemented by a case study, which use a typical connection system and have the goal of instituting evaluating bases for the efficiency of the established methodology.

II. STRATEGY FOR THE REACTIVE POWER COMPENSATION

Figure 1 presents a simplified single line diagram, which represents an equivalent circuit representing the access of a wind farm to a given electrical grid. Based on the control functions of the power electronics converters that exist in such systems, the wind farm could be represented by an equivalent current source, which is associated with the impedances Z_I, Z_T and Z_S, referring respectively to, the internal network of the wind farm, the substation transformer and the equivalent on the grid.

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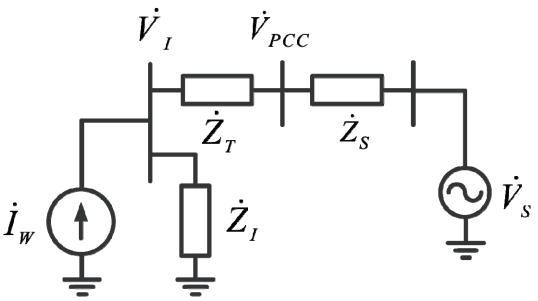

Fig. 1. Simplified single line diagram, in fundamental frequency, referring to the access of a wind farm.

Under these conditions, the voltage at the coupling point of the wind farm is calculated by (1), which relates to the above-mentioned variables.

$$\dot{V}_{PCC}=\frac{\dot{Z}_T+\dot{Z}_I}{\dot{Z}_S+\dot{Z}_T+\dot{Z}_I}\dot{V}_S+\frac{\dot{Z}_S\,\dot{Z}_I}{\dot{Z}_S+\dot{Z}_T+\dot{Z}_I}\dot{I}_W \qquad (1)$$

where V_{PCC} is the voltage on the coupling point, I_W is the current produced by the wind farm, V_S is the equivalent voltage on the grid. The above expression makes clear there is a strong relationship between the busbar voltage and the current produced by the wind farm.

By knowing the dependence of the reactive component produced by the wind farm and the voltage level, the definition of the reference values for the reactive power flow, under the terms established in this study, are based on the traditional droop control described in [11] . In this sense, keeping in mind the strategy that aims at the operation of a wind turbine unit, in terms of supplying reactive power in a similar manner as STATCOM devices [14], the dispatch of reactive power is determined by a curve similar to that presented in Fig 2. This uses as input the voltage variations at the wind turbine unit coupling point.

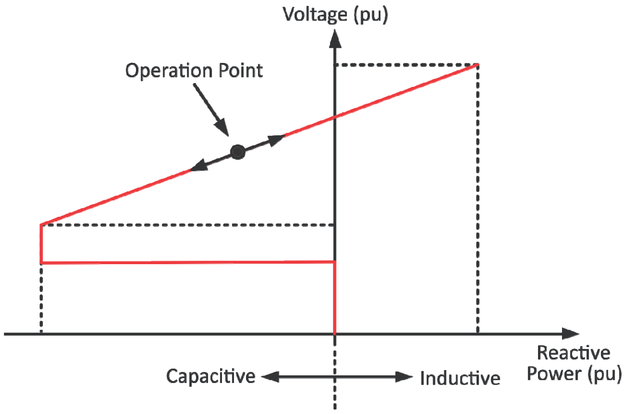

Fig. 2. The used droop characteristic.

Generically, equation (2) defines the behavior of a droop type control system.

$$V_{PAC}-V_n=K_v(Q_{ref}-Q_n) \qquad (2)$$

where Q_{ref} is the reactive power used as a reference by the wind turbine unit, V_n is the rated voltage on the connection busbar, Q_n is the reactive power associated to the rated voltage, K_v is the gain on the droop curve.

