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COMPLETE POWER ELECTRONICS CONVERTER FOR SMALL WIND TURBINE WITH ASYNCHRONOUS GENERATOR

KOMPLEKSOWY PRZEKSZTAŁTNIK ENERGOELEKTRONICZNY DO MAŁEJ TURBINY WIATROWEJ Z GENERATOREM INDUKCYJNYM

Abstract: This paper presents a complete solution for automation and grid integration of a small wind turbine with variable speed asynchronous generator. Structure of a system is presented and AC-DC-AC power electronic converter with its auxiliary circuits is discussed in detail. Results of the 10 kW prototype system operation are illustrated.

Streszczenie: W artykule przedstawiono kompleksowe rozwiązanie przeznaczone do automatyzacji oraz integracji z siecią elektroenergetyczną małej turbiny wiatrowej z generatorem indukcyjnym o regulowanej prędkości. Zaprezentowano strukturę systemu i omówiono szczegółowo przekształtnik energoelektroniczny AC-DC-AC wraz z obwodami pomocniczymi. Pokazano wyniki działania prototypowego układu o mocy 10 kW.

Keywords: *wind energy integration, AC-AC converters*
Słowa kluczowe: *integracja energii wiatru, przekształtniki AC-AC*

1. Introduction

Over the last couple of years number of small power installations utilizing Renewable Energy Sources (RES) has grown in tremendous rate. Two main technologies are photovoltaics (PV) and small wind turbines (SWT). PVs are less complicated and can be easily scaled but they are efficient only in some geographical areas. Therefore, also SWTs are very attractive, especially in places, where economical utilization of PV is not profitable.

There are three typical configurations of SWT [1,2]:

- Low-speed permanent magnet synchronous generator (PMSG) + diode rectifier and grid inverter,
- High-speed PMSG + gearbox + diode rectifier and grid inverter,
- High-speed asynchronous induction generator + gearbox + active rectifier and grid inverter (proposed solution).

SWTs configurations with low-speed PMSG are simple, but more expensive compared to others mainly due to high cost of the generator. On the other hand, the cheapest solution of commercially available asynchronous induction generator (IG) has nominal speed of about 1000-1500 RPM. It is not optimal speed for blades, thus a gearbox is required. To achieve maximum efficiency, SWT needs to operate with variable rotational speed, that is adjusted to operate in maximum power point (MPP).

Generator type also affects an emergency stop procedure of the wind turbine. It can be simply solved in PMSG because terminals can be shorted to stop the rotor, while IG needs external brake to achieve this functionality. Moreover, fully controlled converter is necessary for IG excitation, which is complicated compared to diode rectifier, that is sufficient for PMSG [3,4]. Therefore, replacement of expensive low-speed PMSG through cheap high-speed IG is not a trivial problem and demands complex structure of AC-DC-AC power electronic converter with auxiliary circuits to provide safe, reliable and efficient operation of SWT [5].

2. Small wind turbine

Converter described in this paper is dedicated for grid-tied operation with SWTs with nominal power of 5 kW and 10 kW [6]. Fundamental parameters of a turbine are given in Table 1. View of the turbine is presented in Fig. 1. Turbine adopts passive yaw system, where upwind turbine position is provided by tail.

In emergency situations, when high wind speed threatens stability of a turbine, tail is folded 90° downwind by an electromechanical actuator. In these cases motor shaft is blocked by a disc brake, that is integrated with the induction generator.

Fig. 1. View of SWT components

Table. 1. Parameters of a Small Wind Turbine

Nominal power	5 kW / 10 kW
Nominal wind speed	10 m/s
Type of generator	asynchronous
Nominal generator speed	1500 RPM / 1000 RPM
Gear ratio	7,5 : 1
Type of gearbox	planetary
Turbine diameter	4,7 m / 6,5 m
Pole height	10-15 m

A planetary gearbox is attached in the axis of a high-speed generator shaft, while rotor blades are placed directly on a low-speed shaft of a gearbox. No pitch control is applied in the turbine, therefore control of wind turbine power can be only done by adjustment of rotational speed. When wind speeds up to nominal converter controls rotational speed to provide operation at optimal tip speed ratio, that assures maximum power at given wind speed [2,7]. At high wind speeds converter has to reduce rotational speed of a rotor to fall down from optimal tip speed ratio and provide stall effect, that reduces output power. That in turn requires excessive torque and therefore generator currents must be raised. Thus operation in this mode is limited by thermal capacity of generator and converter.

