Performing Wind System with Rectifier with Near Sinusoidal Input Current

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Abstract: - The RNSIC-1 (rectifier with near sinusoidal input currents converter), is the foundation of a wind generator system that is presented. The three inductances that make up a traditional RNSIC–1 converter are eliminated in the proposed arrangement, and the SCIG generator's leakage inductances fill their place. This is what makes it new. The wind system's role in the load currents is discussed. Lower power losses, smaller harmonic input currents, fewer EMI issues, excellent dependability, and cheaper costs are characteristics of the new wind system. This new wind system could be used for partial variable speed wind turbines (usually 70% to 100% synchronous speed) and lower hydro connector squirrel cage induction generators (SCIG).

Key-Words: - Power converter, AC-DC converter, PWM converter, three – phase rectifiers, squirrel-cage induction generator, AC-DC power conversion.

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1 Introduction

Although the cost of the energy they produce is still expensive, the development of wind systems has made some impressive strides in recent years. The maximum output of a wind system should be determined by wind speed, [1], [2].

Wind turbines are characterized by a simple construction and dependability in operation in the majority of solutions with constant speed.

Yet, the mechanics are put under strain by these solutions. Induction generators are typically used in systems with constant-speed wind turbines.

The usage of variable speed systems is a trend in wind systems. The variety of applications and generator types have increased as a result of the development of systems with variable speed, [3], [4].

A back-to-back PWM converter is used in the rotor circuit of a double-fed induction generator (DFIG) drive system for high-power applications.

The generator’s speed typically varies by more than 30% of the synchronous speed.

Back-to-back systems, however, have the drawback of using slip rings in the rotor circuit and necessitating unique protective circuits, [5], [6], [7], [8], [9], [10], [11].

The variable speed wind turbines are built to provide the most electricity possible given the wind speed.

The total installed wind power capacity rose exponentially over the past few years, rising from 158 GW in 2009 to 283 GW by 2010, [3].

Small-to-medium-scale (1-100 kW) wind turbines are pervasive, according to the British Wind Energy Association and the American Wind Energy Association.

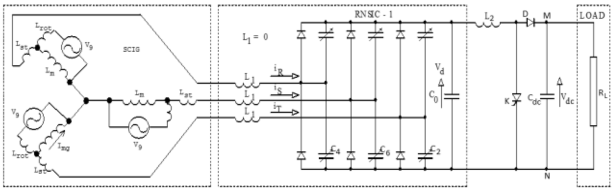
Small-to-medium-sized wind turbines in the US with 100kW or less in production made up about 20% of installed electricity generating in 2010.

The proposed wind farm in work can be an economical solution for small and medium wind turbines power up to several hundred kW.

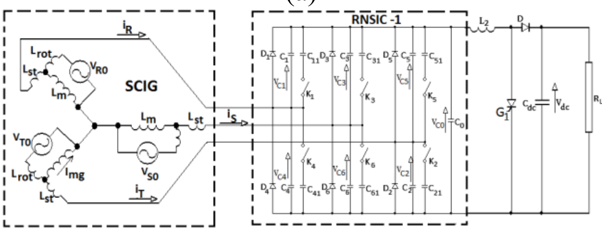
2 New Wind Systems with a SCIG and RNSIC – 1 Converter

A new variable–speed wind system is presented in Figure 1. Electricity supplied by the SCIG is transmitted over the network using an RNSIC - 1 of a boost converter and a PWM inverter.

Figure 1 depicts a novel variable-speed wind system. A boost converter and a PWM inverter comprise the RNSIC-1, which is used to transmit SCIG-supplied electricity through the network. Three capacitive stages are present in a novel AC-DC converter, [12]. Capacitors C_1–C_6 that are permanently connected in parallel to diodes D_1–D_6 make up the first step. The switches K_1, K_3, and K_5, respectively, are connected in series with the capacitors C_{11}, C_{31}, and C_{51} in the second stage. Capacitors C_{41}, C_{61}, and C_{21} are connected in series with switches K_4, K_6, and K_2, respectively, to complete the third step.