Keeping in mind that the rated conditions for reactive power supply are given by $V_n = 1\,pu$ and $Q_n = 0\,pu$, one has, in (3), the fundament that guides the mechanism for the definition of the reactive power dispatch.

$$Q_{ref}=\frac{V_{PCC}-V_{min}}{K_v} \qquad (3)$$

The constant K_v can be calculated by (4), which considers the voltage variation range at the coupling point, as well as the maximum values for the reactive power flow. In this regard, it needs to be highlighted that the power electronics converter has a higher capacity for supplying reactive power, having in mind that this operational condition implies a reduction in the converter active power supply capacity.

$$K_v=\frac{V_{max}-V_{min}}{Q_{max,cap}+Q_{max,ind}} \qquad (4)$$

where V_{max} is the maximum voltage at the coupling point, V_{min} is the minimum voltage on the coupling point, $Q_{max,cap}$ the limit for the capacitive reactive power converter, $Q_{max,ind}$ the limit for the reactive power inductive converter.

Once the reference value has been calculated for the supply or consumption of reactive power, it is necessary, through a control loop, to synthesize the voltage at the output of the wind turbine unit, with the aim of meeting the required action. In this regard, on the assumption that the complex treated herein uses a voltage source converter, the adjustment for the power flow between the wind turbine unit and the power grid is realized by controlling the current produced by the inverter. Therefore, the result of the operation should be manifest in the obtaining of the desired amplitude and phase angle of the three-phase output voltages. This is achieved through the control system synthesized in the diagram shown in Fig 3. The given arrangement is constituted by PI controllers adjusted using the "Modulus Optimum" and "Symmetrical Optimal" techniques [15]. Additionally, a "Dual Second-Order Generalized Integrator FLL" (DSOGI-FLL) performs grid synchronization [16].

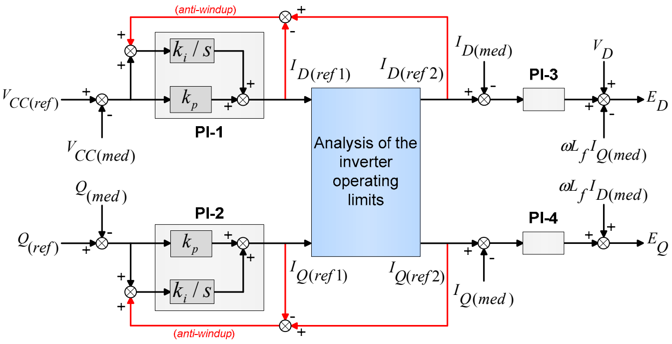

Fig. 3. Basic structure of the inverter unit control strategy.

The signals generated by the PI-1 and PI-2 controllers correspond to the input variables from the block identified as "analysis of the inverter operating limits". This block checks the reference values determined by controllers PI-1 and PI-2 do not exceed the rated capacity of the inverter unit. In addition, it falls on this unit to define the operational priority, being that under such a condition, where the initial references infer upon the rated capacity of the inverter unit being exceeded, the reference value of the direct axis current is conserved at the expense of the reference value for the quadrature axis current, as shown in Fig. 4.

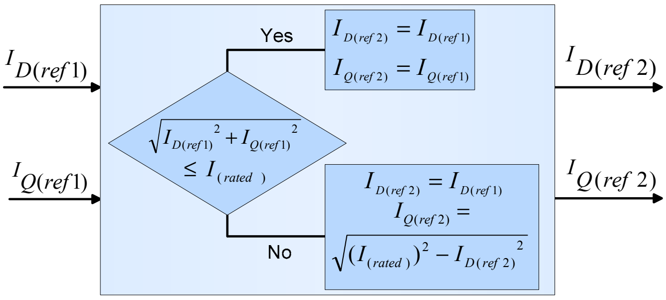

Fig. 4. Detailing of block "Analysis of the inverter unit operating limits".

III. ELECTRICAL SYSTEM SIMULATED

In order to demonstrate the efficacy of the methodology destined to reactive power compensation, a case study considering the electrical grid indicated in Fig. 5 was computationally simulated and distinct operational conditions were applied to highlight the voltage control strategy herein considered. The computational work in this study was performed using the ATP/EMTP platform.

