Simulations a Wind Power Generation with a Squirrel-Cage Induction Generator and Rectifier with Near Sinusoidal Input Current

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ABSTRACT
Taking into account that wind energy is green energy, one expects that its share in electricity generation to increase in the future. In the past years, we have witnessed a remarkable technologic progress, but, currently, the electricity produced from this source is not fully competitive, economically speaking. A wind system must extract maximum power when the wind speed has large variations [1, 2]. When it all started, certain installed wind turbines functioned at near constant speed.

KEYWORDS: *Power converters, power electronics, DC-AC conversions.*

I. INTRODUCTION

Generally speaking, constant speed solutions are characterized by a simple and reliable construction of the electrical parts, while the mechanical parts are subject to higher stresses and additional safety factors must be incorporated in the mechanical design. Most fixed speed turbines use induction generators. Figure 1(a) presents a version of the wind systems, with fixed speed and with partially variable speed. This wind turbine has a fixed speed controlled mechanism, with asynchronous squirrel cage induction generator (SCIG), which is directly connected to the grid through a transformer. This concept needs a reactive power compensator to reduce (to eliminate almost entirely) the demand for reactive power from the turbine generators to the grid. A smoother grid connection takes place when incorporating a soft-starter as shown in Figure 1(a). Regardless of the aerodynamic power control principle related to a fixed speed wind turbine, wind fluctuations are transformed into mechanical fluctuations and, further, into electrical power fluctuations. Thus, the main disadvantages of this solution are: it does not support speed control, it requires a stiff grid and its mechanical construction must be able to support a high mechanical stress produced by the wind.
In order to surpass these issued, the tendency of the modern wind turbine technology is, without any doubts, directed towards variable-speed concepts. The variable-speed systems offer a great amount of advantages [3-14]:

- the turbine can be adjusted to the local conditions or to imperfections related to blade characteristics;
- reduced aerodynamic noise at a low wind speed by decreasing the turbine speed;
- the useful energy captured on partial load is maximized through the optimal speed operation;
- reduced power fluctuations;
- reduced lengthy stress on the rotor blades and on the transmission system.

The doubly fed induction generator that uses a back-to-back PWM converter in the rotor circuit (Scerbius drive) has been for a long time a standard drive option for high-power applications involving a limited speed range according to Fig. l(b).

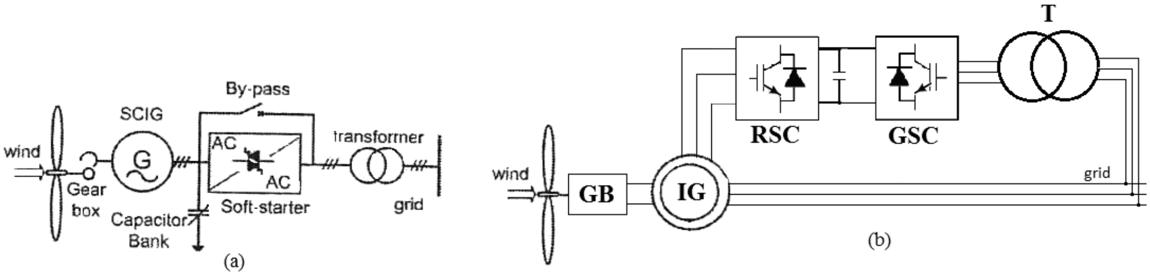

Fig. 1 Variants of wind systems with constant speed and partial variable speed. (a) Fixed speed wind turbine with directly grid connected squirrel-cage induction generator; (b) Double fed induction generator using back-to-back PWM converter

The stator is directly connected to the grid, while a partial-scale power converter controls the rotor frequency and thus the rotor speed. The power rating of this partial-scale frequency converter defines the speed range (typically ± 30% around synchronous speed). The smaller frequency converter makes these concepts economically attractive. In this situation, the power electronics is enabling the wind turbine to act as a dynamic power source to the grid. However, its main disadvantages are the use of slip-rings and the protection of schemes / controllability in the case of grid malfunctions. During the past few years, the total installed wind power capacity has exponentially increased from approximately 158 GW in 2009 to 283 GW by 2010 [3].

According to the British Wind Energy Association and the American Wind Energy Association, small-to-medium-scale (1-100 kW) wind turbines are found very often. In the United States small-to-medium scale wind turbines with outputs of up to l00 kW contributed in 2010 to 20% of the installed power generation.

The suggested wind farm can be an economical solution for small and medium wind turbines that have a power up to several hundred kW.

