Torque fluctuation and critical clearing time in wind power generation by induction machines

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Abstract. Squirrel cage induction machines represent a common solution widely adopted in wind generation. The induction machine is simple, reliable, cheap and requires very little maintenance. Some problems are, however, connected with the use of induction machines in wind power generation systems. In particular two effects have to be taken into account: the torque fluctuations at the generator shaft and the critical clearing time (CCT). Both problems represent a serious limitation for weak networks in which the first effect can cause flicker effect while the CCT is very short. In the paper a full modelling of a wind energy plant constituted by *n* machines is presented. Using the set-up model the behaviour of the plant for a different number of connected machines is analysed. In particular, the system stability connected with voltage sags and network faults is studied.

1. Introduction

Generation of electricity using wind power has received considerable attention worldwide in recent years. The continuous trend of increasing the number of integrated Wind Power Based Embedded Generators (WPBEGs) is likely to influence the operation of existing distribution networks as well as the design and planning of the future distribution networks.[1]
The choice of the electrical machine to be coupled with the wind turbine is a problem that can be solved only by taking into account many factors. The wind turbine operates the conversion of kinetic energy stored in the air mass into mechanical energy available at the turbine shaft. The efficiency of this conversion depends on the ratio between air mass velocity and turbine rotating speed. For this reason, to maximize the energy conversion efficiency it is necessary to regulate the rotating speed of the system. However, the speed regulation implies a more complex electrical generation system and, therefore, the choice of the electrical machine is a problem solved differently case by case.[2]

Based on electrical topology, commercial wind generators in the 1-2MW range can be organized in four categories[3]:

- Standard squirrel cage induction generator connected directly to the grid;
- Wound rotor induction generator with variable rotor resistance;
- Doubly fed asynchronous generator;
- Synchronous or induction generator with full size power converter.

At present, induction machines are widely spread because of their low costs, high reliability and low requiring of maintenance.
This paper deals with high power induction machines connected to weak networks. In the technical literature [3] it has been evidenced that in dynamic studies, a single large generator may not represent the full range of dynamic behaviour of the wind generation facilities for all types of system disturbance. For this reason a numerical model for simulating a WPBEG plant constituted by *n* induction machines has been realised and used to analyse either the flicker phenomenon or the CCT in presence of a voltage sag or a network fault. The results obtained are related to the number of machines that constitute the plant because simulations show that the dynamic behaviour of the plant depends on the number of the machines.
Wind turbines produce a not constant torque due to different aerodynamic effects; the most important of these effects is the tower shadow that for an *n*-blades turbine causes a torque oscillation at a frequency equal to *n* times the rotational speed. Because of the low rotational speeds the frequency of the torque oscillation is very low and, so, not filtered by inertia masses; this causes an oscillation in the current supplied by the generator. If the power of the generation unit is relevant compared to the network power at the junction the voltage across the generator can present flicker oscillations. However the use of more than one machine should reduce the flicker effect. In fact, the blades of the different turbines are, probabilistically, delayed and, therefore, the fluctuations in the currents injected by the

different turbines compensate themselves. Of course, the benefit is greater if the delay is uniformly distributed between the turbines. However, if the number of generators is sufficiently high the delay between the blades can be, reasonably, considered distributed.
The CCT of a WPBEG can be defined as the maximum fault duration that a fault can remain on a network feeder without having WPBEG losing its stability [1]. The problem of stability of the induction machine working as a generator grid connected is due to the fact that the electromagnetic torque is dependent, as a first approximation, on the square of the terminal voltage. When the last one goes down to zero the prime motor torque is not more compensated by an electromagnetic torque and the machine accelerates. If the increasing of the speed is big enough the induction motor slip overpass the value of maximum torque and the stability of the system is compromised. If this situation happens the system will find a new equilibrium working condition in the zone in which the asynchronous machine works as an electrical brake. This means that the machine will absorb both electrical and mechanical energy and dissipate it at its inside [4]. The final speed is, approximately, double than that of normal operations because the electromagnetic torque decreases for a speed increasing in brake operation.

2. System modelling

The generation system is constituted by *n* wind turbines coupled with *n* induction machines. All the turbines and the electrical machines are equal and are connected all together to a weak network. A schematic representation of the system is reported in fig. 1.

