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PMSG based residential wind turbines: possibilities and challenges

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Abstract. This paper presents an overview of technologies for wind energy conversion into electrical energy with the help of residential wind turbines. The theory of wind energy conversion into mechanical energy is shown. Wind velocity distribution and normalised energy yield examples are given to improve understanding of wind energy availability and converter operation modes. Additionally the wind velocity dependency of the height above ground is explained. The pros and cons of wind turbine generators are analysed. Converter topologies galvanically isolated for interfacing a permanent magnet synchronous generator based variable speed wind turbine with a residential power network is analysed. Main emphasis is on the combination of a rectifier and an isolated quasi-Z-source (*qZS*) based DC/DC converter topology proposed by the authors. The topology (rectifier coupled with a *qZS* based galvanically isolated step-up DC/DC converter) is essential to generate regulated DC voltage (400 V DC typical for 230 V AC output) despite wide variations in the output voltage of a wind generator. The operation principle of the proposed topology is described. Experimental and simulation results are presented and analysed.

Key words: Renewable energy, power converter, wind turbine.

INTRODUCTION

Continuous growth of the earth's population and standard of living leads to stable growth in energy consumption. Limited availability of fossil energy resources urges us to make use of renewable sources for electric energy generation. Wind energy is quite an attractive form of renewable energy especially at high latitudes where the feasibility of applying direct solar energy conversion technologies is limited. The commercial potential of wind energy (72 TW) is five times higher than world energy demand in all forms. However, the installed capacity in the middle of 2012 was only 254 GW (Archer & Jacobson, 2005; World…, 2012). Wind turbines are the most popular wind energy conversion technology today. The power of installed windmills is being increased continuously especially when the places of turbine installation move from on-shore to off-shore. Although the energy yield is higher for large inland and off-shore installations, the issue of transmission and distribution losses is still of major concern. Distributed generation and smart grid technologies are introduced to reduce transmission losses by bringing closer energy generation and utilisation and reducing load variations over time. Micro-generation is a part of the smart grid and distributed generation philosophy.

A micro-generator is an electrical energy source that includes all interface units and operates in parallel with the distribution network. Current rating of such devices is limited up to 16 A per phase or 11 kW (CENELEC, 2007). Some energy sources can be connected directly to the distribution network, but in the case of DC power sources or variable speed wind turbine (*VSWT*) systems it is necessary to use a power converter that interfaces the source and the grid. An interface converter is the most important part of the *VSWT*-based micro-generator that is responsible for the conversion of generator voltage with variable frequency and amplitude into usual AC power for a distribution network at high efficiency. Additionally, it is responsible for maximum power extraction from wind by means of proper turbine speed control (Manfred & Stiebler, 2008).

The generator converts the mechanical power of a wind turbine into electrical energy. The main drawback of DC generators is the frequent maintenance of brushes. This is the main reason why DC generators cannot be found in commercial applications (Fig. 1). Wound rotor asynchronous generators have slip rings and brushes, allowing to feed the rotor winding. For this feature they often are named doubly-fed induction generators (*DFIG*). *DFIG* are often used in the *VSWT* where the ratio value of the maximum and minimum speed is not more than two. The main feature of *DFIG* utilisation in the *VSWT* is the speed regulation possibility with the help of a small converter whose power value is only 20% of the turbine's nominal power. The disadvantage of all asynchronous machines is the limited number of pole pairs and for this reason they cannot be used in directly-driven wind plants.

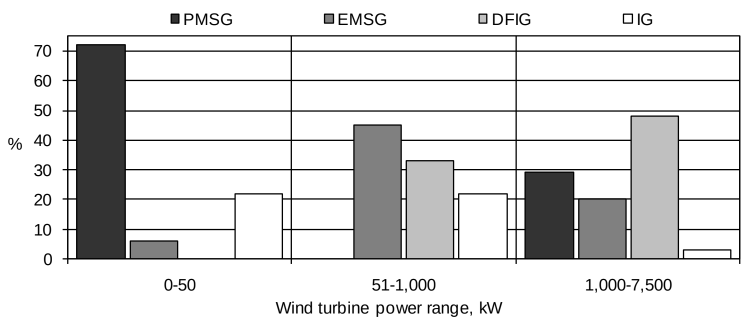


Figure 1. Generator type distribution by wind turbine power range.