(a)



(b)

Fig. 1: (a) Scheme for calculating inductances L_m, L_{st}, $L_{rot,}$ and L_1 ; (b) Wind system with SCIG and RNSIC – 1 converter (without inductance L_1)

Figure 1 depicts a novel variable-speed wind system. A boost converter and a PWM inverter comprise the RNSIC-1, which is used to transmit SCIG-supplied electricity through the network. Three capacitive stages are present in a novel AC-DC converter, [12]. Capacitors C_1–C_6 that are permanently connected in parallel to diodes D_1–D_6 make up the first step. The switches K_1, K_3, and K_5, respectively, are connected in series with the capacitors C_{11}, C_{31}, and C_{51} in the second stage. Capacitors C_{41}, C_{61}, and C_{21} are connected in series with switches K_4, K_6, and K_2, respectively, to complete the third step.

The SCIG can operate at partial speed thanks to the reactive power provided by the RNSIC-1 converter. When the generator speed changes between 70% and 100%, the capacitive steps enable an essentially constant magnetizing current. The RNSIC-1 converter has the benefit of giving an induction generator stator almost sinusoidal current. At fixed-speed wind turbines, when the stator currents have high harmonic content, this benefit is not realized. The proposed converter in Figure 1 ensures a more balanced load for capacitors and diodes when compared to the wind system solution described in [12].

According to Figure 1, a boost DC-DC converter can be added to the DC connection to achieve a variable speed dependent on wind speed. The input PWM inverter connected to the network is used to apply the output voltage V_d from the RNSIC - 1 converter, which amplifies the value of Vdc.

According to Figure 1, more IGBT transistors or GTO transistors can be connected in parallel to provide a greater power wind system of approximately 1 to 2 MW. An AC-DC converter that produces harmonics of low-valued stator currents in SCIG is shown in Figure 1. Harmonics in the distribution network's current or voltage do not affect how this converter operates, [12].

We'll think about a load resistor with rated current $I_{(1)r}$ and rated value R_{Lr}. Where V_{max} is the maximum AC input voltage and V_{dc} is the rectified average voltage, $V_{ref} = 3\sqrt{3}V_{\max}/\pi$ is the reference voltage characteristic for three-phase rectifiers with diodes. The rectifier's rated voltage is $V_{dr} = V_{ref}/\left(1-2L_1C\omega^2\right)$.

The three L_1 inductors shown in Figure 2 are absent from the RNSIC - 1 in the proposed wind system in Figure 1. This is one of the system's primary distinguishing features. The three equivalent circuits L_{eq}, which are generated from the SCIG generators, fill their place. The L_{eq} inductors can be thought of as lacking any loss resistance for simplicity's sake, and their inductance merely consists of the stator inductance L_{st}, rotor inductance L_{rot}, and magnetization inductance L_m. A minimal value of V_{min} and a maximum value of V_{max} are represented by the power supplies V_g. About 0.7 is the ratio between these figures. The stator currents i_R, i_S, and i_T of the SCIG are kept constant with THD% values less than 5% when the L_1 inductances are replaced with L_{eq} ones.

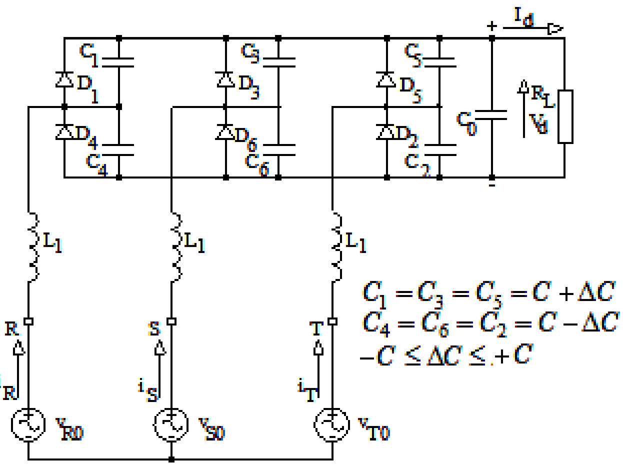


Fig. 2: RNSIC-1 converter with six DC capacitors

In Figure 3, the equivalent induction generator circuit for the induction generator with iron losses taken into account is shown.

