Contents
Author Index
Home

15th INTERNATIONAL SYMPOSIUM on
POWER ELECTRONICS - Ee 2009
XV Međunarodni simpozijum Energetska elektronika – Ee 2009
NOVI SAD, REPUBLIC OF SERBIA, October 28th - 30th, 2009

CONNECTION OF A DFIG-BASED WIND FARM TO THE TRANSMISSION NETWORK

Igor Kuzle, Davor Škrlec, Darjan Bošnjak, Tomislav Capuder, Hrvoje Pandžić,
Faculty of electrical Engineering and Computing, Zagreb, Croatia

Abstract: *The growing concerns regarding electric power quality and availability have led to the installation of more and more distributed generation. This paper presents some of the power electronics interfaces necessary for the connection of the large scale wind farms to the power systems. The paper also includes a simulation of a large-scale wind farm Vucipolje connection to the Croatian power grid. It shows the possibilities for power delivery to the rest of the system with an emphasis put to flicker emissions and upper harmonics.*

Key Words: ***Wind power generation, Induction Generators, Power Electronics, Wind Energy***

1. INTRODUCTION

Wind power is becoming an increasingly significant source of energy. The community is looking more and more towards wind power to provide a renewable source of energy, with rising fuel prices and growing concern over the presence of greenhouse gases in the atmosphere. During the last decade, wind power capacity has increased at an astounding rate, and the costs of harnessing wind energy have been continually decreasing [1]. At the end of 2005, the total installed capacity of wind power in Europe had reached the landmark of 40500 MW, and the capacity is continually growing.

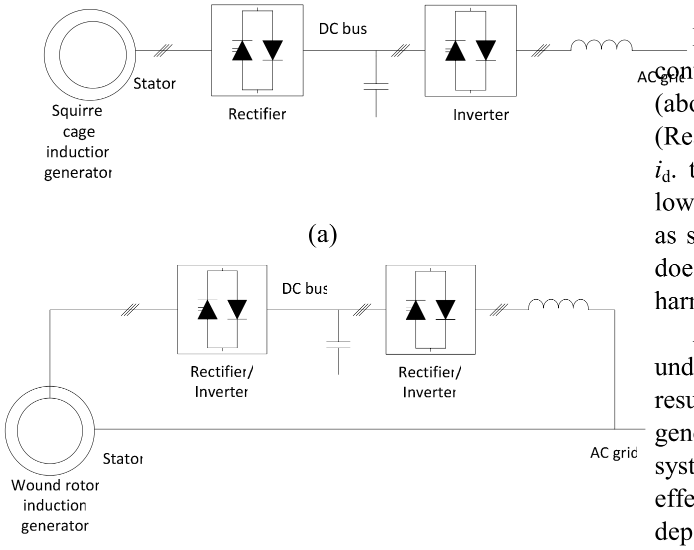
The stability and reliability of the power system depends strongly on the penetration of wind farms in such systems. Consequently the Operators have modified their Grid Codes in the last years to improve the integration of the large wind farms to the grid. Wind farms must maintain uninterrupted generation throughout power system disturbances, supporting the network voltage and frequency, and therefore, extending features such as low voltage ride through, or reactive an active power capabilities. Low voltage ride through is particularly important to maintain the voltage stability, especially in areas with high concentration of wind power generation. If the wind turbine is not designed to achieve these requirements and disconnects from the grid during a power system disturbance, this may result in severe stability failures in the grid, which in turn could amplify the disturbance.

Due to the policies and incentives offered in the developed countries, the industry has developed a technology that allows large wind farms to be considered as a serious alternative to traditional power plants. The more relevant advances in this field have been based in the Double Fed Induction Generator and the power electronics that allows the wind turbine accomplish with the code of each country for a safe operation of the electric grid.