Synchronous generators have no limitation on the number of pole pairs that make them suitable for directly-driven wind turbines. A multi-pole synchronous generator can be made with permanent magnet excitation (*PMSG*) or electromagnetic excitation (*EMSG*). The losses and the price of different synchronous generator types are the main aspects that determine their popularity in concrete power ranges. Analysis of the wind turbines, commercially available by their generator type at different power ranges (Fig. 1) shows that the most popular are *PMSG* for small wind turbine applications. The main drawback of *PMSG* is the dependence of its output voltage on the rotation speed. Since the speed ratio n_{max}/n_{min} for the *VSWT* can reach 4 times, the interface converter should have good voltage boost properties to ensure stable output voltage.

WIND ENERGY CONVERSION AND AVAILABILITY

This section introduces the properties of wind energy, emphasising wind energy extraction by means of *PMSG* based *VSWT*. Operation modes of *VSWT* with fixed blades are analysed and generator characteristics are given.

Only a part of the total wind energy can be extracted. The available energy part in wind is described by the power coefficient *Cp* (Equation 1). The theoretical maximum value of this coefficient is 0.59 and it is called the Betz limit (Manfred, 2008).

$$P_{turbine} = 0.5 C_p A \rho v^3 . \quad (1)$$

The practical values of *Cp* lie between 0.4 and 0.5 for industrial wind turbines (Manfred, 2008). This power coefficient is a function of the tip-speed ratio λ. The tip-speed ratio shows the relation between the circumferential velocity of the blade tips and the wind velocity:

$$\lambda = \frac{r\Omega}{v} , \quad (2)$$

where r is the rotor radius and Ω is the angular rotor speed.

Rotors are usually designed so that power coefficient *Cp* has the maximum values at the tip-speed ratio in the range from 4 to 8. Since the coefficient *Cp* is the function of the tip-speed ratio the power extracted by the wind turbine depends on the wind velocity and the rotational speed. Power curves at different wind velocities for turbines with fixed blade position are shown in Fig. 2.

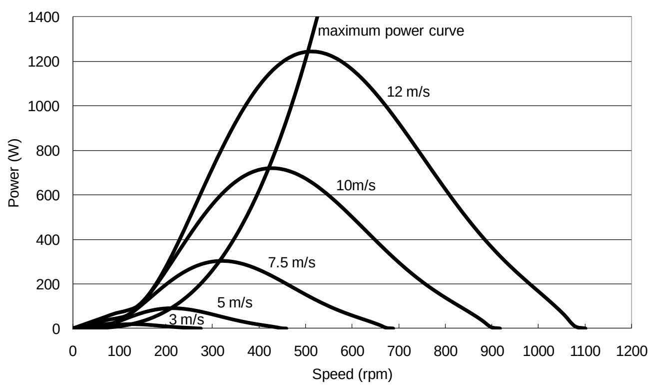


Figure 2. *VSWT* power vs. rotation speed of turbine at different wind velocities.

Fig. 2 indicates that the maximal power can be captured from wind turbines only if they are of a variable speed type. This figure illustrates also another feature of variable speed turbines: generator's speed is four times lower at the cut-in wind speed than at the rated velocity.

The wind velocity determines the rotational speed of the wind turbine and the generator. Since it has direct impact on power converter operation modes, an example of wind velocity distribution with average value 5.4 m s^{-1} at 10 metre height is shown in Fig. 3a, but the corresponding energy yield in Fig. 3b.

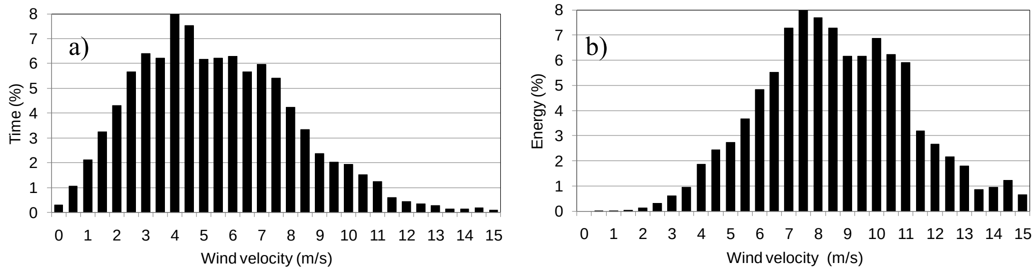


Figure 3. An example of wind velocity distribution (a) and normalised energy yield (b).