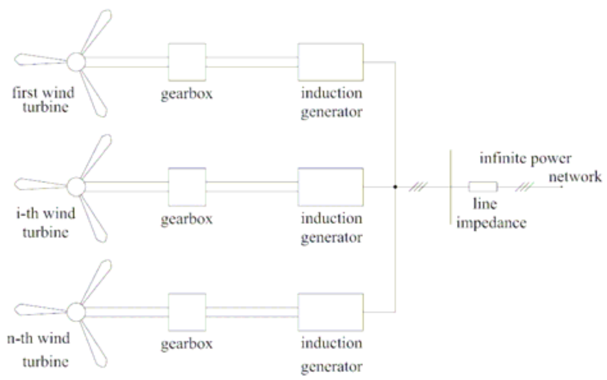

Fig. 1. Wind generation system scheme

A numerical model has been realised to simulate the system reported in fig 1 with any number of turbines. In this way the effect of the number of turbines on the flicker and on the CCT can be easily studied.
In order to simulate the behaviour of the whole system each component has to be modelled. The weak network can be modelled by an ohmic inductive impedance connected between an ideal voltage generator and the node to which the generators are connected. Values of phase resistance and inductance are function of the short circuit power and of the power factor of the network at the connection point by means of the following:

$$\begin{aligned} r_{cc} &= \frac{V_{\Delta}^{2}}{P_{cc}} \\ \frac{\omega\, l_{cc}}{r_{cc}} &= \tan(\arccos(\varphi)) \end{aligned} \tag{1}$$

in which ω indicates the voltage pulsation [2].
To simplify the analysis, and to make the simulations quicker, a model of the induction machine working as generator that doesn't take into account the saturation of the magnetic circuits of the machine has been used. The model, written in term of stator and rotor fluxes can be written as:

$$\begin{cases} \boldsymbol{v}_s = r_s\, \boldsymbol{i}_s + \dfrac{d}{dt}\boldsymbol{\Phi}_s\,; \\ 0 \;= r_r^{'} \boldsymbol{i}_r^{''} + \dfrac{d}{dt}\boldsymbol{\Phi}_r - j\, p\omega_r\, L_r\, \boldsymbol{\Phi}_r\,, \\ M_{el} = \dfrac{3}{2}\, p\, L_m\, \Im m\left\{ \overset{\vee}{\boldsymbol{i}}_s\, \boldsymbol{i}_r^{'} e^{jp\theta} \right\}; \\ M_{el} - M_r = J\, \dfrac{d^2}{dt^2}\theta. \end{cases} \tag{2}$$

in which the fluxes are defined as:

$$\begin{aligned} \boldsymbol{\Phi}_s &= L_s\, \boldsymbol{i}_s + L_m\, \boldsymbol{i}_r^{'}\, e^{jp\theta}\,; \\ \boldsymbol{\Phi}_r &= L_m \boldsymbol{i}_s + L_r \boldsymbol{i}_r^{'}\, e^{jp\theta}\,, \end{aligned} \tag{3}$$

The gearbox is considered ideal and modelled with a fixed ratio between turbine and generator speeds, then with the inverse ratio between the torques at the two shafts.
The wind turbine has been modelled as a prime torque in input to the electrical machine. This prime torque cannot be considered constant because of the tower shadow effect. This effect can be explained considering that the tower offers a resistance to air flow when this one passes through the blades. The torque produced, for a constant wind speed, is periodical function of the time and can be developed in Fourier series. Considering only the first term, the torque is:

$$\begin{aligned} T &= T_0 + T_1 \cos(\psi)\,; \\ \psi &= \omega_{rw} t \end{aligned} \tag{4}$$

For a 3 blade turbine, ψ varies in the range [-π/3, π/3], because it takes into account the angular displacement between the blade nearest to the tower and the tower itself [5]. The mean value of the torque produced by the turbine can be evaluated as:

$$T_m = \frac{1}{2}\rho\pi R^2\, \frac{v_w^3}{\omega_{rw}}\, C_p \tag{5}$$

where:

ρ = air density;

R = turbine radius;

v_w = wind speed;

ω_{rw} = turbine rotating speed;

C_p = power coefficient dependent on pitch blade.