Many of the newer, larger turbines being produced are variable speed turbines, which use doubly fed induction generators (DFIGs). These are induction generators which have their stator and rotor independently excited. Because of their variable speed operation, wind generators of this type can be controlled to extract more energy from the wind than squirrel cage induction generators. Additionally, DFIGs have some reactive power control capabilities and other advantages. The effect of DFIG converters have not been considered in this paper.

2. WIND TURBINES

The wind turbine can be operated at either constant or variable speed and coupled to either a synchronous or induction generator producing power system frequencies. The latter has been widely used due to simplicity and lower cost. The variable speed turbine has a simpler mechanical system and is the preferred solution in newer installations. Fig. 2 (a) shows an induction generator system. An alternative method of operating the induction generator is by means of the Scherbius drive scheme. These systems were implemented in the past as slip energy recovery systems based on a diode rectifier fed a dc current link into a thyristor inverter connected to the ac grid. The line commutated converters are being replaced with self commutated, typically IGBT based, converters, Fig. 1 (b) [2]. The rotor is fed at a frequency such that the sum of the mechanical and the rotor slip frequencies is equal to the ac grid frequency. The power rating of the converters depends upon the speed range selected. The converter system can reverse power which allows operation of the induction generator above rated synchronous speed.



(a)

(b)

Fig. 2. *Wind turbine electrical system.*
(a) Variable speed induction generator and
(b) Doubly fed induction generator

3. POWER ELECTRONIC INTERFACE FEATURES AND CAPABILITIES

In the scheme presented above the interface to the ac grid uses a self commutated Pulse Width Modulation (PWM) dc/ac inverter. This interface allows the generation scheme to be configured for a number of functions as described below. Some of these functions have been previously implemented on ac synchronous generators through the excitation system, namely for reactive power control, power system stabilization and power system damping. It should be noted that a number of these functions cannot be implemented using the more conventional power interface scheme: for 'example, induction generators and thyristor converters do not allow control of the reactive power, since they draw an amount of reactive that is related to the operating conditions.

A. Power quality issues

Generators equipped with rotating Converters, either induction or synchronous generators, produce sinusoidal voltages, assuming the machine harmonics have been taken care of (distortion induced 3rd harmonic and slot harmonics, typically 18th or higher). However, static power converters may inject significant harmonic currents into the ac system. This is the case for the following:

a) Thyristor converters, which can be viewed as current sources. Six pulse converters typically inject odd harmonics of order 5, 7, 11, 13, ...
b) Self commutated six pulse converters operating at fundamental frequency, in which case the harmonic orders are the same as for thyristor converters, or operating at low frequencies, a few hundred Hz (GTO based).

However, typical self commutated voltage source converters switch at effective frequencies above 1 kHz (above AC Grid Fig. 2. Current regulated PWM inverter. (Real power component: i_d, reactive power component: i_d. the 17th harmonic) and do not introduce significant low frequency harmonics. They can therefore be viewed as supplying clean power. This assumes that the ac grid does not have resonant frequencies at one of the inverter harmonic frequencies.

Although &e voltage produced may be sinusoidal under steady state conditions, there may be transients resulting in flicker with some types of distributed generation, particularly wind and photovoltaic energy systems. This is the result of varying output power. The effect on the voltage at the point of connection will depend upon the strength of the ac grid to which the DG is connected and the speed of response of its voltage regulator. In addition, the control of the DG must take into account the possible voltage unbalance of the ac grid.

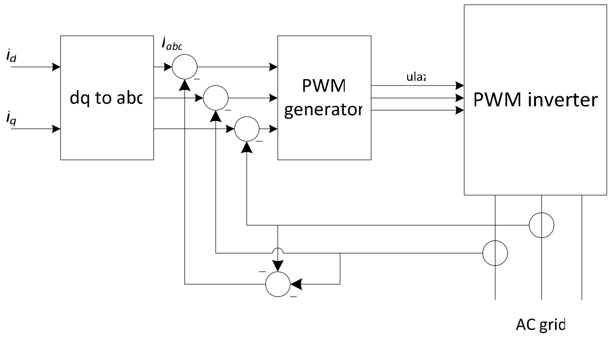


Fig. 2. *Current regulated PWM inverter*

B. Power flow control

The converter can be considered as a static synchronous ac source, coupled to the ac grid through a reactor, in many cases provided by the coupling transformer. Since the converter is self commutated, it can produce an ac voltage of an arbitrary amplitude and phase, Fig. 5 (b). In a manner similar to synchronous generators, Fig. 5 (c), there are two control variables:

1) The position of the fundamental component of the inverter output voltage V_{c1} relative to the ac grid voltage V_L, defined by the load angle 6, Fig. 5 (d). The power transferred from the inverter to the ac grid, on a per phase basis, is given by:

$$P = \frac{V_L V_{c1}}{X}\sin\delta = V_L I_{L1}\cos\Phi$$

2) The amplitude of the inverter output voltage V_{c1}, controlled by the modulation index of the PWM pattern generator. This amplitude directly controls the amount of reactive power drawn or injected into the ac grid:

$$Q = \frac{V_L(-V_L + V_{c1}\cos\delta)}{X} = V_L I_{L1}\sin\Phi$$

where X is the coupling reactance between the inverter and the ac grid. The reactive power depends upon the angle between the line current fundamental component I_{L1} and the grid voltage V_L. The inverter can therefore be operated at any desired power factor, including unity power factor. This is in contrast to line commutated converters that always operate at a lagging power factor. In typical applications, the power factor may be 0.8, corresponding to a reactive power of 0.6 pu. This reactive power is usually supplied by the ac grid, or in large installation, by power factor correction capacitors. Self commutated converters therefore have a lower kVA converter rating.

However, it may be desirable to operate the DG system so it supplies reactive power to the grid. In the current mode, this is achieved by adding a reactive current, i4, component to the reference inverter current id defining the real power transfer, Fig. 2. The *d* and *q* axis currents can be controlled independently. Supplying reactive power however significantly increases the converter kVA rating. If a reactive power of 0.6 pu is supplied in addition to the 1.0 pu real power, the converter rating increases by 17 % to 1.17 pu. For 1.0 pu reactive power, this figure increases to 1.4 pu.

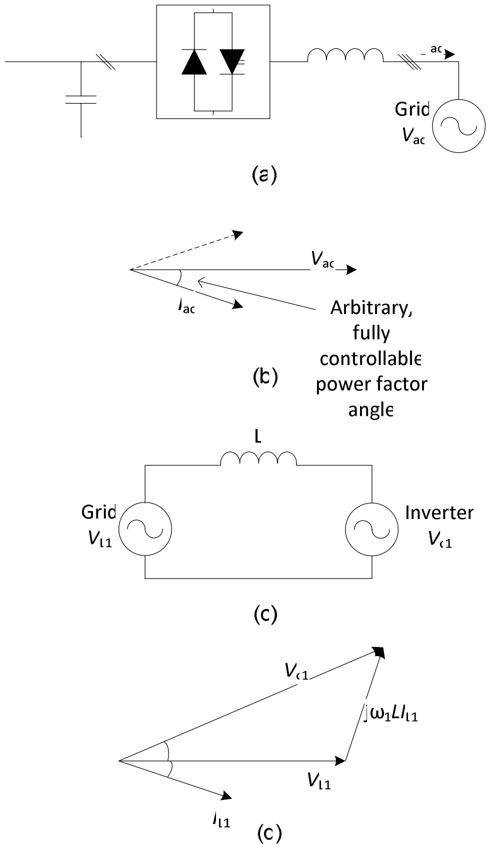


Fig. 3. *PWM inverter power control.*
(a) Simplified representation. (b) Voltage-current relation.
(c) Per phase equivalent circuit at fundamental frequency
$(V_{L1} = V_I j\omega L = X)$.
(d) Phasor diagram at the fundamental frequency.