II. VARIABLE - SPEED WIND SYSTEM WITH A SCIG AND RNSIC CONVERTER

A variable - speed wind system is presented in Fig. 2. The electricity supplied by SCIG is transmitted within the network using a rectifier with near input current (RNSIC) of a boost converter and of a PWM inverter.

A new AC - DC converter has three capacitive steps [15- 19]. The first steps is constituted by capacitors C1 – C6, that are permanently connected in parallel to diodes D1 - D6. The second step is made of capacitors C11, C13 and C51, that are connected in series with switches K1, JC3 and K5. The third step is accomplished by connecting in series capacitors C41, C61 and C21 with switches K4, K6 and K2.

The RNSIC converter supplies reactive power for SCIG, in order to operate with partial speed. The capacitive steps allow a virtually constant magnetizing current when the generator speed varies within 70 % - 100 %.

The main advantage of the RNSIC converter is that it provides the stator current practically sinusoidal for the induction generator. This advantage is not obtained in the case of fixed speed wind turbines, where the stator currents have high harmonics. Compared with the wind system solution presented in [17], the converter suggested in Fig.2 ensures a more balanced load for capacitors and diodes.

In order to obtain a variable speed that depends on the wind speed, a boost DC- DC converter can be inserted in the DC connection, according to Fig. 1. The output voltage Vd from the RNSIC converter increases the value of Vdc and applies the input of the PWM inverter, connected to the network.

In order to obtain a higher power wind system of approximately 1-2 MW, more IGBT or GTO transistors can be connected in parallel. Fig .2 presents an AC - DC converter that generates harmonics of stator currents of low values in SCIG. The functioning of this converter is not influenced by current or voltage harmonics in the distribution network [15], [16]. We will take into account the load resistor of the rated value R_{Lr} and of the rated current $I_{(I)r}$.

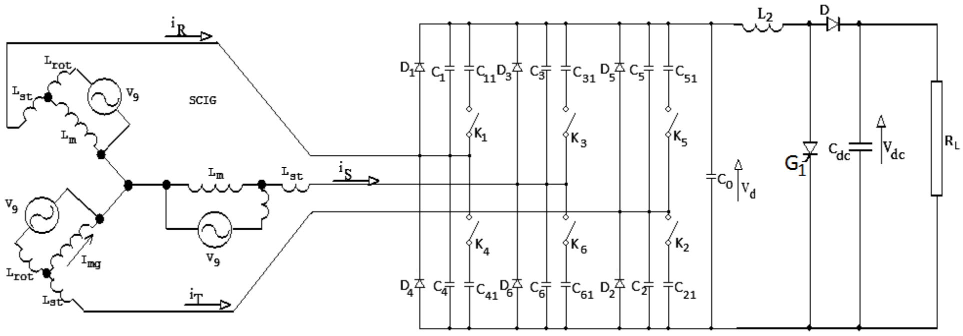

Fig.2 Wind system with SCIG and RNSIC converter

In the case where V_d represents the rectifier's average voltage, $V_{ref} = 3\sqrt{3}V_{max}/\pi$ represents the reference voltage characteristic for three phase rectifiers with diodes and V_{max} is the maximum magnitude of the AC input voltage. The rated rectifier voltage is $V_{dr} = V_{ref}/\left(1-2L_1C\omega^2\right)$.

The main features of the wind system suggested in Fig. 2 are: the RNSIC from its structure does not have the three L_1 inductors, according to Fig. 3. Their role is taken over by the three equivalent circuits L_{eq}, which are derived from the SCIG generators. Due to simplification reason, the L_{eq} inductors can be considered without any loss resistance and their inductance is made up only of the stator inductance L_{st}, rotor inductance L_{rot} and magnetization inductance L_m. The power supplies the V_g range from a minimum value V_{min} to a maximum one V_{max}. The ratio between these values is approximately 0.7. The replacement of the L_1 inductances with the L_{eq} ones maintains the stator currents I_R, I_S and I_T of the SCIG with THD % value lower than 5%.