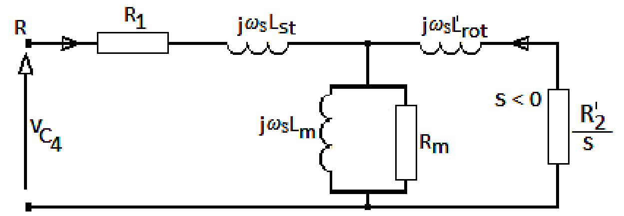


Fig. 3: The equivalent circuit of the induction generator in which the iron losses are taken into account

The induction generator can supply electricity to the network since the slip speed has a negative value.

3 Operation of the Introduction Generator Connected to the Proposed Wind System

Based on the presence of a remanence E_{rem} in the rotor, the induction generator's self-excitation process is shown in Figure 4, [1]. The resistive-capacitive load for this generator is represented by the RNSIC-1 converter in Figure 1 with several capacitive stages. It can be observed that two or three diodes may be in the pipeline by looking at the waveforms of phase currents and conduction times for the diodes D_1 through D_6 for large current I_d in Figure 5(a) and Figure 5(b).

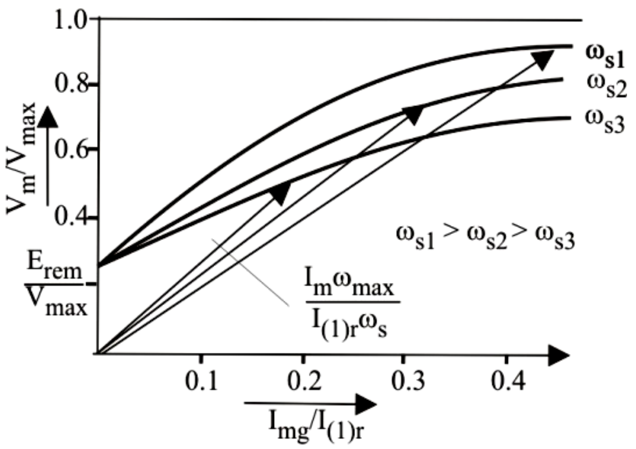


Fig. 4: Variations of ratio V_m/V_{max} as a function of $I_{mg}/I_{(1)r}$ for different values of ω_s

The waveforms of phase currents and conduction times for the tiny currents of I_d are shown in Figure 6(a) and Figure 6(b).

The fundamental harmonic of the phase current, or $I_{R(1)}$, and the phase voltage, for instance, form a negative angle. The voltage induction capacitive current delivered by the battery reduces with a decreasing frequency generator if a single-phase capacitor is connected to the generator.

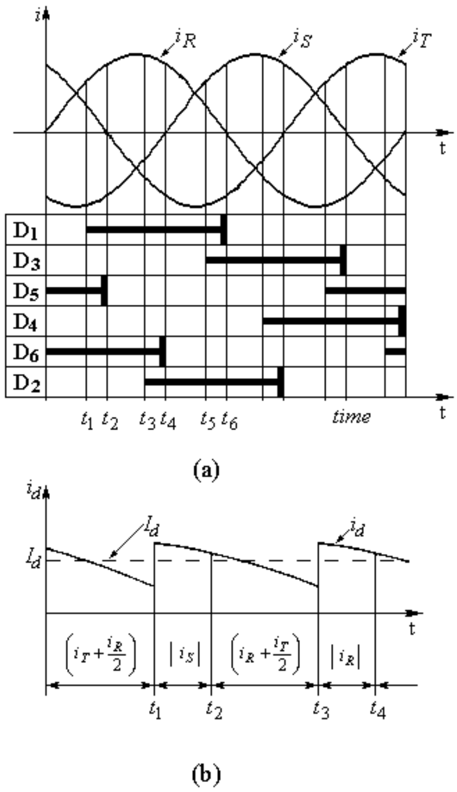


Fig. 5. Waveforms of phase currents for large values of current I_d (a) waveforms of currents i_R, i_S and i_T (b) DC i_d