Since the analysis of statistical data takes a lot of time and can be inaccurate due to yearly wind variations, the Reyleight-distribution (Fig. 4) can be used for optimal wind turbine selection and converter optimisation purposes (Manfred, 2008). These distributions are characteristic of Baltic coastal regions due to similar average wind speed (Rathmann, 2003) and so can be used as a reference for interface converter design.

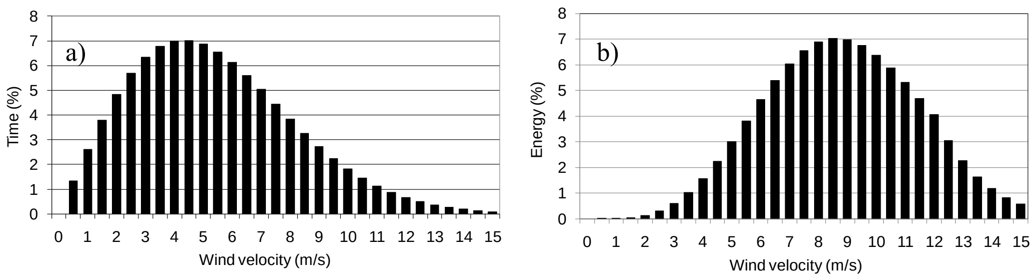


Figure 4. A Reyleight-distribution with v_{av} = 5.4 (a) and normalised energy yield (b).

Three distinct operating modes of the variable speed wind turbine generator can be emphasised: slow speed, rated speed and high speed. Slow speed occurs when the wind velocity lies in the range from 3 m s^{-1} till 7 m s^{-1}, rated speed between 7–8 m s^{-1} and high speed mode at higher velocities. This division of modes is made according to the normalised energy yield (Fig. 3b). The rated speed corresponds to wind velocity with maximum energy.

The distribution of wind velocity per wind turbine modes is presented in Table 1. It shows that the wind turbine is still one quarter of the time and half of the time works at low speed. The turbine captures more than half of the energy at high speed mode only 15% of the time. Such wind behaviour rejects the possibility to utilise all turbine power in residential loads without some energy storage.

Table 1. Wind turbine modes

Turbine modes	No speed	Slow speed	Rated speed	High speed
Wind velocity range	0–3 m s^{-1}	3.5–6.5 m s^{-1}	7–8 m s^{-1}	8.5–25 m s^{-1}
Time	23%	46%	16%	15%
Energy	0%	22%	24%	54%

Fig. 5 illustrates the average wind speeds in Baltic countries at 50 m height. These values are more useful for commercial applications due to similar height of mast. Since the masts of small turbines are shorter – around 20 m, the average wind speeds are significantly lower. The average wind speed v_2 at height z_2 can be calculated from a reference speed v_1 at z_1:

$$v_2(z_2) = v_1 \frac{\ln(z_2/z_0)}{\ln(z_1/z_0)}, \quad (3)$$

where z_0 is roughness length dependent on country (0.03 m – farmland; 0.1 m –trees; 0.5–1.6 m – forests) (Manfred, 2008).

Fig. 6 illustrates an example of the average wind speed change above the terrain. The reference speed is 5.4 m s^{-1} at 10 m height in this example. As one can see the average wind speed changes significantly with height and higher mast expenses should be evaluated before the turbine installation.

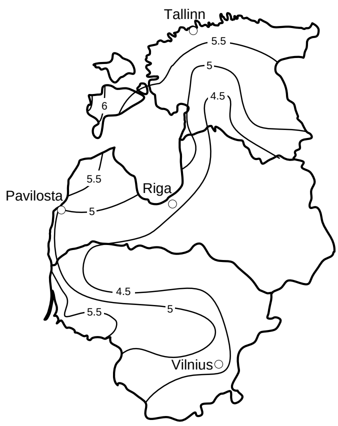


Figure 5. Average annual wind speed in Baltic countries at 50 m height above terrain.

