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Smart grid integration of the new electrical production technologies. Case of a DFIG in WECS

Salma El Aimani

Physics-Chemistry Department, Ibn Zhr University
Polydisciplinary of Ouarzazate, P.B. 638, 45000 Ouarzazate, Morocco
s.elaimani@uiz.ac.ma

Abstract— **The development of renewable energies: intermittent production, the arrival of new uses such as electric vehicles, as well as the prospect of transforming consumers into real actors of the electrical system, require a radical evolution of the electrical networks. Intelligent electrical networks, also known as Smart Grids, allow a dynamic optimization of the current networks, from production to the consumer, through the contribution of new information and communication technologies. The electrical system then becomes predictive, communicative and controllable. They constitute a brick of possible answers to the stakes of the energy and ecological transition. In this paper, a particular study of these networks is highlighted. The integration of a particular wind turbine of 1.5 MW and its impact on the distribution network will be presented. The simulations of scenarios of these systems are carried out with Matlab Simulink TM.**

Keywords— **Power quality, Grid integration, Doubly Fed Induction Generator (DFIG), Wind Energy Conversion System (WECS), Voltage dips.**

I. INTRODUCTION

Today, electricity as a commodity in its own right becomes essential not only for the daily lives but also for the economy of the country. Indeed, lower power outages have considerable economic and societal consequences. For example, in the north eastern United States, the financial loss due to a blackout was estimated between seven and ten billion [1]. Thus, the need for reliable and economical power systems is a challenge increasingly important. Other aspects such as the liberalization of electricity market, the desire to preserve the environment and the growing concern over the issue of exhaustion of fossil fuel reserves will lead, increasingly, to consider the increased use based decentralized renewable energy production (wind, solar, etc.).

Production units based on renewable energy (RE), set apart hydropower plants were at the beginning of their development, mostly small sizes. These units are therefore initially connected to the distribution network or the term distributed generation - which qualifies any power source connected directly to the distribution network -. As the technology develops, the renewable power plants become larger and therefore are connected to the higher voltage levels (transport). The arrival of the production at all levels is a challenge to both new and important for network managers. These last operate a system that was designed for unidirectional power flow from production plants to consumers by first passing through the transport network and then by the distribution network. The arrival of renewable energy, especially on the distribution networks, the situation changes (variable production can reverse power flow in lines) [2] and can generate a number of problems and constraints that must limit the effects. To limit such damaging consequences safety networks, distributors impose strict limits for any new connection. This has the effect of limiting, small, penetration of renewable. To preserve the safety of the electrical system, ensure continuity of service and maintain the quality of supply of electrical energy, while continuing to promote the integration of renewable energy, it is important to seek innovative solutions to solve this problem.

To treat the points discussed above, this paper will consist of four main parts: The first part will concerns the integration of wind power in networks. It will summarize the problems of integration and systems and storage associated with wind turbines. In the second part, a study these networks in the presence of renewable energy sources, mainly wind turbines will be discussed. The impact of these sources on the distribution and electricity network will be highlighted. In the third and final part, the study of the integration of a particular DFIG based WECS and its impact on the distribution network will be presented. The paper ends with a general conclusion and prospects.

II. IMPACTS OF RENEWABLE ENERGY SOURCES (RES) ON THE GRID:

A. Introduction

Interconnection of large-scale production systems based on renewable energy to electrical grids could create many technical problems such as: changing the power flow, the voltage change, the loss of stability of the network, the impact on the selectivity of the protection plan, the imbalance of current and voltage, the risk of islanding. It therefore becomes important to evaluate the reception capacities of the network of these decentralized generation, mainly according to the modification of the power flow, the voltage quality, the correct operation of switchgear, the selectivity of protection systems, overall stability, the balance the network and the risk of islanding. In this section will be developed problems induced by the integration of renewable energy in the networks.

B. Impact on Electrical Power

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High insertion decentralized production of renewable energy such as wind can induce on the network two types of phenomena:

- A change in the direction of power flow: possibility that was not taken into account when designing distribution network. This latter is designed to power consumption facilities and therefore at low cost, with little possibility for discharging large wind power in a low charge density zone, which is the case in a radial distribution network.
- Energy traditionally flows from upstream (point of connection to the transmission system) to downstream (loads). Connecting a group departure can reverse the direction of power flow, for example, a drive malfunction non-directional protection (Fig. 1).

