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**Research and Development of Interface
Converter for PMSG Based Wind Generator**

Summary of doctoral thesis

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DOCTORATE WORK PRESENTED TO OBTAIN THE DOCTOR'S DEGREE IN ENGINEERING SCIENCES

Doctorate work for the doctor's degree in the engineering sciences was publicly presented on the 02.08.2011 at 10:30 o'clock in Riga Technical University, Kalku str. 1 – 119

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CONFIRMATION

Hereby I confirm that I have worked out the present doctorate work, which is submitted for consideration to the Riga's Technical University for the degree of Doctor of engineering sciences. Doctorate work has not been submitted in any other university for obtaining the Doctor's degree.

Lauris Bisenieks

Date

The doctorate work is written in English language, contains: 108 pages, introduction, 3 chapters, conclusions, 88 figures, 74 formulas, 13 tables, 100 references and 2 appendixes.

SIGNIFICANCE OF THE TOPIC

Continuous growth of the earth population and improving standards of living are the main driving forces for the continuous growth of the energy demand. Although the energy use per unit of gross domestic product (GDP) is declining in most countries, the GDP increase is faster than efficiency growth, causing to use more and more resources for energy production. It is forecasted that this trend will continue in the upcoming decades. Limited availability of fossil energy resources, such as coal, natural gas, oil and nuclear, urge to make use of renewable sources for electric energy generation. Moreover, the use of fossil fuels are connected with greenhouse gas emissions and in case of the nuclear energy, there is a high potential of radiation product leakage that can cause irreversible damage to environment, but used fuel and old utility disposal is connected with high expenses after the closure of nuclear power stations. Environmental aspects and expenses are additional driving forces for technology development of alternative energy usage.

The cost of electrical energy from alternative energy sources is major concern that prohibits wider its utilization. This is particularly true for micro and small wind turbine applications due to the low typical installation height and as a result lower average wind speeds that leads to lower produced energy. Since there is no possibility to affect average wind speeds, the only way how to increase the energy output of wind turbine systems (WTS) is to improve the efficiency of all its components. This dissertation is devoted to new power electronics converter development for micro and small wind turbines.

OBJECTIVE OF THE WORK AND FULFILLED TASKS

The objective of this doctoral work is to research and develop of interfacing converter for PMSG based variable speed wind turbines. Since the whole interfacing converter is a complex system consisting of a power converter, control unit and other elements, several specific tasks are defined:

- analysis and comparison of DC/DC converters with HF isolation in context of PMSG based VSWT interfacing converter with quasi impedance source (qZS) converters for wind applications;
- analysis of wind theory and PMSG based variable speed wind turbine properties to define the requirements for interfacing converter;

- analysis of qZS DC/DC converters in context of VSWT applications;
- development of interfacing converter prototype for wind applications;
- analysis of experimental results and conclusions of system potential;
- development of new qZS DC/DC converter topology with improved boost properties.

METHODS AND MEANS OF RESEARCH

In order to estimate the proposed idea of new interface converter for PMSG based VSWT the number of simulations was performed in PSIM and Matlab Simulink. QZS DC/DC converters were simulated in PSIM, but behaviour of controlled rectifier was evaluated by Simulink.

To verify the correct operation of proposed interface converter with multistage boost operation the experiments were carried out. Controlled rectifier was tested with PMSG at different speed and respective power levels, firstly. Then the tests with qZS DC/DC converter with HF isolation were carried out at corresponding voltage and power levels, to evaluate the predicted operation modes.

Analytic analysis of qZS based DC/DC converter with improved boost properties was done.

Analysis of proposed interface converters suitability for different VSWT applications was carried out.

SCIENTIFIC ORIGINALITY

A novel interface converter based on controlled rectifier with PFC functionality and qZS DC/DC converter with HF isolation has been elaborated and verified by means of simulations, analytic calculations and experiments;

A novel simplified interface converter based on uncontrolled rectifier and qZS DC/DC converter with HF isolation has been elaborated and verified by means of simulations and experiments for micro wind turbines;

A novel qZS DC/DC converter with switched inductors are proposed and analytic equations are given.