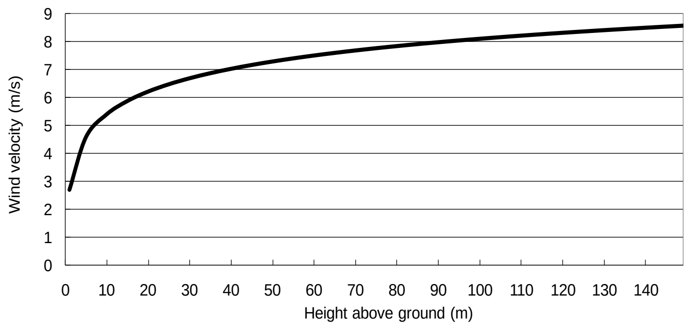


Figure 6. Wind speed change above ground.

PMSG BASED WIND TURBINE

PMSG based *VSWTs* have three distinct operation modes: silent mode, variable speed operation mode and constant speed mode. A turbine is silent in two cases: wind speed is below a cut-in level or above the cut-off speed. If the speed is below its cut-in level it produces insufficient torque to move the turbine. At the same time winds above the cut-off level may damage the turbine, which must be stopped in such conditions. A turbine usually starts to operate at 3 m s^{-1} and it should be stopped at wind speeds above 25m s^{-1} (Manfred, 2008). Turbines operate at variable speed in the wind velocity range from cut-in to rated wind speed. Rated wind speed differs by turbine types, but often has the value of 12 m s^{-1}. Constant speed mode takes place above the rated wind speed. Turbine output power remains constant at this mode (Fig. 7).

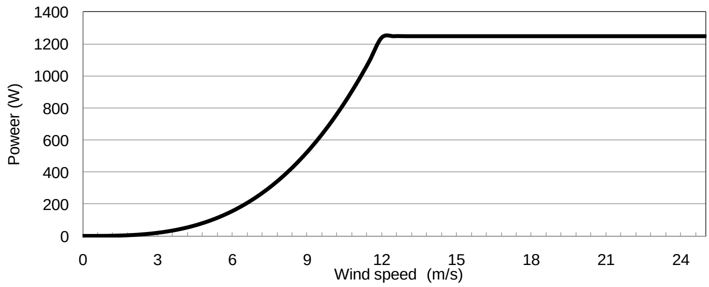


Figure 7. Output power of 1.25 kW *VSWT*.

PMSGs with 8 pole pairs are considered as a power source in this research. Its line voltage is 140 V at 375 rpm, but it can operate up to 510 rpm. This speed is considered as the maximum power operational point for the turbine and the generator. Generator power reaches 1,250 W at this point, but the output voltage is 183 V.

Cut-in speed for a turbine is 150 rpm and it can produce 40 W, but the generator voltage is only 48 V at this point. So this is the lowest input voltage for a converter. Generator speed and voltage characteristics are shown in Fig. 8.

Since the generator voltage range is quite wide and the value is relatively low, the appropriate interface converter topology for micro turbines is the key to the good performance/quality ratio.

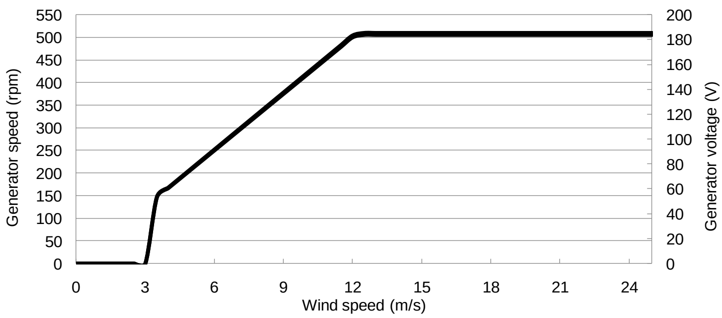
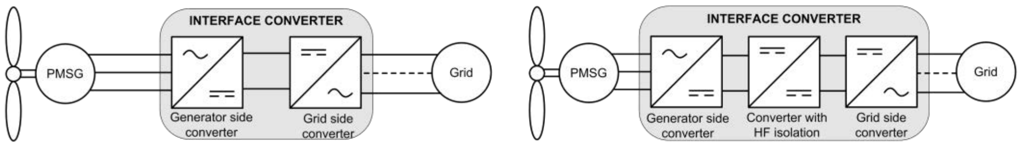


Figure 8. Generator speed and voltage vs. wind speed.