The model of the whole generation system can be obtained by linking the models of each single turbine+generator unit. Writing of the model it has to be taken into account that at each induction generator is connected a capacitor for the power factor correction. All the capacitors are, of course, connected in parallel. The model for n machine, therefore, is:

$$\left.\begin{aligned} & \boldsymbol{v}_c = r_s\, \boldsymbol{i}_{sh} + \frac{d}{dt}\boldsymbol{\Phi}_{sh}\,; \\ & 0 \;= r_r^{'} \boldsymbol{i}_{rh}^{"} + \frac{d}{dt}\boldsymbol{\Phi}_{rh} - j\, p\omega_{rh}\, L_r\, \boldsymbol{\Phi}_{rh}\,, \\ & T_{elh} = -\frac{3}{2}\, p\, L_m\, \Im m\left\{ \overset{\vee}{\boldsymbol{i}}_{sh}\, \boldsymbol{i}_{rh}^{'} e^{jp\theta_h} \right\}; \\ & T_{wh} - T_{elh} = J\,\frac{d^2}{dt^2}\theta_h \end{aligned}\right\} \text{for } h = \{1..n\}$$

$$n\,C\,\frac{d\boldsymbol{v}_c}{dt} = \boldsymbol{i}_{cc} - \sum_{h=1}^{n} \boldsymbol{i}_{sh} \tag{6}$$

$$\boldsymbol{v}_g = r_{cc}\boldsymbol{i}_{cc} + l_{cc}\frac{d\boldsymbol{i}_{cc}}{dt} + \boldsymbol{v}_c$$

where

- $\boldsymbol{v}_c$ is the space vector of the voltage at the connection point;
- $\boldsymbol{v}_g$ is the space vector of the infinite power network voltage (see fig. 1);
- $\boldsymbol{i}_{cc}$ is the space vector of the current fed by the network;
- T_{wh} is given by the (4) and (5).

3. Simulation System

In order to compare the behaviour of the generation system at the variation of the number of wind turbines, the numerical simulations have to be done with a constant ratio between the rating power of the generation plant and the power of the network at the connection point. For this reason, the simulations have been done in such a way that n wind turbines are connected to a network with short circuit power equal to n times a *unitary* power defined as the power of the network to which a single turbine is connected.
Each induction machine is a 800 kW. Its main data are reported in tab. I.

Tab. I. Induction generator parameters

P_n [*kW*]	$V_{\Delta n}$ [*V*]	p	r_s [*Ω*]	r'_r [*Ω*]	l_s [*mH*]	l'_r [*mH*]	L_m [*mH*]
800	6000	4	1.6	0.92	20	20	529

The power of the generation system has been chosen about 10% of the network power at the connection point. So the *unitary* power is equal to 10 MW. At each induction machine is, moreover, connected a capacitor for the power factor correction. Of course, the n capacitors connected to the n induction generators are in parallel each other. The characteristic values of the network and of the capacitance, for a single machine, are reported in tab. II.

Tab.II. System parameters

r_{cc} [*Ω*]	l_{cc} [*mH*]	C [*μF*]
0.40	12.6	25

As above discussed the wind turbine has been modelled as a primary input torque. This torque, according to the above reported considerations, has been chosen as sum of a constant value and a sinusoidal component. The torque mean value is 221 *kNm* that corresponds, at 30 r.p.m. at an input power of almost 700 *kW*. The wind turbine torque versus time law is reported in fig. 2.