The magnetizing current $I_{mg} = I_{(1)r} \sin\varphi$ has a nearly constant amplitude without harmonics if you use a battery with multiple parts. Through the use of magnetizing inductance, K_1–K_6 switches are adjusted to maintain a nearly constant magnetizing current.

Given that the load resistance R_L and the currents i_R, i_S, and i_T are essentially sinusoidal and have amplitude, DC I_d can be determined using the equation:

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

where t_1 is the time in Figure 5(b) and Figure 6(b) that is indicated. Time t_1 diode opening equals π/ω then DC I_d be canceled, and currents i_R, i_S, and i_T are only capacitive.

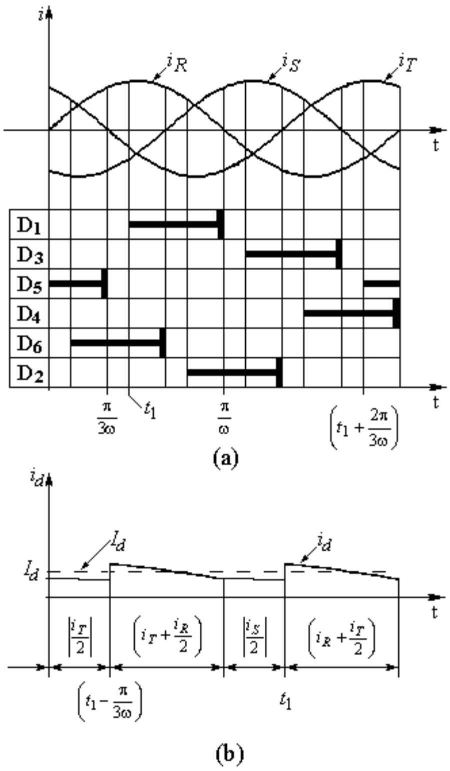


Fig. 6: Waveforms of phase currents for low values of current I_d (a) waveforms of currents i_R, i_S and i_T (b) DC i_d

This circumstance happens when using a boost converter.

The converter RNSIC – 1 DC capacitors provide a virtually sinusoidal stator current for SCIG while also adding 5% to 10% to C_0 capacity. If the capacitor C_0 has a smaller capacity, for example $C_0/2 = 1500\mu F$, the transient processes in the wind system are reduced practically in half. You can get such a period of transient decreased from 100 ms to about 50 ms. Boost converter consists of inductance L_2, capacitors C_0 and C_{dc}, and GTO thyristors. Two thyristors that are connected in antiparallel can be used to implement the switches. Low currents that pass through these switches mean that very little electricity is lost as a result. For the fluctuation range between and, the average currents that pass through the switches do not exceed (3 - 6%)$I_{(1)r}$. The aforementioned average values are required to select the thyristors for the switches.

Without inductances L_1, the RNSIC-1 converter's capacitors serve a dual purpose. On the one hand, they guarantee input currents i_R, i_S, and i_T that are close to sinusoidal, and on the other, some capacitors connected in parallel with the capacitors C_0 at V_d enable a better load.