INTERFACE CONVERTER TOPOLOGIES AND ISSUES

The interface converter rectifies the input AC with variable voltage and frequency, adjusts voltage levels and inverts DC voltage into AC with grid voltage and frequency. Additionally, it should have maximum power point tracking (*MPPT*) functionality to extract more power from wind. Different topologies of the interfacing converter are discussed in the literature (Pathmanathan et al., 2008; Dehghan et al., 2009; Deng, & Chen, 2009; Xiaodong & Bhat, 2009; Mittal et al., 2009; Zhang et al., 2009; Bisenieks et al., 2011). Basically, they can be categorised as topologies without galvanic isolation (Fig. 9*a*) (Dehghan et al., 2009; Deng, & Chen, 2009; Mittal et al., 2009; Zhang et al., 2009) and those with high frequency (*HF*) isolation (Fig. 9*b*) (Pathmanathan et al., 2008; Xiaodong & Bhat, 2009; Bisenieks et al., 2011). This paper is devoted to the isolated topologies, i.e. where the generator and grid sides are galvanically isolated by means of a *HF* transformer.



a) b)

Figure 9. Generalised block diagrams of interface converters for *VSWT* with *PMSG*: without isolation (a) and with high-frequency isolation (b).

Earlier converter topologies with *HF* isolation for the *PMSG* based *VSWT* have several drawbacks, such us high complexity of the dual LCL DC/AC converter (Xiaodong & Bhat, 2009) or high currents of transformer primary winding of the isolated buck type converter with the uncontrolled rectifier (Pathmanathan et al., 2008) at rated and maximal loads.

In 2010 researchers of the Department of Electrical Drives and Power Electronics of Tallinn University of Technology proposed a new type of isolated interface converter for *PMSG* based wind turbines (Bisenieks, 2011) (Fig. 10). The proposed interface converter utilises the multistage energy conversion. First, the controlled rectifier converts the generator voltage U_{gen} from the *PMSG* into a DC voltage U_{DC1}. The *qZS* DC/DC converter offers galvanic isolation and voltage level adjustment between the generator side and the grid side DC links. Utilisation of a unique *qZS* network and appropriate control offers an additional voltage regulation freedom at high efficiency. In such a way both converters together are responsible for the stabilised grid side DC link voltage U_{DC2}.

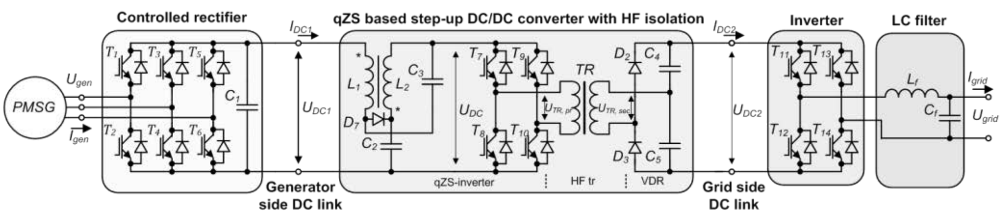


Figure 10. Power circuit of the multistage interface converter.

Since the controlled rectifier needs additional control and measurement circuitry that increase the price of the converter, the multistage topology better fit the small wind turbine applications. This paper proposes a simplified topology (Fig. 11) of the interface converter with the *HF* isolation transformer for micro *PMSG* based *VSWT* systems.