Design of interface converter is described for further market ready product development;

Comparison of proposed topologies of interface converter is made.

PRACTICAL APPLICATION OF THE WORK

The elaborated prototype of the interface converter can be further developed to commercial product and launched on the market for micro and small wind turbine systems. Typical application of such system can be considered as stand-alone and grid connected systems

WORK APPROBATION

The approbation of work has been realized by presenting the results of the research at the following international conferences:

1. Bisenieks L., Galkins I. Estimation of Converter Topologies for Small Wind Turbine // Topical Problems in the Field of Electrical and Power Engineering*Doctoral School of Energy and Geotechnology II : Proceedings, Estonia, Parnu, 14.-19. June, 2010. - pp 25-28.

2. Bisenieks L., Vinnikov D., Galkins I. New Isolated Converter for Interfacing PMSG Based Wind Turbine with Distribution Network // Topical Problems in the Field of Electrical and Power Engineering*Doctoral School of Energy and Geotechnology II: Proceedings, Estonia, Parnu, 10.-15. January, 2011. - pp 100-107.

3. Bisenieks L., Vinnikov D., Galkins I. New Isolated Interface Converter for Grid-Connected PMSG based Wind Turbines // Proceedings of 10th International Conference on Environment and Electrical Engineering, Italy, Rome, 8.-11. May, 2011. - pp 869-872.

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REFERENCES

INTRODUCTION

Continuous growth of the earth population and improving standards of living are the main driving forces for the continuous growth of the energy demand. Although the energy use per unit of gross domestic product (GDP) is declining in most countries, the GDP increase is faster than efficiency growth, causing to use more and more resources for energy production. Limited availability of fossil energy resources, such as coal, natural gas, oil and nuclear, urge to make use of renewable sources for electric energy generation. Moreover, the use of fossil fuels are connected with greenhouse gas emissions and in case of the nuclear energy, there is a high potential of radiation product leakage that can cause irreversible damage to environment, but used fuel and old utility disposal is connected with high expenses after the closure of nuclear power stations. Environmental aspects and expenses are additional driving forces for technology development of alternative energy usage.

The cost of electrical energy from alternative energy sources is major concern that prohibits wider its utilization. This is particularly true for micro and small wind turbine applications due to the low typical installation height and as a result lower average wind speeds that leads to lower produced energy. Since there is no possibility to affect average wind speeds, the only way how to increase the energy output of wind turbine systems (WTS) is to improve the efficiency of all its components. This dissertation is devoted to new power electronics converter development for micro and small wind turbines.

Wind energy is quite an attractive form of renewable energy especially at high latitudes where feasibility to apply 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 [8]. However, the installed capacity in 2009 was only 159GW and there are the huge potential of growth [23].

Mechanical energy of wind turbines are converted in electrical energy with help of appropriate generators. Permanent magnet synchronous generators (PMSG) predominate in small turbines and become popular in large power range due to multipole design that eliminates the need for gearbox [19].

Although the energy yield is higher for large inland and off-shore installations, the issue of transmission and distribution losses still is of major concern. Distributed generation and smart grid technologies are introduced to reduce transmission losses by bringing closer energy generation and utilization and reducing load variations over time. The charging control of the

electric vehicles can be the main load balancing feature, and can serve as energy buffer for unpredictable wind energy generation. The rapid popularity increase of electric and plug in hybrid cars will eliminate additional expenses for electric energy storage devices from wind in near future, but utility grid can absorb energy excess during strong wind periods.

DC link utilisation for connection of generating and consuming units is beneficial in smart grid applications [13], but due to slow technology implementation in real consumer applications the AC based smart grid systems will be used in transition stage [35].