True, there are different DC capacities, however, they can be used at a rate of 8% to 10% of the capacitor C_0. Compared to those of the AC type, the DC capabilities are smaller and more affordable. For the voltages applied capacities in the big current mode regime, one can formulate the following relations:

$$V_{C1} + V_{C4} = V_{C0} \tag{2}$$

$$V_{C3} + V_{C6} = V_{C0} \tag{3}$$

$$V_{C5} + V_{C2} = V_{C0} \tag{4}$$

This system is running in SCIG generator mode at rated speed. If a battery of capacitors with a specific value is connected to a SCIG generator control, it can create a network of power. Depending on the generator's speed, the SCIG generator operation described in the paper is carried out in three steps. Figure 7 depicts the power variation P transmitted throughout three working steps by the wind turbine of the shaft generator for various values of wind speed V_w.

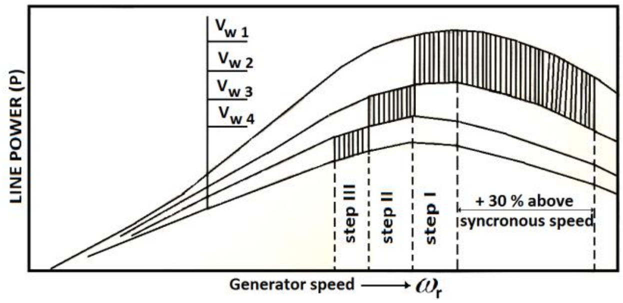


Fig. 7: Power delivered to the hub shaft at various wind speeds

4 System Comparison of Wind Turbines

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 8a 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 an 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 8a. 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.

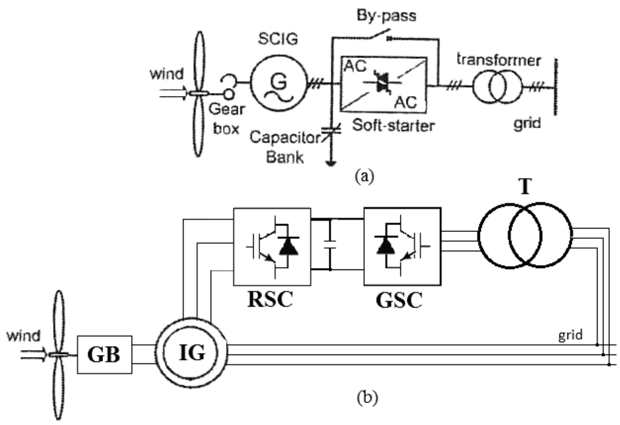


Fig. 8: Variants of wind systems with constant speed and partial variable speed. (a) Fixed speed wind turbine with direct grid-connected squirrel-cage induction generator; (b) Double-fed induction generator using back-to-back PWM converter.

To surpass these issues, the tendency of modern wind turbine technology is, without any doubt, directed toward variable-speed concepts. The Variable-speed systems offer a great number of advantages, [3], [4], [5], [6], [7], [8], [10], [11]:

- the turbine can be adjusted to the local conditions or 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 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 Figure 8b.

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 enable 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.

The main advantage of the RNSIC - 1 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 [14], the converter suggested in Figure 1b ensures a more balanced load for capacitors and diodes.

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 Figure 4. The output voltage Vd from the RNSIC - 1 converter increases the value of Vdc and applies the input of the PWM inverter, connected to the network.

When the performance of the various wind turbine topologies is compared, a discrepancy between cost and grid performance is revealed.

Specifically, the wind system presented in the study, the double-feed induction generator (DFIG), the brushless double-fed induction generator (BDFIG), and the permanent magnet synchronous generator (PMSG) are the only variable speed wind systems to which further reference is made.

1. For equal power, SCIG is the simplest generator that might have an RNSIC-1 converter on the soil surface (without L_1 inductances). This indicates that the type with SCIG, [5], requires less reinforced concrete for the pillars supporting the wind system, [13].
2. The investment in the SCIG system is smaller as a result of the aforementioned factors, [9].
3. A 30% speed synchronism variation of speed limiters is possible with DFIG.
   The usage of slip-rings and the controllability of the protective schemes in the event of grid faults, however, are its principal shortcomings. About 30% of the power from the DFIG generator can be contained in the three-phase transformer. It is required because voltages on the rotor rings must be kept to a minimum, even if DFIG is directly connected to the grid, [4], [5].