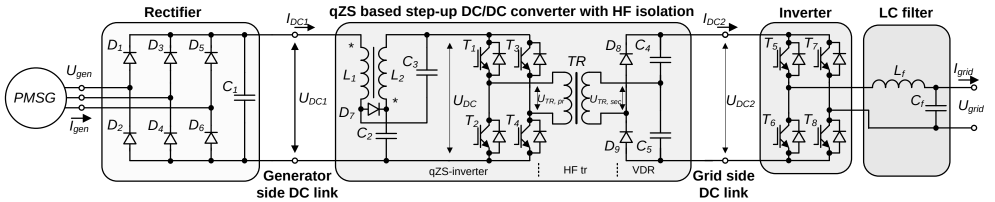


Figure 11. Power circuit of the proposed interface converter.

The controlled rectifier is substituted with an uncontrolled one to reduce the number of switches and simplify the control circuitry. The necessary boost is obtained only by *qZS* DC/DC converter. Converter operation modes at different wind speeds for the particular application with 1.3 kW *PMSG* are illustrated in Fig. 12.

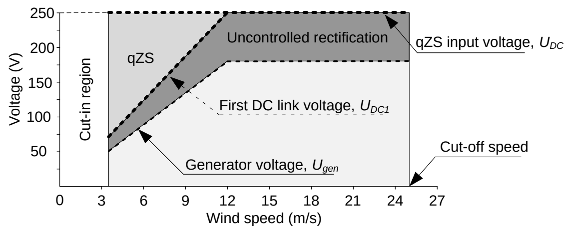


Figure 12. General operation modes of the converter.

First, the rectifier converts the variable voltage with the variable frequency U_{gen} from the *PMSG* into a DC voltage U_{DC1}. The generator side DC link voltage range is between 70 V at cut-in conditions and 250 V in constant speed mode.

The *qZS* based step-up DC/DC converter is stabilising the grid-side DC link voltage U_{DC2} at 400 V DC despite the variation of the generator-side DC link voltage U_{DC1} in the range from 70 V to 250 V. Neglecting losses in components, the output voltage of the *qZS* based step-up DC/DC converter operating in the continuous conduction mode (*CCM*) could be estimated as (Vinnikov, 2010)

$$U_{DC2} = \frac{2 \cdot U_{DC1}}{n} \cdot \left(\frac{1}{1 - 2 \cdot D_S} \right) \tag{4}$$

where U_{DC1} is the generator-side DC link voltage, *n* is the turns ratio of the primary and secondary windings of the isolation transformer and D_S is the shoot-through duty cycle. The shoot-through is a special operation state of the *qZS* based step-up DC/DC converter, when the primary winding of the isolation transformer is shorted through both the upper and lower switches of both phase legs. The unique *qZS*-network (see Fig. 11) makes the shoot-through states possible, effectively protecting the circuit from damage. Moreover, the shoot-through states are used to boost the magnetic energy stored in the DC-side inductors L_1 and L_2 without short-circuiting the DC capacitors C_2 and C_3. This increase in the inductive energy in turn provides the boost of the voltage seen on the inverter output during the active states of the inverter. In that way, by keeping the voltage U_{DC} constant the inverter could be operated with a fixed duty cycle value, thus ensuring constant volt-second and flux swing of the isolation transformer *TR* (Bisenieks, 2011).

As it is seen from Fig. 11, the proposed *qZS*-inverter has the input inductor *L1* that buffers the source current. It means that in the *CCM* the input current never drops to zero during the shoot-through states. However, in the case of small loads, relatively low switching frequency and low inductance values of *L1* and *L2*, the *qZS*-inverter could start to operate in the discontinuous conduction mode (*DCM*) and the input current falls to zero during some part of the switching period. In the current application, similar conditions could appear during the operation of a wind turbine near the cut-in region, when the *PMSG* power drops to minimum (Bisenieks, 2011).

The operating period of the *qZS*-inverter in the *DCM* generally consists of an active state t_A, a shoot-through state t_S and a discontinuous conduction state t_D

$$\frac{t_A}{T}+\frac{t_S}{T}+\frac{t_D}{T}=D_A+D_S+D_D=1\,, \tag{5}$$

where D_A, D_S and D_D are the duty cycles of active, shoot-through and discontinuous conduction states, respectively.