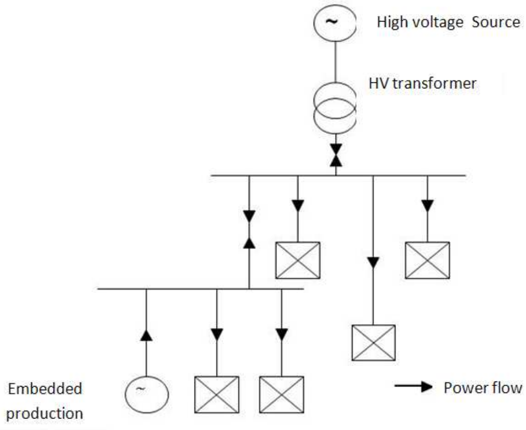

Fig. 1 Example of radial network and modification of power flow

C. Impact on RMS voltage

Fig. 2 shows the first impact of integration of wind energy conversion system in the grid. It is necessary to control the voltage drop and the reactive power increasing from upstream to downstream, while ensuring the compliance with contractual and regulatory requirements management. In the electrical network of HV and EHV line, voltage fluctuations are mainly induced by the reactive power flows, unlike the distribution (for EHV lines) [3].

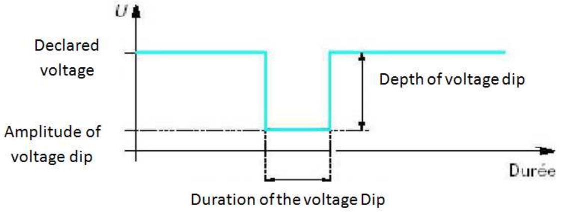

Fig.2 Variation of RMS voltage value in electrical network.

Fig. 3 shows a classification of voltage dips in electrical networks. Voltage dips A, B and C are the most involved in radial networks.

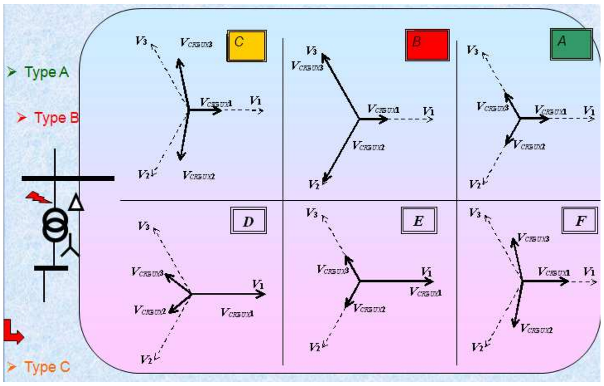

Fig. 3 Classification of voltage dips in electrical networks

D. Flicker

Flicker is short and rapid voltage variations that appear in the electrical grid which may cause flicker of incandescent light bulbs. This can arise if the production unit is connected to a renewable energy system with low power short circuit, frequent changes of its primary energy while causing significant power variations (Fig.4).

This phenomenon is especially observed for a constant speed wind turbines because there is no buffer between the input mechanical power and the electric energy fed to the grid. To determine the flicker occurring during a continuous operation, measurements are made and compared with the reference voltage to quantify the rate of voltage flicker.

The phenomenon of flicker can also occur when switching between areas of operation of wind turbines. Variable speed wind turbines using power converters face these problems; however, they are penalized by the harmonic generation in the electrical grid.

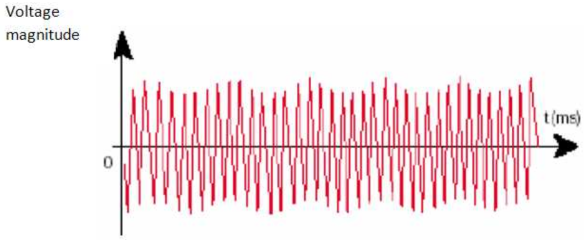

Fig. 4 Rapid and short variation of voltage

III. STUDIED CONFIGURATION

The objective of this part is to illustrate the impact of DFIG (Doubly Fed Induction Generator) wind turbine on a distribution network as a case of renewable energy source and its penetration into a medium voltage grid (Fig. 5). This WECS is directly powered from the grid through the stator and through the rotor static converters. The architecture of a grid will first be presented as well as the constraints in terms of production quality that should satisfy any production connected to a medium voltage network. Two types of impact will be addressed:

- The impact on the quality of supply including voltage and current, as well as fluctuations in power according to the fluctuations of wind profile applied.
- The impact on the quality of the supply in terms of harmonic propagation of generated current and voltage by the use of converters power electronics.

