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Laboratory Tests, Modeling and the Study of a Small Doubly-Fed Induction Generator (DFIG) in Autonomous and Grid-Connected Scenarios

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Abstract

Doubly-Fed Induction Generators (DFIGs) are widely used in wind power production nowadays. Their key advantages are the low power rating of the converter used for connecting to the network, and the ability to produce and feed the network with reactive power. This paper investigates the capabilities of DFIGs in low-cost wind turbine systems. Namely, it examines the performance and constraints of using general-purpose motor drives instead of back-to-back connected inverters in such systems. A small laboratory DFIG machine is studied in this context, assuming both autonomous and grid-connected scenarios. The analytical model of the machine is initially calculated, and the system is simulated in MATLAB-Simulink, using a uni-directional power converter. Simulation results are presented, accompanied by an analysis of the control technique of the power converter. Experimental results from a laboratory setup based on a low-cost commercial inverter, normally used for controlling a 1kW 3-phase induction motor, are also presented. Finally, the system efficiency - optimal operation points and limitations on the turbine range of operation are discussed.

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Keywords

Doubly-Fed Induction Generator; DFIG.

I. Introduction

The Doubly-Fed Induction Generator (DFIG) is the most widely used generator type in modern wind turbines. This is a result of the advantages that DFIG-based wind turbines have over the more traditional squirrel cage induction generator (SCIG) and synchronous generator (SG)-based architectures, summarized in Figure 1 [1, 2].

In the past, SCIG-based turbines operating according to the "Danish concept" connected to the grid directly, i.e. not through power electronic converters, and ran at effectively constant speeds (Fig. 1a). Compared to those, DFIG-based turbines offer the advantages of a) speed variation, which enables maximum power absorption from the wind in a wide range wind speeds, and b) voltage – reactive power control. Nevertheless, similar features are also offered by variable-speed, SCIG or SG-based turbines, connecting to the grid through power electronic converters, rated at the power of the generator (Fig. 1b). The advantage of DFIG-based turbines (Fig. 1c) in this case is the power rating of the converters, which only needs to be a fraction of the generator power, typically around 30%. This reduces the converter cost and increases the overall efficiency.

The typical configuration of power converters in a DFIG is illustrated in Figure 2. It consists of two IGBT-based inverters connected back-to-back, which allows bidirectional power flow, from the rotor of the machine to the grid and vice-versa. It is known that power flows from the rotor towards the grid when the rotor speed is higher than the synchronous speed (super-synchronous operation), and from the grid towards the rotor in the opposite case (sub-synchronous operation).

In this study, a commercial motor drive is employed instead, with the simplified converter structure of Figure 3 (see dashed box). This is consists of a uni-directional AC-DC-AC converter, that is, a passive single-phase rectifier at the grid side and a three-phase inverter at the rotor side. Since power can only flow from the grid towards the rotor, the generator can only operate at sub-synchronous speeds.

In the following sections, this study investigates the capabilities of small DFIG-based turbines, with the above converter structure. It begins with a derivation of an analytical model for the generator and continues with the presentation of simulation results from MATLAB-Simulink and experimental results from a laboratory setup. The results include turbine operation in both grid-connected and scenarios autonomous, illustrated in Figures 3a and 3b, respectively.

II. Inverter Control

This section describes the principles for setting the inverter parameters that determine its fundamental voltage waveform, namely its amplitude (or rms value), frequency and phase, for the grid-connected and the stand-alone scenarios.

A. Grid-connected scenario

Frequency

As for high-power wind turbines, the inverter frequency should be selected according to the desired speed. The desired speed will normally be provided by an MPPT algorithm, based on the absorbed mechanical power. As mentioned earlier, the fact that the converter used in this system is uni-directional, only allows for frequencies of a given sign, which lead to sub-synchronous generator speeds. The generator speed, n, will be given by

$$n = \frac{120}{p}\left(f_{grid} - f_{inv}\right)$$

where *p* stands for the pole count of the machine.

Voltage amplitude

The voltage amplitude can be adjusted to control the rotor current. At any time, a minimum amount of rotor current is required to create a rotor magnetic field, adequate to support the applied torque. The minimum current corresponds to the case where the angle between the stator and rotor magnetic fields is 90 electrical degrees, and increases linearly with torque. More current can also support the same torque, but the inverter will be operating with unnecessarily increased losses in this case. The inverter voltage should therefore be adjusted to produce the above minimum amount of current increased by a margin, so that the generator does not lose synchronism in the event of a sudden torque increment. This can be implemented in practice using a Look-up table, which relates the absorbed power and speed to torque, and suggests a voltage level for each torque-inverter frequency pair. This scalar method of voltage control is not as effective as vector control, which, however, would require the implementation of a Phase-Locked Loop (PLL) and possibly a shaft encoder to accurately control the rotor voltage.