In contrast to the *CCM* the operating voltage of the capacitor *C2* during the *DCM* will increase and it will lead to an increased peak value of the DC link voltage during the *DCM*, causing the 'overboost effect' of the input voltage:

$$\hat{U}_{DC(DCM)}=U_{C2}+U_{C3}=\frac{1-D_D}{1-2\cdot D_S-D_D}\cdot U_{DC1}\,. \tag{6}$$

The appearance of the *DCM* in the experimental setup is demonstrated in Fig. 13.

ANALYSIS OF SIMULATION AND EXPERIMENTAL RESULTS

A series of simulations and experiments were performed to verify the proper operation of the proposed *qZS* based interface converter. Tests were performed at three characteristic operation points of the *VSWT* system to demonstrate the converters operation modes in the entire generator voltage and power range (Bisenieks, 2011). These points are: cut-in speed (low voltage and minimum power), rated speed (corresponds to 7.5 m s^{-1} wind speed) and maximum generator speed, power conditions. Rated speed conditions are usually defined as the optimum operation point of the fixed speed turbine.

General parameters of the proposed interface converter are summarised in Table 2.

The PWM shoot-through control technique (Vinnikov, 2010) was implemented during the tests. The *qZS* network was operating at 20 kHz frequency, but isolation transformer at 10 kHz.

Table 2. General specifications of experimental setup

Component	Value or type
T_1–T_4	600 V/12 A IGBT (G4PC30UD
D_7	600 V/120 A fast diode (STTH200L06TV)
D_8–D_9	1.2 kV /60 A FRED (DSEI2x61-12B)
Capacitance of C_1	470 uF
Inductance of L_1–L_2	1.2 mH
Capacitance of C_2–C_3	60 uF
HF transformer turns ratio	1: 1.2
Capacitance of C_4–$C_5$25	uF

In the first test the generator-side DC link voltage was set to 70 V that corresponds to the cut-in wind speed conditions. The load that corresponds to the turbine power at cut-in is 40 W. The qZS based DC/DC converter operates in the discontinuous conduction mode (*DCM*) at such load. The shoot-through duty cycle D_S was set at 0.27 for this mode. Peak DC link voltage U_{DC} is 250 V (Fig. 13) that corresponds to theoretical assumptions stated in (Vinnikov, 2010). The *DCM* for low power operation was chosen to reduce the size of the inductors. Due to long current paths in the laboratory prototype of the *qZS* based DC/DC converter that leads to parasitic inductances, the voltage oscillations can be observed at zero input current intervals. The results of the second test were performed at rated speed conditions: (U_{DC1} = 150 V, U_{DC} = 250 V, power of the turbine was 350W) (Fig. 14).

The third test was performed at the maximum generator-side DC link voltage (U_{DC1} = 250 V), which corresponds to the maximal power of the turbine (1,250 W). At this operating point, when the input voltage equals the desired intermediate DC-link voltage (U_{DC1} = U_{DC} = 250 V), the shoot-through states were eliminated (D_S = 0) (Fig. 15). The intermediate DC link voltage have small voltage ripples due to current pulses caused by charging of the voltage doubler capacitors. These current pulses can be eliminated by bigger capacitance values of the voltage doubler capacitors.

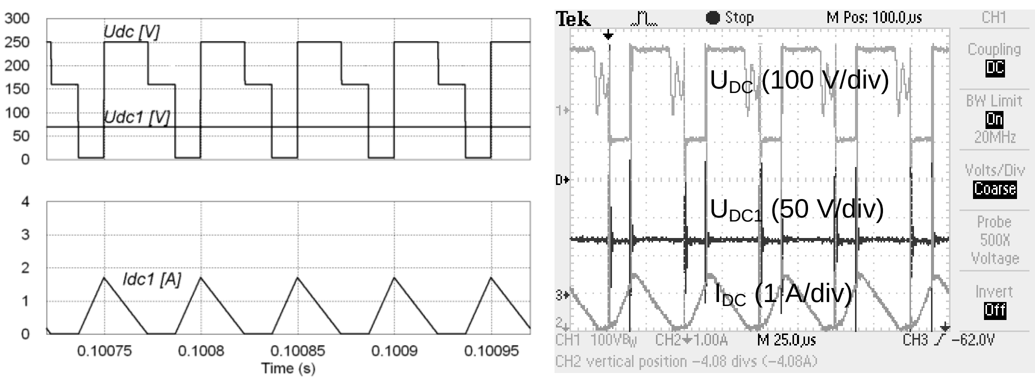


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Figure 13. Simulated (a) and experimental (b) waveforms of generator side and intermediate DC link voltages and input current of the qZS based step-up DC/DC converter at 40 W.