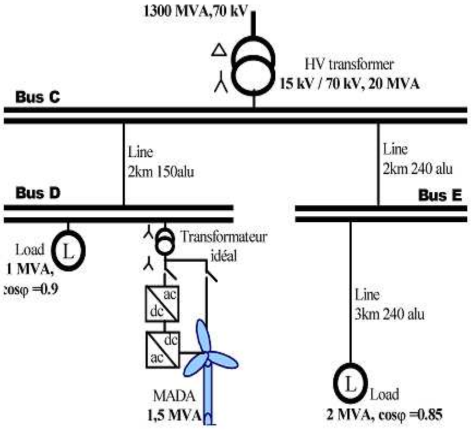

Fig.5 Studied DFIG wind turbine integrated in the electrical network.

Particular modelling of the power converters is developed to take into account these harmonics. The analysis of the studied power converters considers that semi conductors are similar to ideal switches, and they are modelled by switching functions. This modelling is a compromise between the desired precision and the necessary computation time. Then the generalized modelling and control strategy of this system is presented. The proposed global model is simulated with the help of Matlab-Simulink™. By considering a 1.5 MW doubly fed induction generator, we evaluate technical requirements, impacts and limitations on power quality of integrating distributed wind generation into an electrical network simulated by means of Sim power system toolbox. A comparison of two different DFIG control strategies during network balanced and unbalanced faults, is shown.

E. Turbine modelling

Wind turbine is characterized by its aero dynamical torque, which is given by:

$$T_a = C_p(\lambda,\beta)\frac{\rho.S}{2}v^3\frac{1}{\Omega_t} \qquad (1)$$

Ω_t is the angular speed of the turbine, v is the wind speed, β is the pitch angle, S is the swept area of the turbine and ρ is the air density. The power coefficient $C_p(\lambda,\beta)$ represents the aerodynamic efficiency of the wind turbine. It depends on the blade design, the tip speed ratio λ and the pitch angle of the blades β. The tip speed ratio is defined as the ratio between the blade tip speed and the wind speed:

$$\lambda = \frac{R\Omega_t}{v} \qquad (2)$$

R is the blade length.

For a constant pitch angle, the C_p characteristic has to be extended according to the speed ratio. A mathematical expression of the $C_p(\lambda,\beta)$ characteristic has been obtained from these data by using an approximate equation [4] [5]:

$$C_p(\lambda,\beta) = \frac{0.5-1.7(\beta-2)}{10}\sin\left[\frac{\pi.(\lambda+0.1)}{18-0.3(\beta-0.2)}\right] - \frac{1.8}{1000}(\lambda-3)(\beta-2) \qquad (3)$$

F. Power monitoring of the generator

From measured data [6], the power versus speed characteristic is drawn in fig. 6 and highlights the global strategy of the power control. After the starting, a control strategy is designed to extract the maximum power from the wind by setting a torque reference in the Maximum Power Point Tracking (M.P.P.T.) region. This implies large variations of the mechanical speed and large variations of the electrical power. A simple strategy consists in tracking the maximum power by varying the mechanical speed. Hence the expression of the electromagnetic torque reference is proportional to the mechanical speed of the generator, which is sensed:

$$T_{em\_reg} = k\hat{\Omega}^2 \quad (4) \text{ With } k = \frac{C_{p\_max}}{\lambda^3_{C_{p\_max}}}\frac{\rho}{2}\pi\frac{R^5}{G^3} \quad (5)$$

In a third region, the speed is regulated to a value a little bit higher than the synchronous speed to get a hyper synchronous operation. For this operation, the torque reference is set by a closed loop control of the speed (to the value 1750 rpm, see Fig.6). Hence the electrical power is nearly proportional the torque. In the last region, a pitch control enables to limit the power to the maximum rated value (1.55 MW) while the tip speed ratio is forced to decrease the power. From this characteristic, a power monitoring can be derived according to the four regions in order to set a prescribed torque-speed curve in the model (that the DFIG has to track).