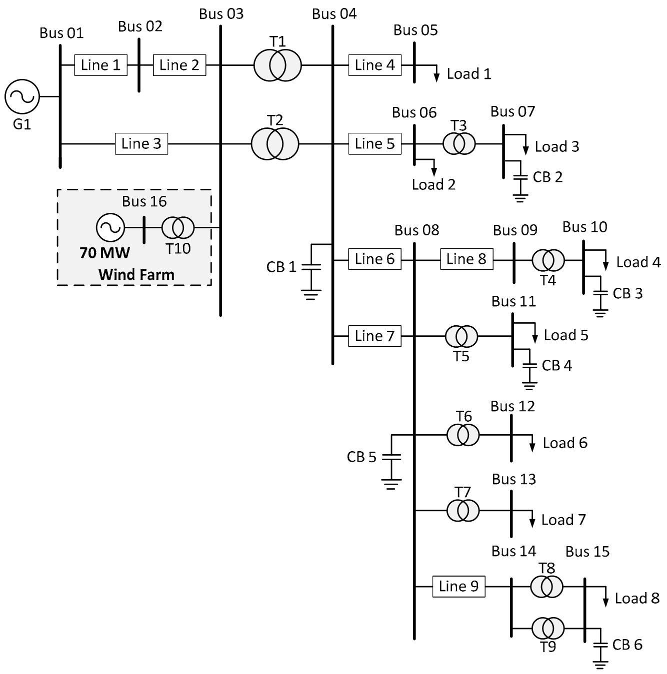

Fig. 5. Single line diagram of the selected electric system.

Tables 1 to 5 show the respective electric parameters. It can be noted that the wind farm is connected to busbar 3 of 138 kV.

TABLE I. EQUIVALENT GENERATOR

Generator	Rated Voltage (kV)	Short-circuit Level (MVA)
G1	138	680

TABLE II. TRANSMISSION AND DISTRIBUTION LINES

Line	Resistance	Inductance (mH)	Capacitance (µF)
1	17.05	152.55	1.14
2	2.51	22.43	0.167
3	16.72	172.51	1.33
4	9.88	60.34	0.48
5	0.06	0.36	0.003
6	2.37	14.48	0.11
7	2.09	18.19	0.14
8	13.05	54.52	0.37
9	0.7	6.06	0.05

TABLE III. TRANSFORMERS

Transformer	Rated Power (MVA)	Rated Voltages (kV)	Impedance (%)
1	60	138/69	15.60
2	60	138/69	15.60
3	12	69/13,8	4.64
4	5	69/13.8	6.01
5	12	69/13.8	8.35
6	12	69/13.8	8.35
7	12	69/13.8	8.35
8	12	69/13.8	6.15
9	12	69/13.8	6.15
10	70	34.5/138	12.0

TABLE IV. LOADS

Load	Active Power (MW)	Reactive Power (MVAr)
1	20.80	8.90
2	1.80	0.80
3	5.40	2.30
4	2.10	0.90
5	7.10	3.00
6	0.90	0.40
7	3.00	1.30
8	18.90	8.10

TABLE V. CAPACITOR BANKS

Bus	Rated Power (MVAr)
4	13.8
7	1.02
10	1.02
11	4.00
8	5.08
15	5.05

Fig. 6 presents details of the wind farm, which contains 35 individual generation units. Each unit was modelled in accordance with the representation given in [17, 18], as highlighted in Fig. 7.

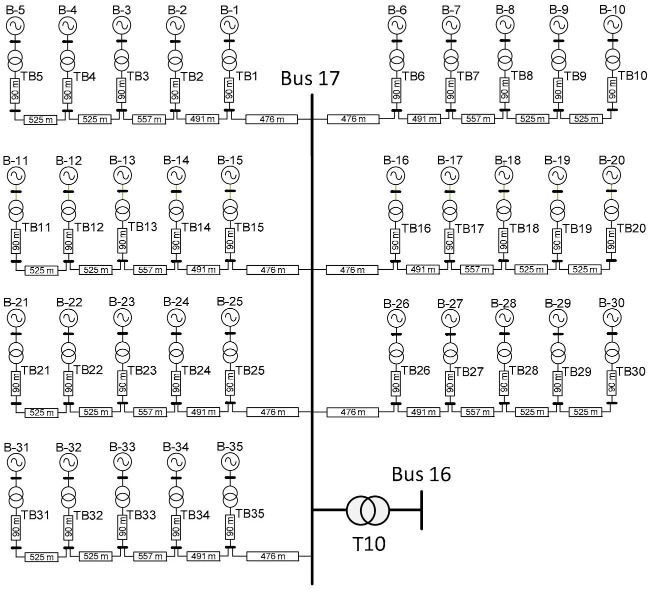

Fig. 6. Single line diagram of the wind farm used in the studies.