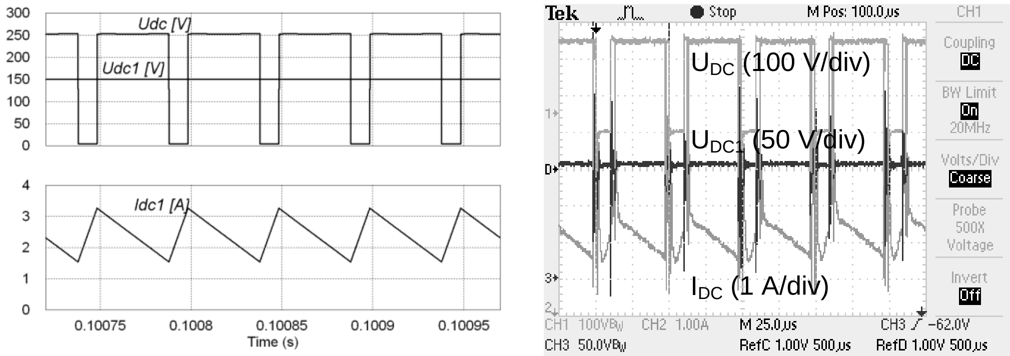

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Figure 14. Simulated (a) and experimental (b) waveforms of generator side and intermediate DC link voltages and input current of the *qZS* based step-up DC/DC converter at 350 W.

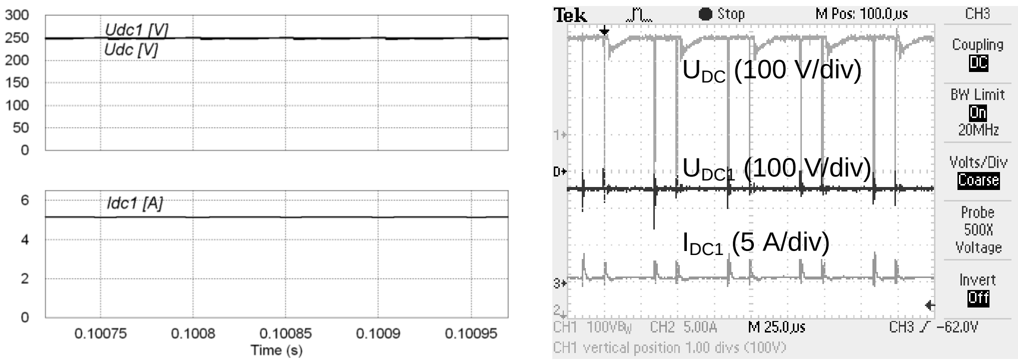

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Figure 15. Simulated (a) and experimental (b) waveforms of generator side and intermediate DC link voltages and input current of the *qZS* based step-up DC/DC converter at 1,250 W.

CONCLUSIONS

The study of wind theory shows that a *VSWT* allows maximum power from air flow to be extracted. *PMSG* based *VSWT* characteristics and wind properties on the Baltic coastal regions were analysed to define the converter operation modes. Converter topologies studied earlier show that they are not well suited for micro VSWT applications due to the complexity and efficiency concerns.

For these reasons the simplified topology of *PMSG* based *VSWT* and grid interfacing converter is presented in this paper. The converter consists of a rectifier, a quasi-Z-source DC/DC converter, a high frequency isolation transformer and a voltage doubler rectifier. Such topology offers necessary voltage boost properties and a simple power circuit. The results of performance tests demonstrate the interface converter ability to ensure the required grid side DC link voltage at all operation modes of *PMSG*-based *VSWT*. This topology could be implemented in residential *PMSG VSWT* applications with power up to 3 kW.

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