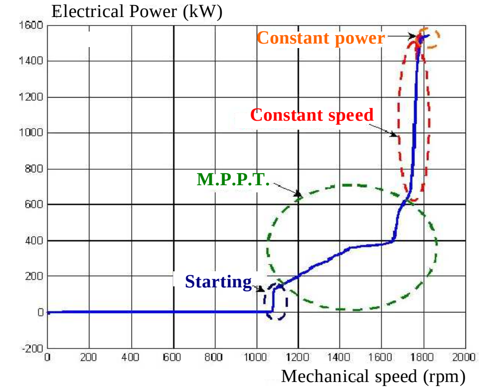

Fig.6 Operating regions of the studied WECS.

G. Power monitoring of the grid connection

The power flow in the power electronic cascade is bidirectional. In a second Park frame (synchronized with the grid), exchanged powers through the filter are expressed as the grid connection as [7]

$$P_t = v_{s_d} i_{t_d} + v_{s_q} i_{t_q} \qquad (6)$$

$$Q_t = v_{s_d} i_{t_q} - v_{s_q} i_{t_d} \qquad (7)$$

i_{t_d} and i_{t_d} are Park components of transmitted currents ($\underline{I_t}$). If the second Park frame is synchronized such that $v_{s_d} \approx 0$ the active power and reactive power can be respectively controlled by i_{t_q} and i_{t_d} . Then we can get a wished power factor (STATCOM mode) by setting the d current reference as:

$$i_{t_{d\_ref}} = \frac{Q_{t_{ref}}}{\widehat{v}_{s_q}} \qquad (8)$$

The q current component is used to control the active power transfer:

$$i_{t_{q\_ref}} = \frac{P_{t_{ref}}}{\widehat{v}_{g_q}} \qquad (9)$$

Both current references are sent to the “grid side controller”. The active power comes from the converted rotor power ($P_{r\,m}$) and the variation of the capacitor DC power. Hence the active power reference is:

$$P_{t_{ref}} = \widetilde{P}_{r\,m} - \widehat{u}\, i_{c\_ref} \qquad (10)$$

The estimation of the converted power is expressed as:

$$\widetilde{P}_{r\,m} = \widehat{u} \left\langle i_r \right\rangle \qquad (11)$$

$\left\langle i_r \right\rangle$ is the equivalent mean value of the modulated current. The capacitor current is set to control the DC voltage to a prescribed value by a PI controller.

IV. VALIDATION OF THE SYSTEM AND GRID INTEGRATION

H. *Comparison with experimental data*

In order to appreciate the accuracy of this model we compare sensed data with simulated results obtained in the same conditions. So the sampled wind speed data are used to feed our model. We present comparisons in dynamic state to highlight wind speed variation effects in one of three studied operating domains: the M.P.P.T. mode (Fig. 7). The closest results are obtained in constant power mode and constant speed mode.

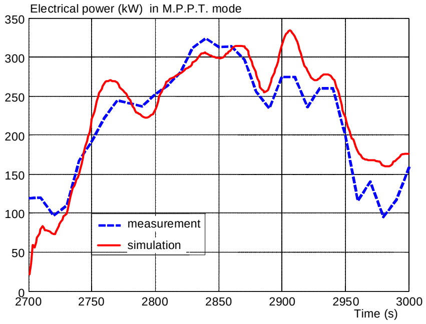

Fig.7 Electrical power in MPPT mode.

I. *Study of harmonic propagation*

The electrical network and its parameters of Fig. 5 have been proposed by the industrial company Laborelec (Belgium). Fig. 8 shows the spectral analysis of one transformer current. The grid frequency is 50Hz and the modulation frequency of power electronic converters is 5 kHz. In the transformer current spectral analysis, we find harmonics due to the switching frequency of the converters with a magnitude of about 0.4% of the RMS current.

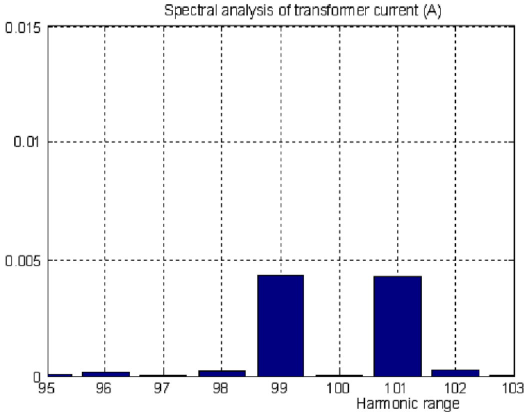

Fig.8 Spectral analysis of total current in the transformer.