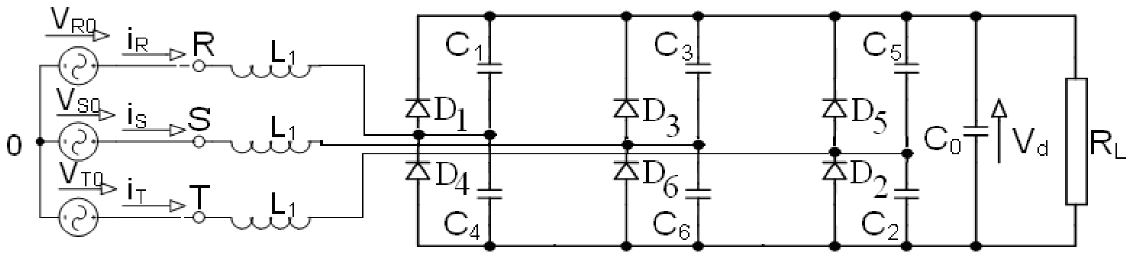

Fig.3 RNSIC converter with six DC capacitors

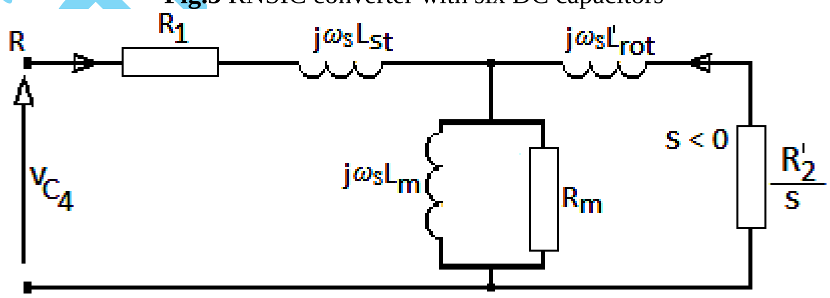

Fig. 4 The equivalent circuit of the induction generator in which the iron losses are taken into account

The equivalent circuit of the induction generator in which the iron losses are taken into account as they are presented in Fig. 4. Because of the negative value of the slip speed, the induction generator is able to deliver power to the network.

III. OPERATION OF THE INTRODUCTION GENERATOR CONNECTED TO THE PROPOSED WIND SYSTEM

The self-excitation process of the induction generator is presented in fig. 5, based on the existence of a remanence E_{rem} in the rotor [1]. For this generator, the RNSIC converter with several capacitive steps, represents a resistive capacitive load.

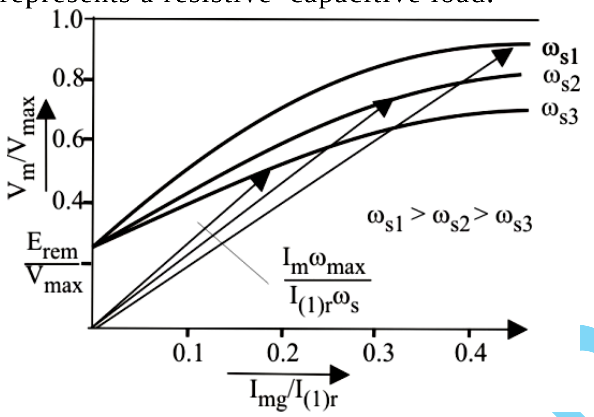

Fig. 5 Variations of ratio V_m/V_{max} as a function of $I_{mg}/I_{(1)r}$ for different values of ω_s

The φ angle between the phase voltage (for example V_{RO}) and the fundamental harmonic of the phase current [i.e. $I_{R(1)}$] is negative. If a single-phase capacitor is connected to the generator voltage induction capacitive current delivered by the battery, it decreases with the decrease of the frequency generator. It you use a battery with more sections, the magnetizing current $I_{mg} = I_{(1)r} \sin\varphi$ has a virtually constant amplitude without harmonics. The K_1-K_6 switches are controlled so as to ensure a virtually constant magnetizing current through the magnetizing inductance L_m.

Taking into account that currents i_R, i_S and i_t are practically sinusoidal and have amplitude t, according to the load resistance R_L, DC I_d can be calculated using the equation:

$$I_d = \frac{3I_{(1)}}{2\pi}\left(1+\cos\omega t_1\right) \qquad (1)$$

where the point of time t_1 is the opening of diodes D_1-D_6, equals $\frac{\pi}{\omega}$, then DC I_d will be canceled, and currents i_R, i_S and i_t are purely capacitive. This situation occurs in order to boost the converter.

The DC capacitors of the RNSIC converter ensure on the one hand the practically sinusoidal stator current for SCIG and on the other hand they contribute to 5% - 10% of the capacity C_o [17].

If the capacitor C_0 has a smaller capacity, for instance $C_0/2 = 1500\mu F$, the transient processes from the wind system are reduced practically in half. You can get such a period of transient decreased from 100 ms to about 50 ms. The boost converter consists of inductance L_2, capacitors C_0 and C_{dc} and GTO thyristors.