Solutions implemented in SWT require much auxiliary electromechanical components as well as proper automation. A proposed solution integrates power conversion and SWT automation into a single converter device. There are many converters dedicated for SWT on the market, but most of them contain only rectifier and inverter and optionally have algorithm of Maximum Power Point Tracking (MPPT) suited for PMSG. Complexity of proposed solution is incomparably higher than commercially available inverters, what is shown in Fig. 2.

Heart of converter consists of two three-phase IGBT-based bridges managed by microcontroller. Besides, there is lots of auxiliary equipment like brake resistor and chopper converter, filters on both bridges, disc brake with its own adapter, soft-start of grid-tie converter, tail folding mechanism, backup supply, RS485 and GSM communication, measurement of voltages, currents, speed and vibration. Components of the converter system will be discussed in detail in following sections.

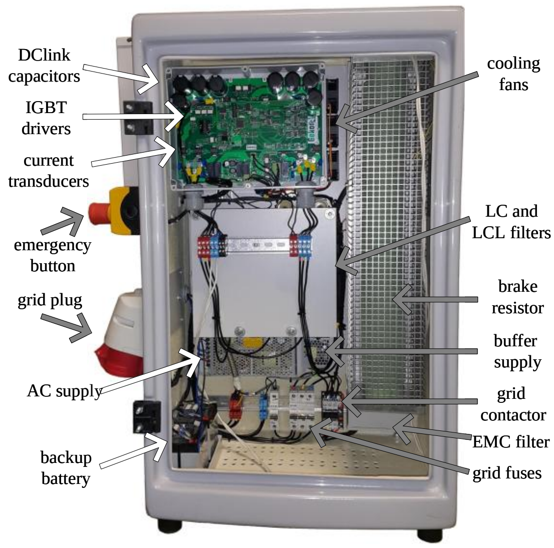

Fig. 3. View on complete case with inverter and all auxiliary equipment

3. Power stage

Power stage (Fig. 4.) includes semiconductors of two active bridges and chopper operating with DC link voltage of 700 V. Thus a minimum class voltage of switches should be not less than 1200 V. The use of MOS or IGBT technology was considered. Conductive losses due to high dynamic resistance of reasonably priced MOS eliminates this technology for relatively slow IGBT switches.