J. *Study during grid disturbances*

In this study, two control strategies of stator flux control will be compared in order to show their influence on the dynamical behavior of the wind energy conversion system against voltage dips. A three-phase fault, causing a voltage dip of 20 % depth and 200 ms duration at the DFIG connection point, will be considered (Fig. 9).

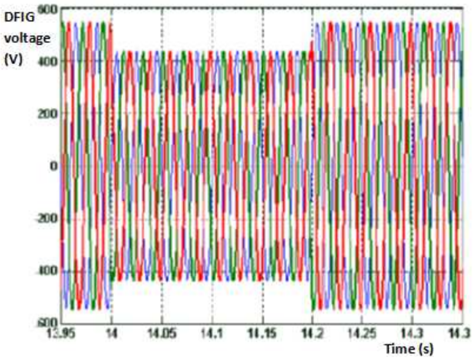

Fig.9 Voltage applied to the DFIG

Without a closed-loop control on the stator flux, we can observe an oscillation of the flux during the voltage dip (Fig. 10). This oscillation is significantly damped when using a closed-loop control of the stator flux. However, with this approach, we can notice a small overshoot on the nominal value of this flux. The stator current and so the total generated current oscillates according to the used approach, On the one hand the voltage dip does not affect the total generated current when the synchronous approach is applied. On the other hand; we can observe that a closed-loop control of the stator flux results in larger oscillations and transient unbalance on stator currents. This induces high magnitudes of short-circuit currents.

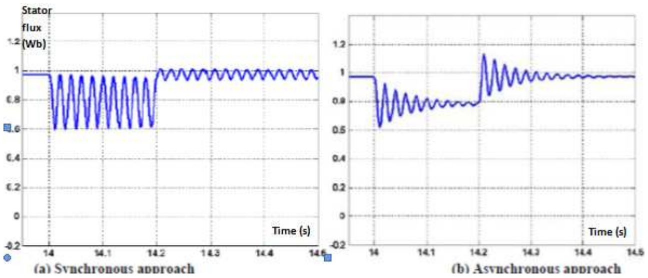

Fig.10 Time evolution (in s) of the stator flux

Obtained simulation results are different according to the used control strategy. On the one hand, the asynchronous approach regulates the stator flux by a closed-loop control, and then the variation of the e.m.f. (V_{s0}) at the stator circuit is very important when the grid voltage (E) decreases (Fig. 11). It is the origin of high magnitudes on the generated current. On the other hand, by using the synchronous approach, the magnitude of the e.m.f. in the stator decreases (naturally), thus, the stator flux decreases too. This leads to reduced magnitudes of the transient currents in the stator. This approach is more interesting in terms of power quality.

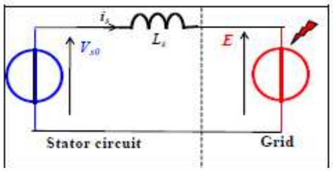

Fig.11 Conclusion on the two approaches

V. CONCLUSION

Many questions remain about how wind turbines can be integrated massively and systematically in electrical networks. The responses to be put into perspective by the wind technology used to convert wind energy into electrical energy. Indeed, the number of high wind speed sites is limited; manufacturers are developing wind power increasingly important in order to maximize benefits from exploitation of this resource. Since the power levels of these turbines are generally connected to the medium voltage distribution network in the case of single machines or small sets of few units, wind farms larger (tens of machines) must be directly connected to high voltage on the transmission network; this is what is intended particularly for off-shore plants. In this paper we have investigated integration a wind energy system into the grid. These investigations are performed with a model taking into account ideal switches for power converters. The latter allows evaluating harmonics due to the switching frequency in the distribution grid. This WECS model has been evaluated through the estimation of propagated harmonics into a distribution network.

A Dynamic behavior of the WECS has been investigated during a typical disturbance (voltage dip) of the electrical network. The synchronous approach seems to give best performances onto the grid current during the grid disturbances. The problems associated with wind sensitivity, compared to network faults were then exposed. Again there are solutions through the use of systems for dynamic recovery voltage (Dynamic Voltage Restorer). One may also consider a reconfiguration of the control strategy of the turbine, which in these operating conditions shall no longer function in extracting the maximum power but come to backup utility. This service is also an illustration of the possible contribution of the DFIG based WECS to the service system.

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