The switches can be made with two antiparallel connected thyristors. Because of the fact that these switches are traversed by low currents, the power losses are negligible. The average currents that pass through the switches do not exceed (3 - 6 %)$I_{(1)r}$ for the variation range of ω_s between ω_{min} and ω_{max}. These above mentioned average values are necessary in order to chose the thyristors of the switches.

The capacitors of the RNSIC converter, without inductances L_1, have a double role. First of all, they ensure near sinusoidal input currents i_R, i_S and i_t and second of all, certain capacitors connected in parallel with the capacitors C_0 at V_d allow a better load.

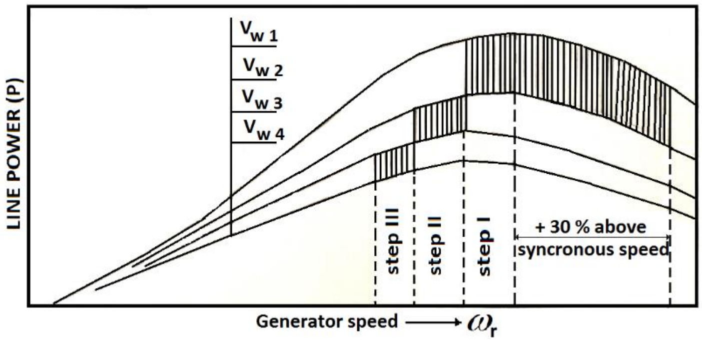

Fig. 6 Power transmitted to the hub shaft of different wind speed

Figure 6 presents the power variation P transmitted by the wind turbine of the shaft generator for different values of the wind speed V_w for three operating steps.

IV. SYSTEM COMPARISON OF WIND TURBINES

The comparison of the different wind turbines topologies in what concerns their performances will reveal a contradiction between cost and performance to the grid. Further reference is made only to certain variable speed wind systems, namely: wind system suggested on paper, double feed induction generator (DFIG) and brushless double fed induction generator (BDFIG).
(1) On equal power, the easiest generator is SCIG, which could have the RNSIC converter on the soil surface (without inductances L_1). This means that the reinforced concrete pillars used to support wind system require less reinforced concrete, in the case of the variant with SCIG [5]. For the reasons above, results that the investment in the SCIG system is smaller [10].
(2) DFIG can have a variation of speed limiters of 30% of speed synchronism.
However, its main disadvantages are the use of slip-rings and the protection schemes controllability in the case of grid faults. The three-phase transformer may have a power of approximately 30% of the DFIG generator power. It is necessary, even if the DFIG is directly connected to the grid, because voltages on the rotor rings must be limited [4], [5].
(3) The BDFIG shows commercial promise for wind power generation due to its lower cost and higher reliability with compared with the conventional DFIG and BDFIG is considered that operates at a speed between 30% of synchronous speed. In many works are presented control scheme for low-voltage applications (LVRT). And for this BDFIG generator requires a three-phase transformer with a nominal power of 30% of the power generator.
(4) The wind system also described in the paper has power losses low. DC capacitors are small dimensions and the stator currents of SCIG they are practically sinusoidal.
(5) A disadvantage of wind system with SCIG and RNSIC converter is the limited range to no more than $(\pm)40\%$ of synchronous speed.

V. SIMULATIONS RESULTS

SCIG connected to terminals R, S and T. After the introduction of the RNSIC converter (without inductances L_1 considered null). The converter has 6 capacitors by 55 μF connected in parallel with diode D_1-D_6 and 6 capacitors connected in series with switches K_1-K_6 for step II and III, as shown in Figure 3. The SCIG induction generator is driven by variable speed DC motor in limits (0.7 - 1) of synchronous speed. This electricity generator debits on a variable load resistance, it is chosen in such a way that the variable speed generator voltage on the capacitor C_{dc} to maintain equal to 651 V.
The simulations system consists of the following parts:
1. An induction generator with the parameters listed below:

- rated power 11 kW;
- the value of the maximum phase stator voltage V_{max}= 311 V;
- the nominal stator current I_{gr} = 24.2 A;
- the maximum stator frequency is f_{max} = 50 Hz;

- the minimum stator frequency is f_{min} = 35 Hz;
- the stator leakage inductance is L_{st} = 0.010 H;
- the rotor leakage inductance is L_{rot} =0,010 H (referred to the stator);
- the magnetization inductance is L_m= 0,140 H.