Micro-generation is a part of smart grid and distributed generation philosophy serving as a power source. It can be connected to distribution network nowadays or to AC based smart grid in near future. Micro generator 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 [7]. Some energy sources can be connected directly to the distribution network, but in the case of DC power sources or PMSG based variable speed wind turbine (VSWT) systems it is necessary to use a power converter that interfaces the source and the AC grid.

VSWT based micro generators consist of a wind turbine, a generator and an interface converter (Fig. 0.1.). Wind turbines capture wind energy and convert it to rotational mechanical energy. The generator converts mechanical energy into electricity, but the interfacing converter rectifies the input AC with variable voltage and frequency, adjusts voltage levels and inverts DC voltage into AC with grid voltage and frequency.

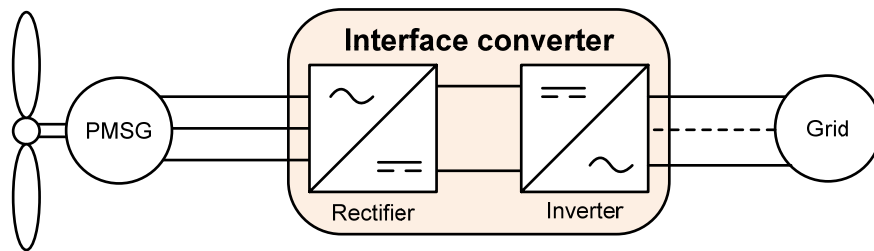


Fig. 0.1. General block diagram of WTS

The main objective of this dissertation is to develop a power part of an interface converter for PMSG based VSWT with power level up to 11kW that can be used as micro generator after control and user interface development.

1. CHALLENGES OF PMSG BASED WIND TURBINE

This chapter is devoted to definition of requirements and operation modes of converter for micro and small wind turbines in context of micro-generator and already developed converter analysis. The development of well

suited converter for wind applications requires understanding of wind turbine generator system (WTGS) characteristics. Wind properties directly affect WTGS characteristics and for this reasons wind theory and wind regime is discussed. Since micro-generator can be connected to low voltage distribution or residential network, the main requirements and grid parameters are stated next. PMSG based WSVT characteristics and analysis of traditional grid tied converter topologies are given in the end of this chapter.

Wind energy conversion

Wind is a kind of air flow and, since this air has its own mass and speed, the wind contains some kinetic energy, which can be extracted. This energy is usually captured by an electromechanical generator which consists of wind turbine, some electrical generator and power electronic converter. Wind turbine transfers the energy from the air flow to the generator, where electrical energy is generated, but converter provides control of generator and turbine. the amount of mechanical power captured by the turbine could be calculated:

$$P_{turbine} = \frac{1}{2} C_p \rho A v^3, \quad (1)$$

where A - swept area (m²);
 ρ - air density (kg/m³);
 v - wind velocity (m/s);
 C_p - power coefficient of wind turbine.

The air density depends on air pressure and moisture, but for practical calculations its value may be assumed as 1.2 kg/m³.

The theoretic maximum value of power coefficient is 0.59 and it is called the Betz limit, but the maximum values lies between 0.4 and 0.5 for industrial wind turbines. Power coefficient is a function of the tip speed ratio (TSR) λ which is another important parameter for wind turbines. The TSR shows the relation between circumferential velocity of the blade tips and the wind velocity:

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

where r - radius of the wind turbine rotor (m);
 v_t - velocity of the blade tip (m/s);
 ω - angular rotor speed (rad/s).

The power coefficient has its maximum at certain TSR value λ_{opt} . Optimum value of TSR depends on turbine aerodynamics and type, for example: $\lambda_{opt}=5...8$ for three blade horizontal axis turbines and 4 to 7 for vertical axis designs [17]. Since the optimum value of TRS is constant for

certain turbine, then rotation speed of turbine should follow wind speed to obtain maximum mechanical efficiency. This aspect directly leads to variable speed operation of wind turbine to get maximum energy from wind. Wind mills with variable speed operation mode are named - variable speed wind turbines (VSWT).