4. Due to its reduced cost and improved dependability when compared to the standard DFIG, the BDFIG exhibits commercial promise for the generation of wind power. The BDFIG is also thought to run at a speed between 30% of synchronous speed. Many studies propose a ride-through BDFIG control technique for low-voltage applications. Additionally, a three-phase transformer with a nominal power of 30% of the generator's power is needed for this BDFIG generator.
5. One of the highest levels of reliability can be found in SCIG with an RNSIC-1 converter, [12].
6. Low power losses are present in the paper's description of the wind system. The stator currents of SCIG are essentially sinusoidal, and DC capacitors are minimal in size.
7. Even though PMSGs (with NdFeB magnets) are more expensive than induction generators, they will gain popularity as energy costs rise. the price of the magnet is sufficiently low. In wind systems, PMSGs will outperform induction generators, [3]. The ability to vary the generator speed between 0% and 100% of synchronous speed is a benefit of PMSG, [3].
8. The limited range $(\pm)40\%$ to only synchronous speed is a drawback of wind systems with SCIG and RNSIC-1 converters (without inductances L_1).

5 Experimental Results

Terminals R, S, and T were connected by a SCIG. After that, the RNSIC-1 converter (without inductances, L1 is regarded as null) was introduced. According to Figure 1, the converter comprises 6 capacitors connected in series with switches K_1–K_6 for stages II and III and 6 capacitors connected in parallel with diodes D_1–D_6. A DC motor with variable speed is used to power the SCIG induction generator between (0.7 and 1) synchronous speeds. This generator of electricity operates with a changing load resistance. The capacitor C_{dc} will always have a voltage of 651 V thanks to the use of the variable speed generator.

A prototype of a wind system with RNSIC -1 was subjected to investigation, lifting it out its advantages, Figure 11.

The prototype is made up of the following elements:

1. An induction generator with the following parameters:
- rated power 11 kW;
- the value of the maximum phase stator voltage V_{max} = 311V;
- 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 (referred to as the stator) is L_{rot} = 0.010 H;
- the magnetization inductance is L_m = 0.140 H.

2. An RNSIC – 1 converter with three capacitive steps. Capacitors C_1 - C_6, have the value C = 55 µF, and the other six capacitors which make up steps 2 and 3 have a capacity equal to 40 µF. The capacitor C_0 out of RNSIC -1 has a value of 3000 µF and includes the contribution of approx. 165 µF - 245 µF.
3. The boost converter is composed of capacitors C_0 and C_{dc}, the inductor L_2 of 10 mH, the diode D_2 and the switch K.
4. A three-phase PWM voltage inverter with how intelligent PS 12017 + power supply + mode control HEF 4752, debited energy SCIG generator is transmitted mains supply R, S, and T.
5. An oscilloscope TPS 2024 with 4 inputs current / voltage electrical isolation between channels + a soft harmonic analysis.
6. A DC motor of 12 kW with variable speed acting SCIG model.

The magnetization inductance L_m depends on the limits of the magnetization current. In general, this current has a value between (0.35 – 0.45) of the rated current. In what concerns the stator leakage inductance L_{st} and the rotor leakage inductance L_{rot} (referred to as the stator) are smaller than the magnetization inductance L_m, having values of (0.05 – 0.10) L_m.

With the boost, the converter can adjust 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 due to the complexity of the equivalent inductance L_{eq} using the following equation:

$$V_{dc} = \frac{3\sqrt{3}V_{max}}{\left[1-2\left(L_{st}+L_{rot}\right)C\omega_{max}^{2}\right]\pi} \tag{5}$$

To provide the practically sinusoidal i_R, i_S, and i_T currents, the following condition must fulfilled for the RNSIC -1 converter.

$$0.08 < \left(L_{st} + L_{rot}\right) C\omega_{max}^2 < 0.12 \quad (6)$$

Some experimental data is presented in Table 1 depending on the ratio ω_s/ω_{max} .