2. An RNSIC converter which has three capacitive steps. Capacitors C_1 - C_6, with the value C = 55 µF, and the other six capacitors which prepare the steps 2 and 3 and which have a capacity of 40 µF. The capacitor C_0 out of RNSIC has a value of 3000 µF and includes the contribution of approx. 150 µF [17], [20].
3. The boost converter is made up of capacitors C_0 and C_{dc}, the inductor L_2 of 10 mH, the diode D_2 and the switch K.

The magnetization inductance L_m depends on the limits of the magnetization current. Generally, this current has a value of 0.35 - 0.45 of the rated current. As to the staler leakage inductance L_{st} and the rotor leakage inductance L_{rot} (referred to the staler) their values are smaller than the magnetization inductance L_m, having values of 0.05 - 0.10 L_m.
With the boost converter one can set the ceded power for the load between zero and the maximum value depending on wind speeds. The nominal voltage V_{dc} can be computed with a (1% - 2%) error given the complexity of the equivalent inductance using the following equation:

$$V_{dc} = \frac{3\sqrt{3}V_{max}}{\left[1-2\left(L_{st}+L_{rot}\right)C\omega_{max}^2\right]\pi} \quad (2)$$

In order to provide the practically sinusoidal I_R, I_S, I_T currents, the fulfillment of the following condition for RNSIC converter is required:

$$0.08 < \left(L_{st}+L_{rot}\right)C\omega_{max}^2 < 0.12 \quad (3)$$

One possibility to turn off the generator sitting idle SCIG consists of decoupling the stator windings of from the mains and the introduction of a continuous current through these windings.
The simulations results presented in Fig. 7 show that the wind system suggested in Fig. 2 can be used as partially variable - speed system (typically ± 30% around synchronous speed). Fig. 7 show the variation of the i_R stator current and of the V_d voltage at the output of the RNSIC converter.

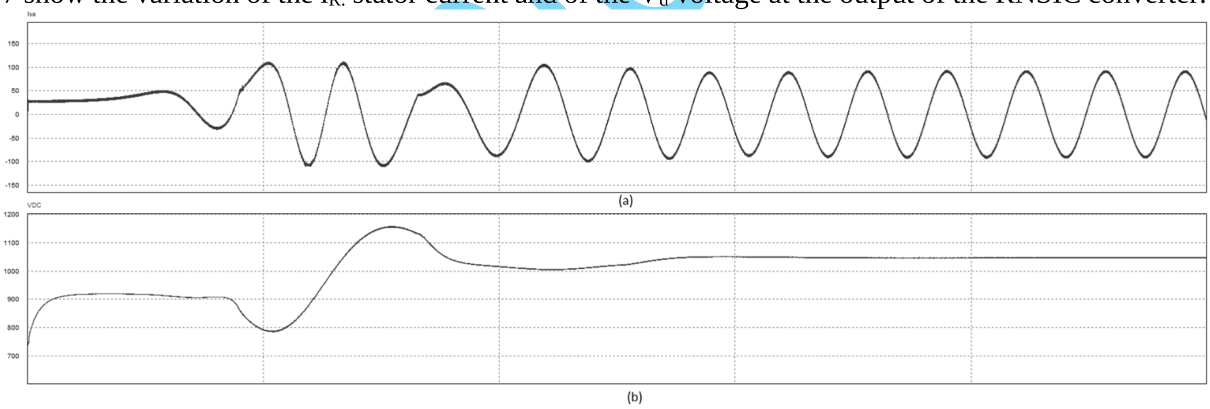

Fig. 7. Simulations results for the transition between the first functioning step, with ω_S/ω_{max}=0.95 and C_{tot}=110µF and second functioning step with ω_S/ω_{max}=0.75 and C_{tot}=190µF (a) stator current i_R and (b) voltage V_d

VI. CONCLUSIONS

- A wind generator system based on a new converter configuration with a rectifier with near sinusoidal input currents converter (RNSIC) is presented.
- The novelty of the suggested configuration consist in the fact that we eliminate the three inductances that are part of a classic RNSIC converter, their function being taken over by the leakage inductances of the SCIG generator. The function of the wind system for the load currents is presented.
- The new wind system is characterized by smaller power losses, small harmonic input currents, reduced EMI problems, high reliability, as well as lower costs. This new wind system could be

used for lower hydro interconnections squirrel cage induction generator (SCIG) and partial variable speed wind turbine (typically +/- 40% around synchronous speed).

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