Nominal rotation speed of turbines is affected by their size. Rated rotation speed of small turbines with rotor diameter less than 2 meters is 500 rpm, usually, but big ones with 126 m rotor only 12.6 rpm. It shows that wind mills are slow running machines and multipole generators are required to eliminate the gear box [22, 38]. The PMSG are often utilized in such applications.

Wind velocity distribution

The wind velocity determines the rotational speed of the VSWT and the generator. Since it has direct impact on power converter operation modes, an example of wind velocity distribution at 10 meter height is shown in Fig. 1.1., but the corresponding energy yield in Fig. 1.2. An average velocity is 5.4 m/s for these distributions. These distributions are obtained from the analysis of Pavilosta weather forecast data for the year 2009.

If only annual average value of velocity is available, then wind velocity distribution can be approximated by Reyleigh-distribution [17].

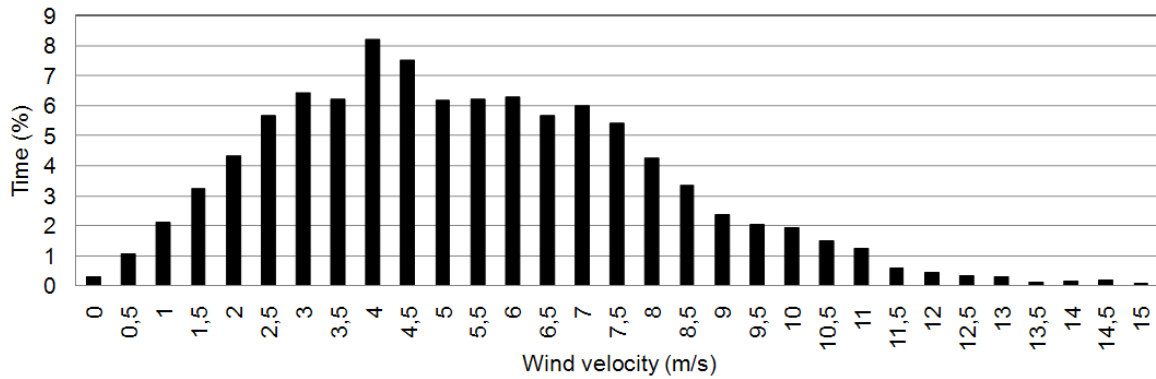


Fig. 1.1. An example of wind velocity distribution

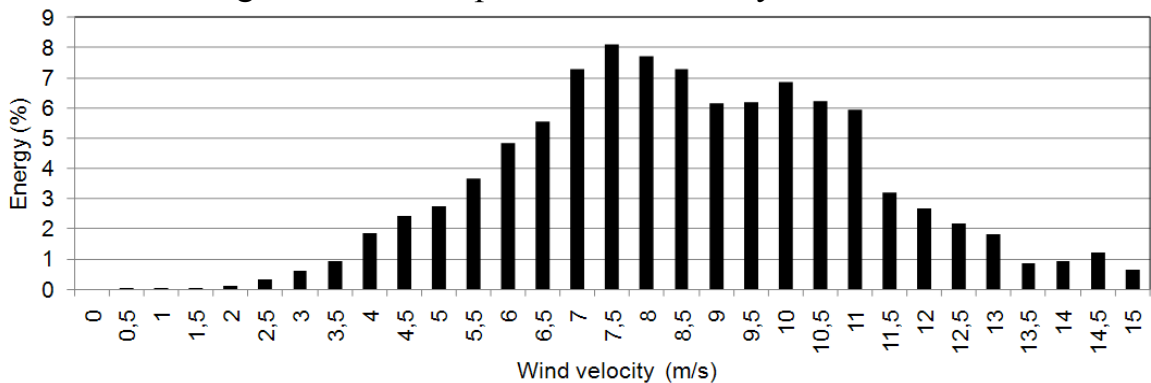


Fig. 1.2. An example of normalized energy yield

WTS power conversion

The wind turbine system consists of two basic parts: a mechanical and an electrical one (Fig. 1.3.). Mechanical part of WTS extracts the energy from wind and makes the kinetic energy of air flow available to the generator shaft. The electrical part converts the electric energy from generator making it suitable for electric grid. The electric generator transforms the mechanical energy into electrical one and acts as the connection point of both parts of WTS [29].

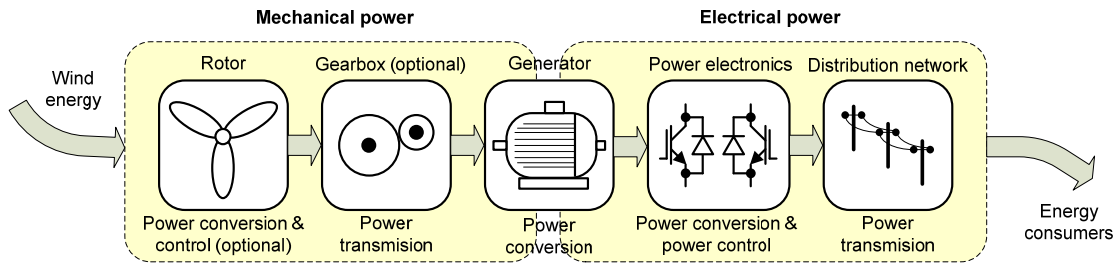


Fig. 1.3. Power conversion in wind turbine system

From WTS description one can see that there are three distinct stages that can be optimized for maximum wind energy extraction: mechanical, electromechanical and electrical. The mechanical stage may regulate the pitch angle of the blades, the yaw of the turbine shaft and the speed of generator shaft. The electromechanical stage can have different structures: different types of generators (synchronous, asynchronous and custom constructions [25]) with variable structure (pole pairs, excitation types) and some power converter for control of generator excitation. An electrical stage can have power electronics converter that adapts the grid and the generator voltages and controls the active and reactive power flows [7].