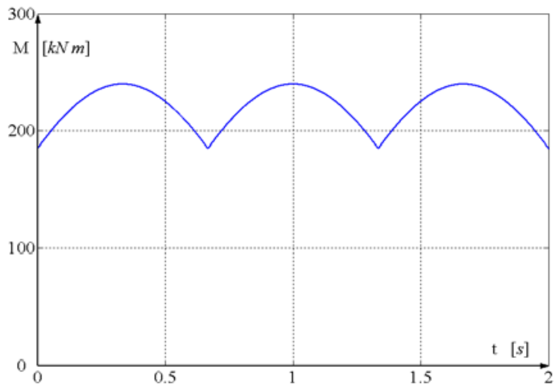

Fig. 2. Simulated wind turbine torque

4. Flicker effect

The system modelled as in (6), operating at steady state (with a infinite power network voltage equal to 1.05 p.u.), has been numerically simulated in Matlab® environment. The simulation has been effected with different number of machines. In the following, the results obtained for 1 and for 5 machines are reported. In particular in fig. (3), (4) and (5) the $\boldsymbol{v}_c$ module, the $\boldsymbol{i}_s$ module and the power supplied to the network are shown for a generation plant with a single machine. The same quantities are reported in fig. (6), (7) and (8) for a generation plant with 5 turbines.
From the analysis of fig. 3 it is evident the presence of the flicker effect due to the variation of the current, and consequently of the power, supplied by the asynchronous generator.
In the simulation the initial delay between the blades of

the different turbines has been supposed equal to $\pi/3n$. This causes the equal distribution of the currents (powers) supplied by the different turbines. This case is, of course, the best case for what concerns the flicker reduction. However, if the number of turbines grows enough, probabilistically, it is plausible an uniform distribution of the blade initial angular positions. The flicker effect, that is relevant in the case of one turbine, is negligible with only 5 turbines.

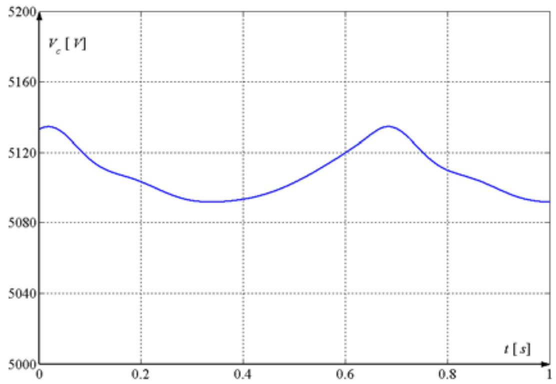

Fig. 3. Steady state connection point voltage space vector module with a single wind turbine

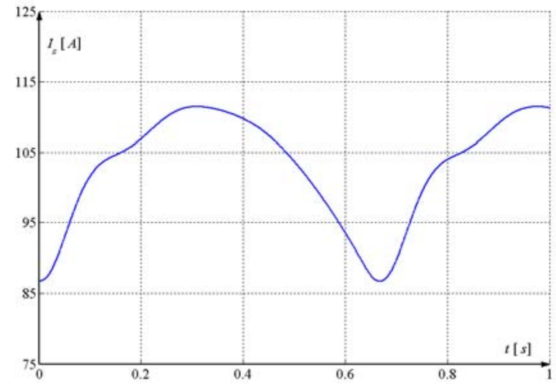

Fig. 4. Steady state induction machine current space vector module with a single wind turbine

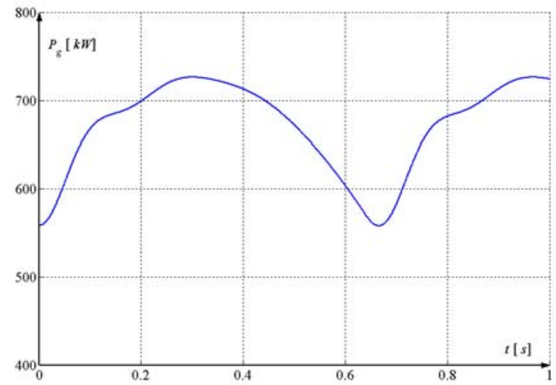

Fig. 5. Steady state electrical power supplied by the induction generator with a single wind turbine

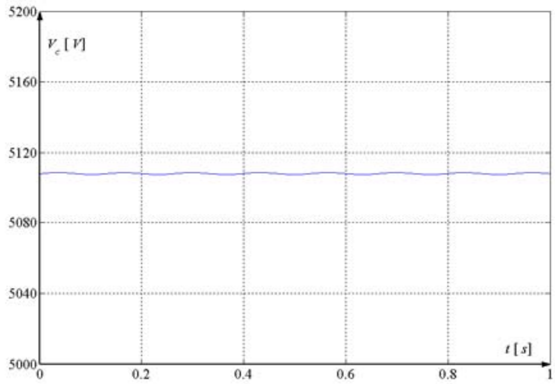

Fig. 6. Steady state connection point voltage space vector module with 5 wind turbines