Phase

The phase of the inverter voltages does not need to be controlled when applying the above method of voltage control. Changing the voltage phase angle will simply alter the mechanical phase shift of the rotor w.r.t. the rotating magnetic field of the stator. The rest of the operating parameters (currents, voltages,

speed, torque) will remain unaffected. Thus, setting the fundamental voltage and frequency of the inverter output, uniquely determines the generator behaviour. As explained in the previous paragraph, in the opposite case (i.e., if the phase of the inverter voltages also affected the system behaviour), a PLL would be necessary to detect the phase of the grid voltages, and the inverter controller would need to devise an appropriate phase shift, in addition to the voltage and frequency. The above characteristic significantly simplifies the controller structure, which is very desirable in a low-cost system.

B. Stand-alone scenario

For stand-alone operation, the machine will need to be connected to a 3-phase load of suitable power. This is to ensure that the stator currents will have a magnitude and phase that can support the applied torque. Due to this restriction, this scenario was left for future study. Introductory experimental results are presented in Section 4.

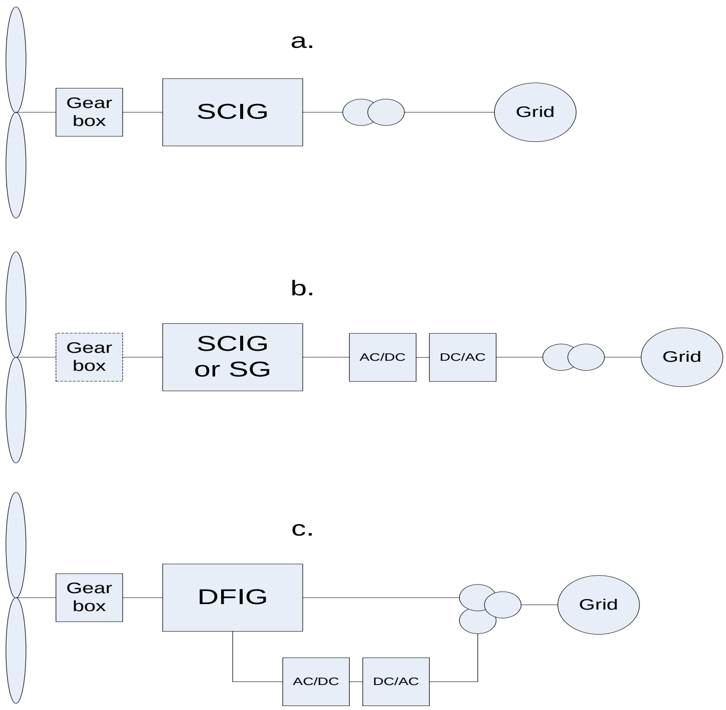

Fig. 1. Wind turbine architectures

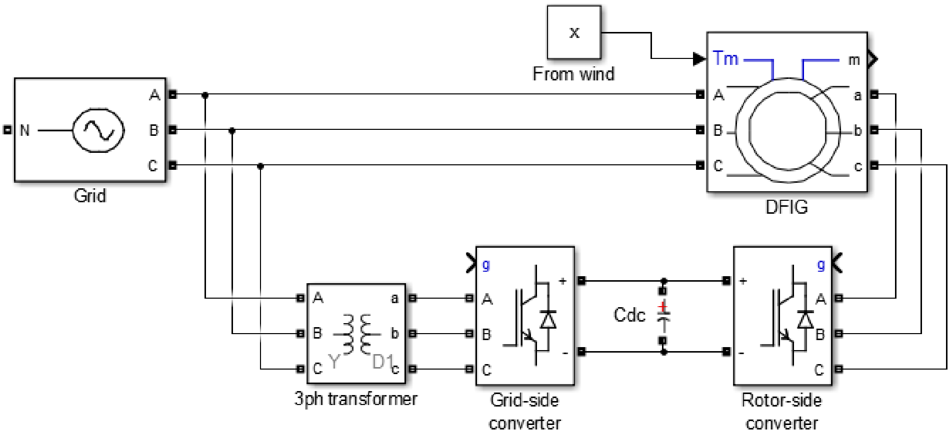

Fig. 2. Typical configuration of DFIG-based wind turbine

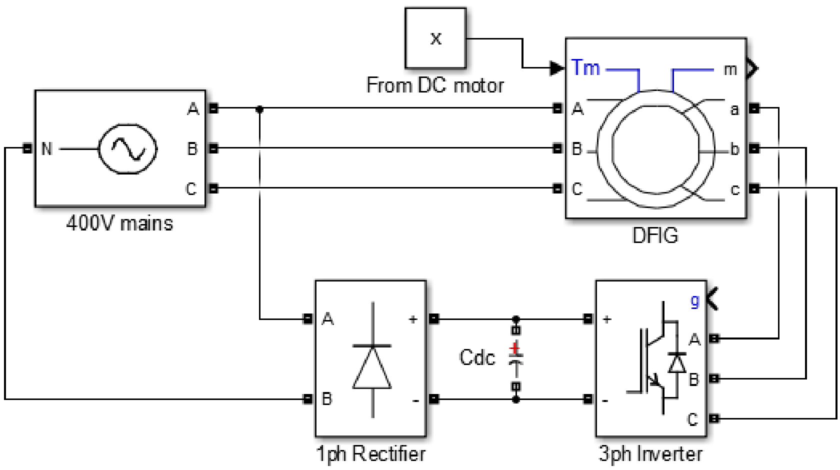

Fig. 3a. Experimental configuration for the grid-connected operation scenario

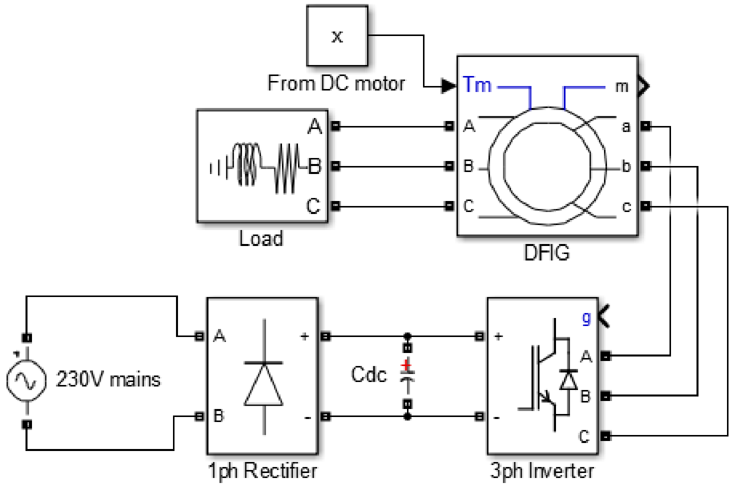

Fig. 3b. Experimental configuration for the autonomous operation scenario

III. Simulation Results

The doubly-fed induction generator used for the lab experiments had the following nameplate/measured parameters:

Table II. Data for simulations test

Parameter	Symbol	Value
Output power	P_m	0.33 HP
Number of poles	p	4
Electrical freq.	f_e	50 Hz
Rated speed	n_n	1450 rpm
Rated voltage	V_n (in star)	380 V
Rated current	I_n	1.1 A
Stator resistance	R_s (measured)	19.4 Ohm
Rotor resistance	R_r (measured)	35.5 Ohm

An approximate model of the machine was constructed in MATLAB-Simulink, based on the above. Figure 4 illustrates simulation results, for the case of the inverter running at 5Hz.

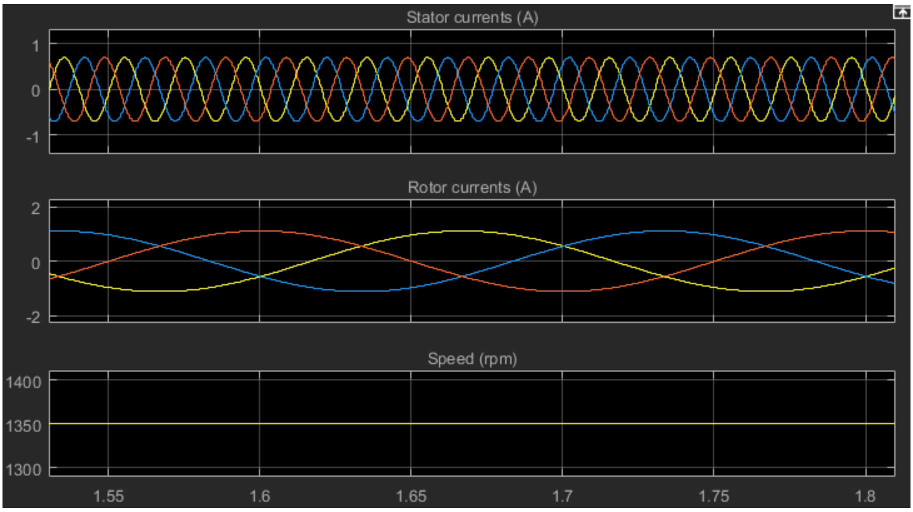

Fig. 4. Simulation results from matlab simulink

IV. Experimental setup – results

A. Grid-connected scenario

Pictures of the experimental setup are shown in Figures 5.