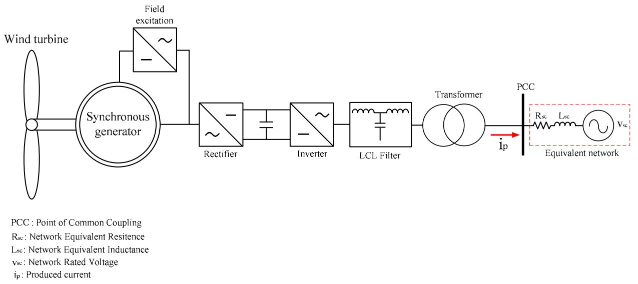

Fig. 7. The single wind generation arrangement.

Table 6 presents the main characteristics of the individual wind turbine.

TABLE VI. CHARACTERISTICS OF THE INVERTER UNIT

Operational Characteristics	Value
Rated Power	2.00 MVA
Inverter DC bus voltage	1200.00 V
Switching Frequency	2500.00 Hz
Filter LCL – Inductance at converter side	0.14 mH
Filter LCL – Capacitance	780.00 µF
Filter LCL – Damping resistance	0.10 Ω
Filter LCL – Inductance at network side	0.14 mH

IV. COMPUTATIONAL INVESTIGATIONS

Once the physical arrangement is defined along with its components, models and respective implementations on the ATP simulator, studies concerning distinct operational conditions were performed. The computational results are described in the sequence. They are focused on the voltage regulation process at the PCC busbar at the occurrence of sudden load variations.

The study shows the overall system performance caused by a load increase in the grid defined by an insertion of 25.0 MW+j12.0 MVAr applied to busbar 4 at t=3s, with its corresponding removal within 2 seconds after the addition.

Although it is possible to adopt winds with distinct features for each wind turbine, for the purpose of this study only two conditions were selected. Both of which correspond to winds with constant speed, respectively with values of 13m/s and 11m/s, which were in turn respectively applied to set 1 (wind turbines B-01 to B-20) and set 2 (wind turbines B-21 to B-35), as indicated in Fig. 8.

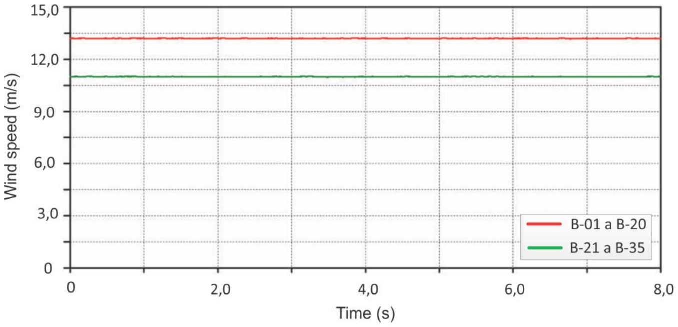

Fig. 8. Profile of adopted wind.

Fig. 9 shows the active power injected by the wind farm onto the connected grid. This remains constant at around 55MW, with or without the activation of the voltage regulation system. Therefore, the additional active load is not supplied by the wind farm itself.

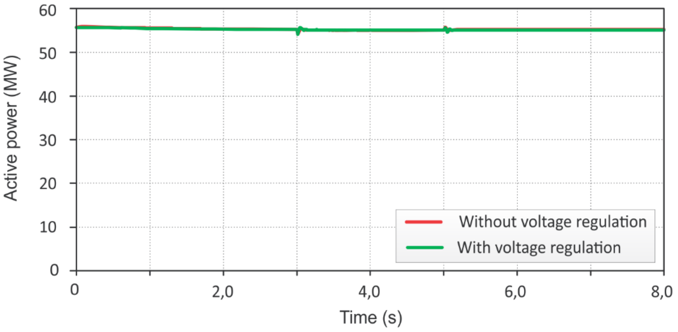

Fig. 9. Active power produced by the wind farm.