4. CASE STUDY

This case study includes a simulation of a large-scale wind farm Vucipolje connection to the Croatian power grid. It shows the possibilities for power delivery to the rest of the system while considering the system security. An emphasis is put to flicker emissions and upper harmonics. The wind farm consists of 41 asynchrous generators with the rated power of 2 MW. It is connected to the 110/35 kV transformer substation. All calculations were carried out in the power system analysis tool NEPLAN.

C. *Flicker emissions and upper harmonics*

Flicker emission and upper harmonics analysis is based on the IEC61400-21 International standard [3]. It provides a uniform methodology that ensures consistency and accuracy in the measurement and assessment of power quality characteristics of grid connected wind turbines (WTs). In this respect the term power quality includes those electric characteristics of the WT that influence the voltage quality of the grid to which the WT is connected.

The Standard defines a normalized measure of the flicker emission during continuous operation of the wind turbine:

$$c(\Psi_k) = P_{st,fic} \cdot \frac{S_{k,fic}}{S_n}$$

where:

$P_{st,fic}$ is the flicker emission from the wind turbine on the grid;

S_n is the rated apparent power of the wind turbine;

$S_{k,fic}$ is the short circuit apparent power of the grid.

The flicker coefficient for continuous operation is the same for short-term (10 min) and long-term period (2h). A normalized measure of the flicker emission due to a single witching operation of the wind turbine is:

$$k_f(\Psi_k) = \frac{1}{130} \cdot \frac{S_{k,fic}}{S_n} \cdot P_{st,fic} \cdot T_p^{0,31}$$

where:

T_p is the measurement period, long enough to ensure that the transient of the switching operation has abated, though limited to exclude possible power fluctuations due to turbulence. A normalized measure of the voltage change due to a switching operation of the wind turbine is:

$$k_u(\Psi_k) = \sqrt{3}\,\frac{U_{fic,\max} - U_{fic,\min}}{U_n} \cdot \frac{S_{k,fic}}{S_n}$$

where:

$U_{fic,\,min}$ and $U_{fic,max}$ are minimum and maximum one period RMS values of the phase-to-neutral voltage on the fictitious grid during the switching operation.

The characteristics are stated for the following types of switching operations:

3) Wind turbine start-up at cut-in wind speed.

4) Wind turbine start-up at rated wind speed.
5) The worst case of switching between generators (applicable only to wind turbines with more than one generator or a generator with multiple windings).

For each of the above types of switching operations, the values of the following parameters must be considered:

1) The maximum number N10 of the switching operation within a 10 min period.
2) The maximum number N120 of the switching operation within a 2 h period.
3) The flicker step factor k_f (ψ_k) for the network impedance phase angles ψ_k = 30°, 50°, 70° and 85°.
4) The voltage change factor k_u (ψ_k) for the network impedance phase angles ψ_k = 30°, 50°, 70° and 85°.

For a wind turbine with a power electronic converter, the wind turbine's emission of harmonic currents during continuous operation shall be stated. These shall be stated for frequencies up to 50 times the fundamental grid frequency (see note 5), as the individual harmonic currents and the maximum total harmonic current distortion. The individual harmonic currents shall be given as 10 min average data for each harmonic order at the output power giving the maximum individual harmonic current. The values shall be specified in a table as a percentage of the rated current. Harmonic currents below 0,1 % of the rated current for any of the harmonic orders need not be specified.

Table 1 shows the maximum number of switching operations for the 10 and 120 minute periods for three characteristic

TABLE I

Switching operations	N_{10}	N_{120}
Start up at cut in wind speed	4	20
Start up at rated wind speed	2	10
Switching delta wye	2	10

Flicker emissions at the characteristic phase angles and the characteristic wind speeds are listed in the table 2.

TABLE II

ang	30°	50°	70°	85°
	c (ψ_k, v_a)			
6,0	2,0	2,0	2,1	2,1
7,5	2,0	2,0	2,1	2,1
8,5	2,0	2,0	2,1	2,1
10,0	2,0	2,0	2,1	2,1

Tables 3, 4 and 5 display the flicker step factor and the voltage step factor at various phase angles and different switching operations.