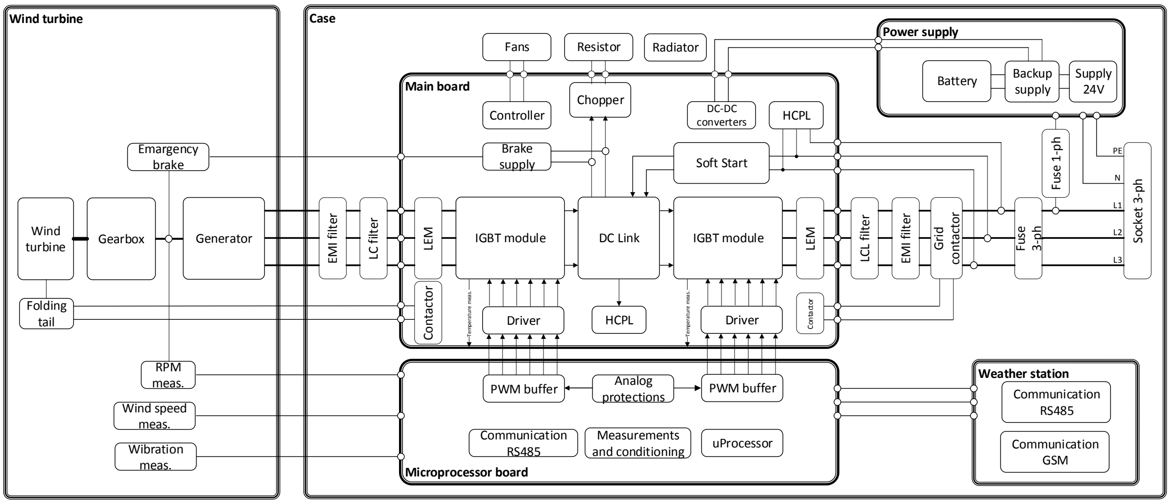

Fig. 2. Block-scheme of entire unit

The use of asynchronous motor forced applying of active bridge rectifier (rated power of 13 kVA), which operates in similar conditions to grid-tie inverter (rated power of 10 kVA), except it has to handle more reactive power than other one. Therefore, from economical reason, it is preferably to use the same semiconductor switches in both bridges. For time reduction and ease of assembly process, power modules were preferred than discrete packages. It also enhances thermal characteristics, eliminating troubling ceramic thermal pads for each individual switch and increases cubic power density. Chosen IGBT module is SEMIKRON SK50GD12T4T, characterised in Table. 2.

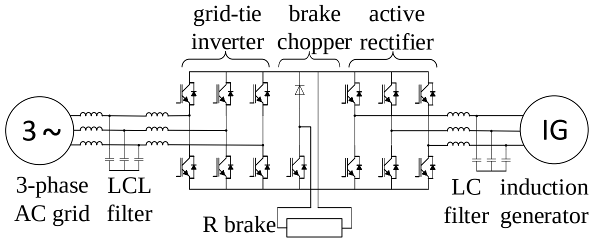

Fig. 4. Scheme of power stage (back-to-back converter + chopper)

Table 2. Parameters of a Small Wind Turbine

Parameter	Value, unit
V_{CES}	1200 V
I_C	60 A
$V_{CE(sat)}$, @I_C=50 A	2 V
t_r	65 ns
E_{ON}, @50 A/600 V	8.3 mJ
t_f	80 ns
E_{OFF}, @50 A/600 V	5 mJ

Module is based on universal package SEMITOP4 (Fig. 5.) which is fully compatible with previous SEMITOP packages and has improved thermal performances using aluminium oxide substrate, fast CAL4 technology free-wheeling diode. Module has integrated NTC temperature sensor, which helps to monitor temperatures of both bridges independently. It is important in such application due to unequal reactive power flow caused by inductive type of IG.

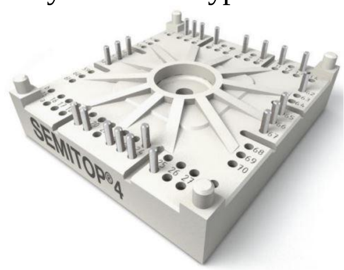

Fig 5. Universal power package SEMITOP4

Switching frequency of semiconductor switches is a trade-off between overall efficiency and volume of reactive elements. IGBT switches can operate at frequency higher than 20 kHz, what is attractive due to noiseless operation of converter, but efficiency is reduced because of high switching losses. Moreover bigger heatsink with faster and louder fans are required. On other hand choosing low switching frequency increases volume and price of reactive components. Thus chosen switching frequency is set to 10 kHz. In fact, negative influence on environment due to operation in audible range of frequency was minimized mainly by usage of inductors core characterized by low magnetostriction factor. Used material is one of most popular ferromagnetic material: 3C90, which is also relatively cheap and commonly available on the market.

According to conducted simulations power losses at full power in active rectifier should be no more than 230 W. Losses for grid-tie converter should not exceed 190 W. This gives efficiency of two-stage AC-DC-AC converter at 96 %, what is quite high efficiency at commercially available back-to-back converters.

To dissipate 420 W of power losses aluminium heatsink is used with three small brushless cooling fans, which also ventilate entire case. Thus, there is no need of additional cooling of case, what lowers costs and makes unit quieter. At full power, temperature of semiconductor switches reaches 90 ^{0} C, when maximum junction temperature declared by manufacturer is 175 ^{0} C.

Power stage is designed properly, with care for reducing stray capacitances and stray inductances, what is confirmed by waveforms in Fig. 6.