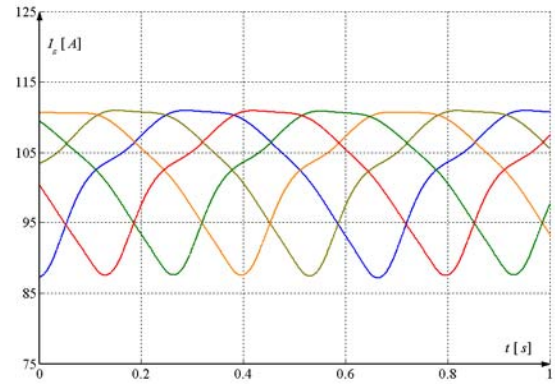

Fig. 7. Steady state vector modules of the currents supplied by the 5 wind turbines

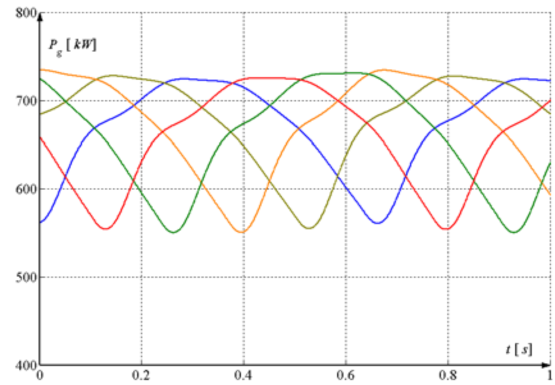

Fig. 8. Steady state electrical power supplied by the 5 wind turbines

5. Critical clearing time analysis

From the results reported in the previous section it is clear that the increasing of the number of machines, with an equal total power, improves the behaviour of the generation system for what concerns the flicker effect. On the other side, the numerical simulations carried out show that the more the number of machine increases the more the CCT reduces. The growing of the turbine number implies a reduction of the stability of the system.

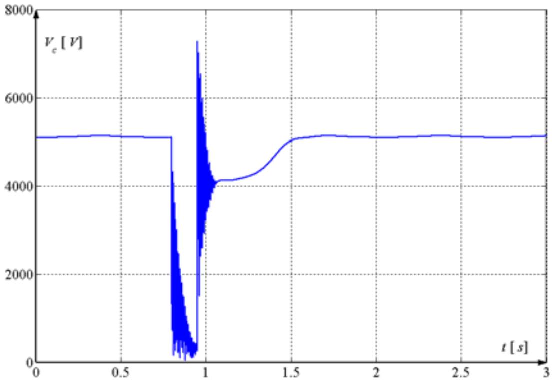

Fig. 9. Connection point voltage space vector module for a voltage drop (0.1 V_n, 150 ms) with a single turbine

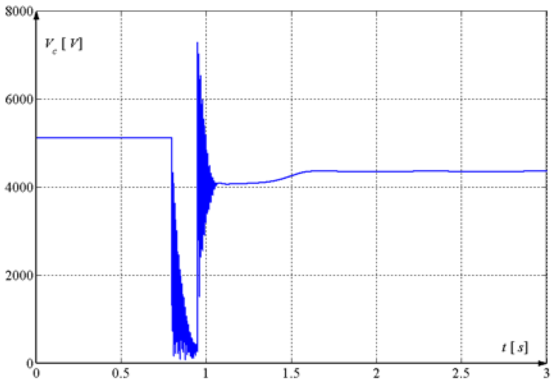

Fig. 10. Connection point voltage space vector module for a voltage drop (0.1 V_n, 150 ms) with 5 turbines

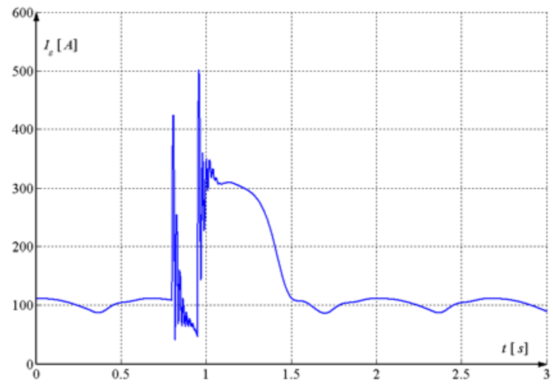

Fig. 11. Machine current space vector module for a voltage drop (0.1 V_n, 150 ms) with a single turbine

In order to evidence this result a voltage drop, (amplitude 0.1 V_n ,duration 150 ms) has been simulated. In the following the $\boldsymbol{v}_c$ module, the $\boldsymbol{i}_s$ module and the turbine speed are reported both for generation plants with a single and with 5 machines.