TABLE III START-UP AT CUT-IN WIND SPEED

Angle ψ_k	30°	50°	70°	85°
$k_\mathrm{f}(\psi_\mathrm{k})$	0,01	0,01	0,01	0,01
$k_\mathrm{u}(\psi_\mathrm{k})$	0,09	0,07	0,04	0,01

TABLE IV START-UP AT RATED WIND SPEED

Angle ψ_k	30°	50°	70°	85°
$k_\mathrm{f}(\psi_\mathrm{k})$	0,05	0,04	0,04	0,04
$k_\mathrm{u}(\psi_\mathrm{k})$	0,96	0,71	0,39	0,16

TABLE IV WORST CASE SWITCHING BETWEEN GENERATORS

Angle ψ_k	30°	50°	70°	85°
$k_\mathrm{f}(\psi_\mathrm{k})$	0,05	0,04	0,04	0,04
$k_\mathrm{u}(\psi_\mathrm{k})$	0,96	0,71	0,39	0,16

Table 5 shows the harmonic currents (as a percentage of the rated current) for the harmonics that are larger than 0,1% of I_n.

TABLE V

Order	Harmonic current [% I_n]	Order	Harmonic current [% I_n]
2	0,2	3	0,1
4	0,2	5	0,8
6	0,2	7	0,2
10	0,1	11	0,5
32	0,1	13	0,2
46	0,1	29	0,1
48	0,2	31	0,2
50	0,1	33	0,1
		35	0,1

D. Power flows and the short circuit current calculation

The calculation results show that it is possible to connect the wind farm Vucipolje to the Croatian power grid. The only prerequisite is the construction of a new 110 kV power line which connects the wind farm connection point with the rest of the power system. The new power line will also have a positive impact on the power system security. Conclusions Also, the analysis shows that the flicker emissions and harmonic currents are in compliance with the IEC61400-21 International standard. Because of the size of the simulation output data, the calculation results were not listed in this paper.

The existing power lines would be sufficient for the wind farm Vucipolje alone, but other planned wind farms were also included in the calculation.

The simulation includes three scenarios concerning other generation units:

- a normal winter day,
- maximum generation and consumption and
- minimum consumption and maximum hydro generation.

Also, the assumed concurrency factor was 1,0 which is highly unlikely to happen in reality because the planned wind farms are geographically very close.

Contingency analysis shows that tripping of the several transmission lines close to Vucipolje causes overloads and requires generation reduction in the wind farms.

5. CONCLUSIONS

This paper demonstrates that it is possible to connect a large-scale wind farm to the Croatian power system. The simulation shows that it would be possible to deliver the required amounts of energy to the rest of the system. Also, the flicker emissions and the harmonic currents are in compliance with the EC61400-21 International standard.

The paper also demonstrates the potential of distributed generation systems equipped with an appropriate power electronic interface to perform functions other than the supply of real power to the grid. These additional functions however require the use of dc/ac self commutated PWM inverter interfaces, such as are found in the newer distributed generation systems. The functions that can be performed include those of conventional synchronous generators such as reactive power compensation

6. REFERENCES

[1] K. Elkington, V. Knazkins, and M. Ghandhari, *On the Rotor Angle Stability of Power Systems with Doubly Fed Induction Generators*

[2] G. Joos, B.T. Ooi, D. Mcgillis, F.D. Galiana and R. Marceau, *The potential of Distributed Generation to Provide Ancillary Services*

[3] Power Quality Measurement IEC 61400-21

[4] J.A.Fuentes, M. Canas, A. Molina, E.Gomez, F. Jimenez, I*nternational Review of Grid Connection Requirements related with Voltage dips for Wind Farms*

[5] D. Škrlec, I. Kuzle, M. Delimar, D. Bošnjak, T. Capuder, H. Pandžić, *Preliminary Analysis of Connection Possibilities of Wind Power Plant Vučipolje to the Transmission Power Grid*