Interface converter topologies for PMSG based VSWT

There are several topologies of interface converters for PMSG based VSWT studied in literature. They can be divided in topologies without isolation and ones with galvanic isolation by means of HF transformer utilisation.

One of the simplest transformerless interface converter topologies consists of uncontrolled rectifier and grid side converter. This topology is the cheapest solution due to low number of controlled switches and simple control system which is necessary only for the grid side inverter. The main disadvantage of this solution is the absence of DC link voltage regulation possibility that leads to lack of extracted power at low speeds [20]. Additionally, this topology does not offer any generator power and speed

control possibilities that exclude MPPT functionality. All these disadvantages make this topology unsuitable for VSWT applications.

The topology with an additional boost converter was introduced to improve the generator power control capability by keeping the power circuit of the converter at a simple level [11]. This topology offers a possibility to extract power at low wind speeds and thus significantly expand the operation range of the PMSG based VSWT system. These improvements are significant, but due to the limited PFC capability and lower efficiency than with a controlled rectifier, it is not feasible to use this topology with a boost converter in high efficiency applications [20].

The back-to-back converter has high control flexibility of a generator torque and current [39]. Implementation of the controlled rectifier allows the generator to operate with the unity power factor and easily implement MPPT functionality.

The energy storage devices like batteries can be added to the intermediate DC link of the back-to-back converter to improve the low voltage ride-through (LVRT) capability. The LVRT capability becomes more and more important in the context of grid code requirements [23]. The main disadvantage of the classical back-to-back converter is only two voltage regulation freedoms of the generator and grid side converters. The generator side converter can boost the generator voltage to obtain the necessary level of the DC link voltage, but the inverter can only reduce it.