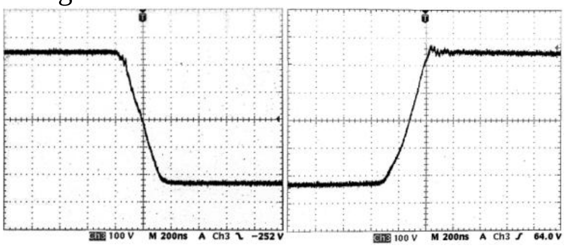

Fig. 6. Waveforms of voltage of IGBT switch in on (left) and off (right) conditions (100 V/div, 200 ns/div)

To minimize switching losess and achieve highest possible efficiency, proper gate drivers and gate resistors are required. On the on and off states of IGBT presented in Fig. 6. there is almost no ringing effect on the voltage waveforms. Best performance is reached with 32Ω gate resistors, what allows to use relatively cheap and easy to use drivers with integrated optocoupler. To limit ringing effect, low-ESR and low-ESL multiterminal capacitor is used, combined with DClink of bulky electrolytic capacitors in parallel connection.

Grid-tied converter has to meet requirements due to Grid Code, it means output waveforms should keep THD of current at limit presented in Table 3.

Table 3. Harmonics limit for equipment that draws input current ≤16 A per phase

Harm[n]	Current [A]	Harm[n]	Current [A]
3	2.30	15-39	0.15x15/n
5	1.14	2	1.08
7	0.77	4	0.43
9	0.40	6	0.30
11	0.33	8-40	0.23x8/n
13	0.21		

A proper topology and parameters of filter was chosen. Best relation of price to performance and damping ability is achieved with LCL filter. Inverter inductors work at heavy duty condition due to high frequency voltage and current waveforms. This eliminates use of traditional iron cores, caling for high frequency ferromagnetic materials like 3C90. A grid inductor of LCL operates in different conditions. This inductor can be made from low frequency materials like iron, what lowers price and reduces volume due to higher saturation induction B than in 3C90. On Fig. 7. current waveforms of inverters inductor (containing higher harmonics) and grid inductor (smooth 50 Hz sinewave) are presented. It should be mentioned, that current measurement for control algorithm is realized on the inverter output, what simplifies wiring of converter, but increases complexity of control algorithm, where processor has to estimate grid current. Moreover, parameters of LCL filter should be constant irrespective of current, temperature and aging of elements.

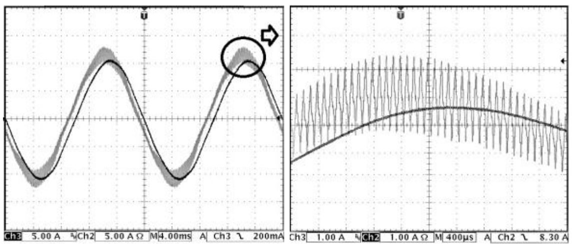

Fig. 7. Current waveforms of inverters inductance (with higher harmonics) and grid inductance (pure sinewave) (left: 5 A/div, 4 ms/div, right: 1 A/div, 400 μs/div)

In series with LCL filter, there is EMC filter connected for damping radio-frequency transients caused by high di/dt while transistors are switched.

Between induction generator and active rectifier, there is LC filter only due to significant inductance of generator windings, which additionally smooths current and lowers filters price. LC filter would be eliminated at all, but there would be a need for a special, very expensive shielded cable to meet electromagnetic compatibility requirements. Furthermore, in lack of LC filter, generator windings insulator will be exposed to high frequency square voltage waveform, what speeds up its aging and can lead to internal short circuit of windings, what finally can stop SWT.

4. Measurement and control

The whole system is controlled solely by TMS320F28069 microcontroller. It is responsible for operation of power electronic converter, as well as measurement and automation of SWT parameters. Microcontroller governs transistors in a power stage through dedicated drivers as well as decides about state of brake chopper, grid contactor, emergency brake, tail folding, starting and stopping of generator and other tasks necessary to proper operation and ensuring safety.

Control of the SWT system and power converter requires following measurements:

• Grid and generator currents (LEM transducers),

• Grid and DC link voltages (HCPL isolation amplifiers),

• Wind speed (cup anemometer),

• Vibration sensor.

All of the signals are provided to microcontroller A/D converters. Additionally voltage and current measurements are equipped with analog overvoltage/current protection, that instantly stops converter operation. For safety reason, state of grid contactor and emergency brake are monitored.

Control board is equipped with communication interfaces to allow local and remote monitoring of the SWT system.