This ratio varies between 1.0 and 0.7. Table 1 presents a total capacity C_{tot} for one phase, corresponding capacitive steps, namely 2x55, 150, and 190 μF. The I_{mg}/I_{gr} ratio, depending on the V_m/V_{max} ratio is presented in Figure 4. If we had adopted an RNSIC – 1 with more capacitive steps, the variation of the magnetization current I_{mg} from the average value would have been even smaller.

One way to turn off the generator sitting idle SCIG consists of decoupling the stator windings from the mains and introducing a continuous current through these windings.

Figure 9 and Figure 10 illustrate the variation of the i_R stator current and of the V_d voltage at the output of the RNSIC – 1 converter for two different functioning cases. In the first case, corresponding Figure 8(a) and Figure 8(b) switch from $\omega_s/\omega_{max} = 0.95$ to $\omega_s/\omega_{max} = 0.75$. In the second case, according to Figure 9(a) and Figure 9(b), switching from $\omega_s/\omega_{max} = 0.75$ to $\omega_s/\omega_{max} = 0.95$.

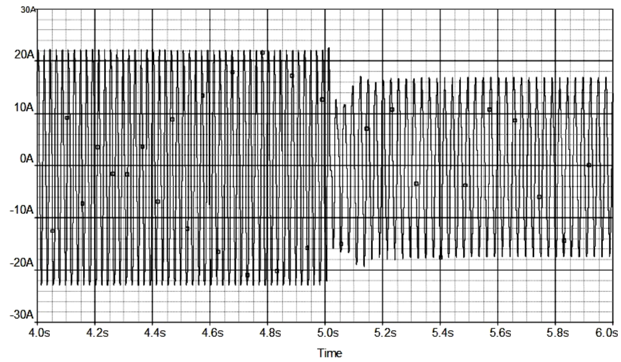
Table 1. System operation for the three capacitive steps

C_{tot}	ω_S/ω_{max}	V_d [V]	$I_{(1)}$ [A]	I_{mag} [A]	THD [%]	$I_{(5)}/I_{(1)}$ [%]	P [W]
110	1.00	651	24.2	7.64	3.03	2.74	10595
	0.95	634	22.1	7.60	3.50	3.09	9750
150	0.90	607	20.6	7.74	2.60	2.34	8610
	0.85	555	19.1	7.69	3.20	2.88	7540
190	0.80	538	17.7	7.78	2.96	2.70	6580
	0.75	488	16.1	7.68	3.94	3.59	5620
	0.70	441	14.4	7.61	5.35	5.06	4680

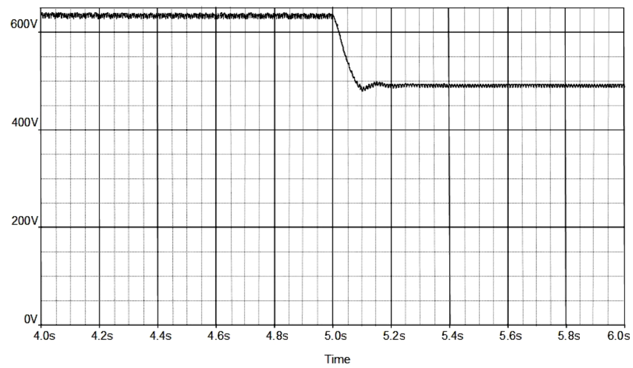
According to the experimental findings shown in Figure 8 and Figure 9, the wind system suggested in Figure 1 can be employed as a partially variable-speed system (usually 30% around synchronous speed).