The voltage at the PCC can be seen in Fig. 10. As already stated, the sudden load connection occurs at the 3 second instant and its disconnection occurs at 5 seconds. In light of the imposed operational conditions, steady state voltage for the situation where the voltage regulation function is activated remains with levels closer to the reference values. This is due to reactive power compensation provided by the wind farm. The processes that occurred before, during and after the insertion of the additional load can be easily noted, as well as the efficacy of the regulation process under study.

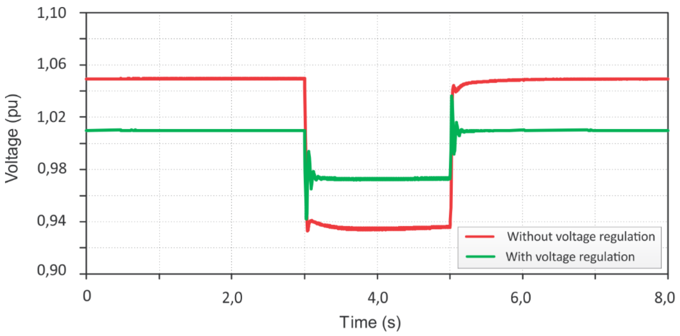

Fig. 10. PCC voltage profile.

The corresponding reactive powers measured at the wind farm connection feeder are presented in Fig.11, which express the behaviour of this variable in virtue of the alterations that occurred on the grid. With the strategy for voltage regulation deactivated, the wind farm possesses an inductive characteristic, where it absorbs around 4.0 MVAr when there is an absence of the new load connection and 5.5 MVAr after its insertion. Such values are intended, in greater part, to supply the reactive power demands required by the internal network of the wind farm. Once activated the control strategy and having in mind the voltage adjustment on the reference levels, the wind farm consumes around 11 MVAr inductive power before the connection of the new load. The moment the load is inserted, the power plant alters its reactive power flow, and now operates as reactive power supplier, supplying 1.25 MVAr.

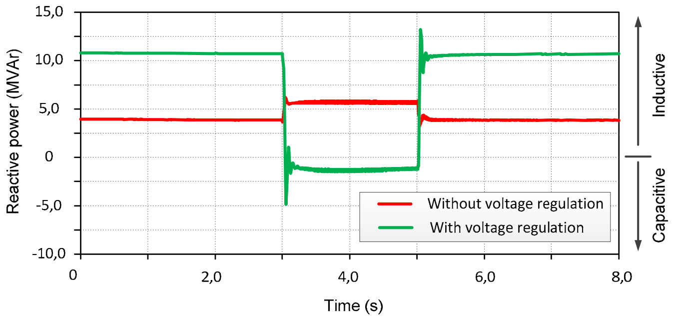

Fig. 11. Reactive power produced by the wind farm.

V. CONCLUSIONS

The present paper focused on the evaluation of a control strategy directed towards full converter wind units, aimed at reactive power flow adjustment and consequently participating in the voltage regulation process at the coupling point. The methodology presented herein supports principally the use of inverter units that already exist in these complexes, as compensation mechanisms, thus eliminating the need to install external equipment, such as capacitor banks, or electronic regulators.

Considering the strategy presented in this paper, the reactive power demand is defined from the measured voltages at the coupling point and a predefined droop curve. The latter allows for a decentralized compensation process, since each wind turbine contributes within its own momentary working state.

In light of the obtained results, the use of wind turbine units for the process of dynamic compensation of reactive power and the participation of voltage control at the coupling point shows itself to be of promise, since voltage variations can be mitigated by use of converters that already exist in this generation. In addition, the presented methodology allows for the operation of wind units, regarding the reactive power flow in similar fashion to STATCOM devices.

Regarding the computational results, even with the lack of any field performance, from a qualitative point of view, there has been a good adhesion to the expected physical behaviour.

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