5. Safety circuits

Safety is one of the most important parts of SWT, especially with unit located near households. Thus, besides inverters, a lot of additional equipment is required like backup power supply, mechanical brake, chopper, folding tail with its actuator, vibration sensor and others.

In normal operation mode, control circuits are powered by 24 V power supply connected to AC grid. Additional buffer supply keeps a battery charged to 27 V and sustains supply source relay in state ‘ACgrid fed’. When there is lack of grid voltage, buffer supply releases supply source relay, connecting battery to 24 V supply rail.

To secure wind turbine during very strong winds, turbine is set in parallel to wind, minimizing its area and reducing mechanical stress. Folding tail is used to control position of turbine. Tail is driven by 24 V/100 W actuator with styptic spring. When actuator is powered, tail decomposes. When there is lack of supply, styptic spring slowly pulls tail to secure position 90 ˚ downwind.

Positioning turbine in parallel to wind is not enough to stop a rotor. Thus an electrical and mechanical brakes are used. Electrical one is used to control motor with increased torque, mechanical one is default tightened when supply is off.

Converter is additionally equipped with brake chopper. A resistor is attached, that allows to turn power generated by turbine into heat. In practical applications it can be used to heat water or air. From the safety point of view a brake chopper is required to dissipate power in cases of loss of grid voltage, when rotor is spinning. Nominal dissipative power of brake resistor is relatively small – 2.5 kW, but for 30 seconds can handle overload of 10 kW. This should be enough to stop all rotating parts: blades, gearbox and rotor of asynchronous motor and safely convert kinetic energy of offline SWT into heat. Braking with chopper and resistor allows to control stop sequence, when generator is overloaded with braking torque much higher than nominal torque. Braking torque can be adjusted by duty cycle of PWM chopper signal.

For safety reasons, chopper current is measured at start procedure, to ensure presence of brake resistor. When current is to low, it can mean lack of resistor and further operation of SWT is blocked.

Safety is one of the most important topic, that’s why in case of failure of braking chopper, backup supply or microcontroller mistake, there is redundant level of protection represented by electromechanical disc brake on the shaft of inductive generator. When SWT operates normally, coil of disc brake is supplied and brake is released, allowing motor to spin. The easiest way to supply brakes coil is use of AC-grid. In case of lack of voltage, brake will rapidly start to slow down generator with very high torque of 150 Nm (nominal IG torque is 71 Nm). This could damage a gearbox or blades. Moreover, in short period of time, disc brake and pads will wear out. Thus in presented converter, coil is supplied from a DC link by DC-DC converter. Until in DClink capacitors is some amount of energy able to excite a motor, electrical braking is applied. In the last phase electromagnetic coil of brake is released, what tightenes mechanical brake to fix rotor.

All described automatic procedures are controlled by microprocessor through inverters power board presented on Fig. 8.

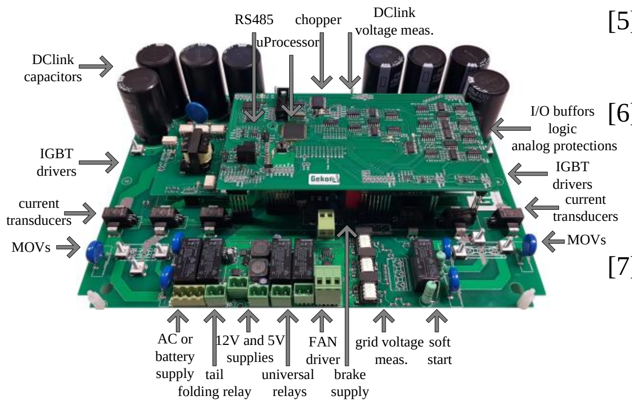

Fig. 8. View of control board (on the top), driver boards (middle) and power board (the largest, on the bottom)

6. Summary

To sum up, Small Wind Turbine is much more complex than photovoltaic power plant. Use of asynchronous induction motor forces application of active rectifier with additional current measurement and control algorithm, when for Permanent Magnets Synchronous Generator only diode rectifier is required. Nevertheless induction motors are more commonly available, simpler in assembly and they do not require neodymium magnets, making proposed in this paper solution cheaper. However complexity and necessity of use lots of auxiliary circuits and actuators forces on designers special attention to every detail, especially for safety reasons in case of lack of grid voltage.

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