The main advantages of the wind system proposed in Figure 1 are:

- The SCIG generator has a lower size than a DFIG generator with the same power.
- Compared with the system proposed in Figure 1, the back-to-back PWM converter requires a three-phase transformer in the rotor circuit. The transformer may have a power output of 30 % of the DFIG and is required to be restricted to the ring-rotor circuit.
- The proposed system has greater reliability.
- The rotation frequency of SCIG from Figure 1 can be up to 30% higher than the synchronization frequency.



(a)



(b)

Fig. 9: Experimental results for the transition between the first functioning step, with ω_S/ω_{max}=0.95 and C_{tot}=110μF and the second functioning step with ω_S/ω_{max}=0.75 and C_{tot}=190μF (a) stator current i_R and (b) voltage V_d

Figure 9 shows the whole picture of the suggested wind system, which must be taken into account, and the DC motor drive system and SCIG generator.

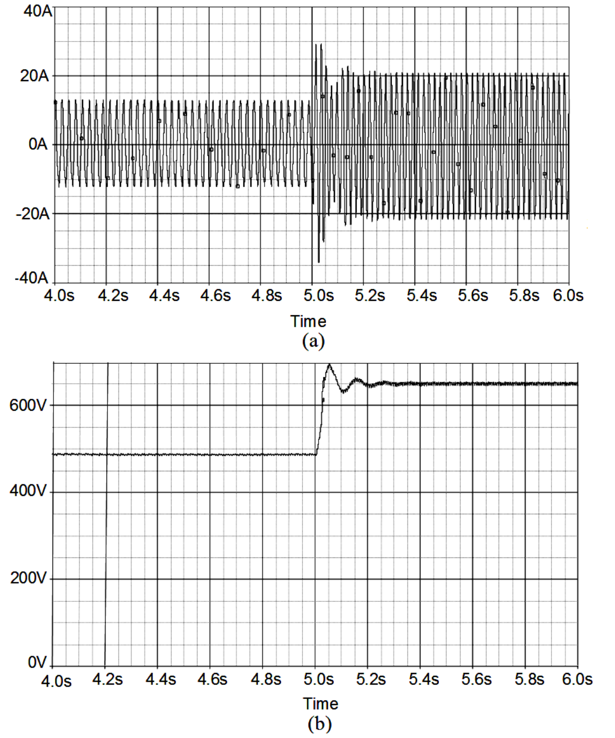


Fig. 10: Experimental results for the transition between the third functioning step with ω_S/ω_{max}=0.75 and C_{tot}=190µF and the first functioning step, with ω_S/ω_{max}=0.95 and C_{tot}=110µF (a) stator current i_R and (b) voltage V_d

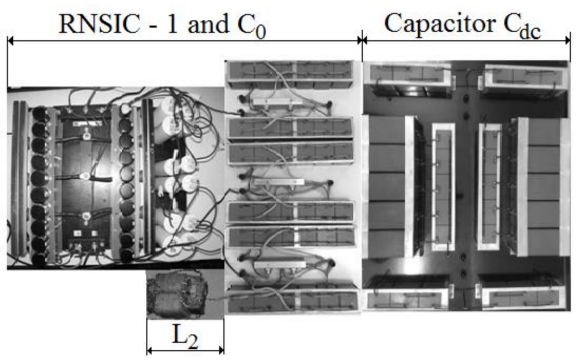


Fig. 11: Experimental system of RNSIC-1 (without inductances L_1), capacitor C_0, inductance L_2, and capacitor C_{dc}.

6 Conclusions

We have introduced a brand-new wind system with an RNSIC-1 converter in this study. The three L_1 inductances of an RNSIC-1 are dropped, and the leakage inductances of the SCIG generator fill their place. The three inductances L_1 are more expensive than the one capacitor RNSIC, cheaper harmonic stator currents, less power losses, and cheaper costs are all characteristics of the new wind system. This wind system can also be utilized for a small hydro hookup with a SCIG and a wind turbine with a partially variable speed (often between 70% and 100% synchronous speed). The effectiveness of the suggested wind system with RNSIC - 1 converter has been demonstrated in laboratory tests.

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