As it is clear from the analysis of the figures the particular considered voltage fault caused the loss of stability only of some of the machines (3/5). This can explain the different voltage level (with flicker effect present) and the different speed oscillation between the steady state conditions before and after the fault. It has to be noted also that, of course, the speed increasing of the machines that lost their stability does not last forever. A new stable working condition will be found with the induction machine working as a brake.

Moreover it has to be said that all the wind turbines in commerce, at present, are equipped with a system to limit their output power and speed. In future works the authors mean to analyse the effect of this mechanical control on the stability of the generation system.

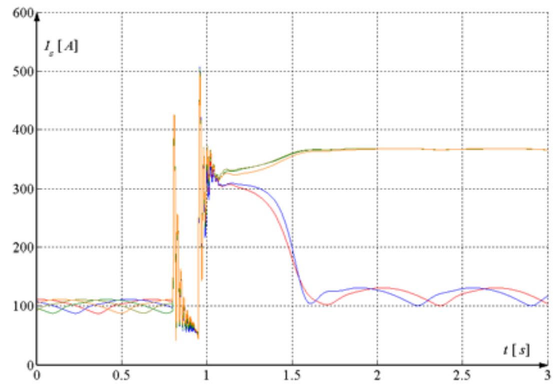

Fig. 12. Machine current space vector modules for a voltage drop (0.1 V_n, 150 ms) with 5 turbines

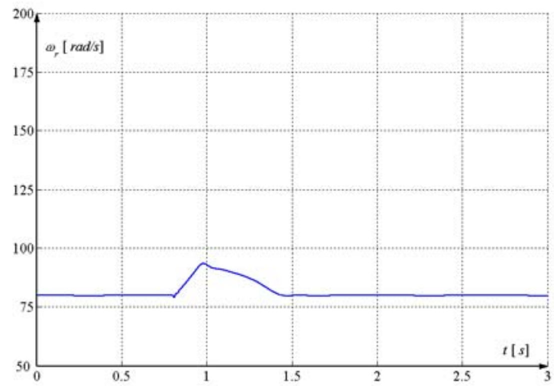

Fig. 13. Machine angular speed for a voltage drop (0.1 V_n, 150 ms) with a single turbine

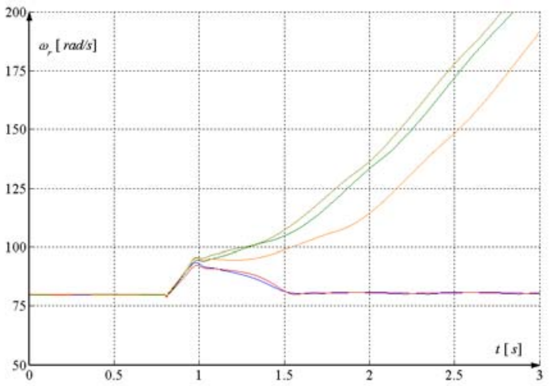

Fig. 14. Machine angular speed for a voltage drop (0.1 V_n, 150 ms) with 5 turbines

6. Conclusions

A model to simulate the behaviours of a wind generation plant equipped with *n* machines has been proposed. In particular, the case of connection of the wind generators to a weak network has been considered. The proposed model neglects either the saturation effect of the magnetic circuits of the induction machines or the control of the maximum power that is mechanically implemented in modern turbines.

The model has been used to analyse the influence of the number of machines on two main aspects of the generation system: i) the flicker effect at steady state; ii) the CCT and the stability of the system as consequence of a fault condition.

In order to make the results comparable the simulations have been done scaling the power of the network in function of the number of machines connected to it. From the analyses of the results it has been shown that the increasing of the number of machines is a favourable factor to reduce the flicker effect but can reduce the stability of the system.

As a future work the authors mean to complete the model including the effect till now neglected and to validate it with opportune experimental tests.

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