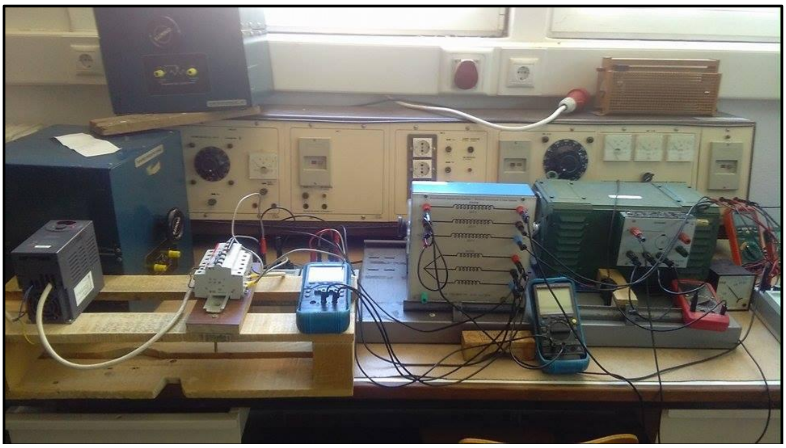

Fig. 5a. Experimental setup

Fig. 5b. Experimental setup

Fig. 5c. Experimental setup

The setup consisted of the following:

- a 4-pole Consulab 0.3HP doubly-fed induction machine, used as a generator,
- a 1.5HP motor drive, connected at the rotor (slip rings) of the above machine,
- a 3HP DC motor, used to apply torque on the DFIG.

As mentioned earlier, the DFIG was operated at the sub-synchronous speed range, i.e. at speeds below 1500rpm. The torque (that is, the current of the dc motor) was adjusted in conjuction with the drive's frequency and voltage, to maintain synchronisation between the two machines and stay within their power ranges. Table I presents representative data collected during the tests. It can be

observed that the speed is always lower than 1500rpm and that the power supplied from the motor drive is positive.

Table II. Measurments by the experimental setup

Hz	rpm	Ir	Pr	Vr	Im	Vm	Is	Ps	Vs
1	1471	1	50	30	5	70	0,5	112,5	388
1	1468	1	50	35	6,26	90	0,75	240	389
1,5	1450	2,2	100	40	6,28	90	0,46	247,5	389
1,5	1453	2,2	100	40	7,6	102	0,75	225	389
1,5	1456	2,2	100	40	5,1	72	0,28	120	389
2	1439	3,55	180	55	3,5	55	0,24	0,1	389
2	1438	2,2	70	40	6,8	95	0,71	300	389
3	1414	2,2	50	35	4,25	65	0,45	75	389
3	1407	2,2	50	35	6,3	85	1,08	225	390
3	1407	2,2	50	35	5,15	82	0,64	165	390
4	1383	4	105	42	3	55	0,1	30	390
4	1376	3,36	115	43	5,33	72	0,36	165	390
4	1380	3	105	43	7	95	0,81	242	390
5	1348	3,4	82	43,3	5	70	0,39	135	394
5	1350	3	82	43,2	5,8	81	0,59	210	394
5	1351	2,55	67	43	6,65	90	0,89	292,5	393
5,5	1332	3	80	46	6,7	95	0,79	307,5	394
6	1323	3,32	100	48	6,73	95	0,7	315	394
6	1321	3,7	115	48	5,63	80	0,45	225	394
6	1318	4,17	125	48	4	62	0,16	90	394

Where:

Hz: frequency on rotor
Rpm: speed of rotor
Ir, Vr: current and voltage on rotor windings
Pr: Power from inverter to the rotor
Im, Vm: dc current and voltage of the motor
Is, Vs, Ps: current, voltage and active power on stator windings

V. Conclusions

This paper investigated the possibility of using commercial motor drives to build low-cost DFIG-based wind turbines. It was shown that, although such configurations can only operate at a narrower speed range (sub-synchronous only), they retain most benefits of back-to-back converter-based DFIG systems, namely the high efficiency and low converter power rating. Given the simplicity and wide commercial availability of low-power motor drives, this type of

configuration can provide an alternative to currently used architectures for low-power wind turbines.

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