Since the VSWT operates at low rotation speeds more than half a time [4] and the output voltage of the generator is significantly lower than the nominal at this mode, the boost properties of the interface converter become an issue. This is especially topical at micro power level, where the nominal generator voltage is lower than the grid voltage.

Implementation of Z-source inverters (ZSI) has become popular in recent years in applications where additional voltage boost is necessary [10]. The ZSI topology features the PWM inverter coupled with a symmetrical lattice network consisting of two inductors and two capacitors connected in X-shape. The ZSI has inherent voltage boost and buck capability using the shoot-through switching states in each phase leg of the PWM inverter. This enables the wind generation system to achieve the demanded variable-speed operation.

Converters with HF isolation represent the interface converter group mainly addressed for WTS connected to the residential power grids or systems connected to DC bus (smart grid applications, for example). Interfacing converters with HF (Fig. 1.4.) isolation are the main topic of this research.

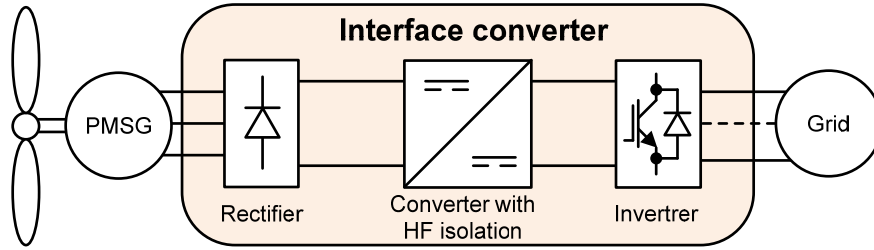


Fig. 1.4. Interface converter with a HF isolation

Residential network

Small wind turbine systems are usually utilised at rural and residential houses and are connected to residential power network. These networks are low voltage part of distribution network and utilize 400 V line to line voltage or 230 V phase to neutral voltage. These voltages can vary depending on load conditions and distance from substation. Voltage tolerances for the residential networks are defined by the standard EN 50610 [27]. The interface converter should be able to transfer the power from wind turbine to grid at all power network operation conditions predefined by the standard requirements. It means that output voltage of converter should be higher than nominal at least by 15% or reach the 265 V value for one phase system [24].

PMSG based WSVT characteristics

Utilization of PMSG in VSWT applications becomes more and more popular during last decades [2] especially at micro and small power WTS. The popularity of the PMSG usage is determined by three features: high efficiency, possibility of multipole design implementation and maintenance free operation. Despite the many advantages of PMSG there are some major drawbacks.

The main drawback of PMSG is the dependence of its output voltage on the rotation speed. The difference between the minimum and the maximum voltage can reach four times in VSWT applications [28]. This drawback can be easily overcome with the help of an appropriate interfacing converter. Another drawback is high weight and price of multipole PMSG that leads to utilisation of fast running machines together with gearbox for large scale turbines [28].

The 8 pole PMSG generator with 1.2 kW power was used as power source in this research. The main parameters of the generator are collected in Table 1.1. The generator was driven by asynchronous motor with belt transmission. The motor speed was controlled by ABB frequency converter to imitate the wind turbine speed change and obtain all operation modes of VSWT.

Table 1.1

Parameters of PMSG

Nominal power	1160 W
Nominal current	5 A
Nominal voltage	134 V
Nominal speed	375 rmp
Phase resistance	1.2 Ω
Phase inductance	5 mH
Number of pole pairs	8

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 that must be stopped at such conditions. A turbine usually starts to operate at 3.5 m/s and it should be stopped at the wind speed above 25 m/s [17]. 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 meters per second. The turbine has rated output power at rated wind speed. Constant speed mode takes place above the rated wind speed. The output power of turbine remains constant at this mode. Fig. 1.5. illustrates the maximal power curve of the example wind turbine with rotor diameter of two meters that match to our PMSG.

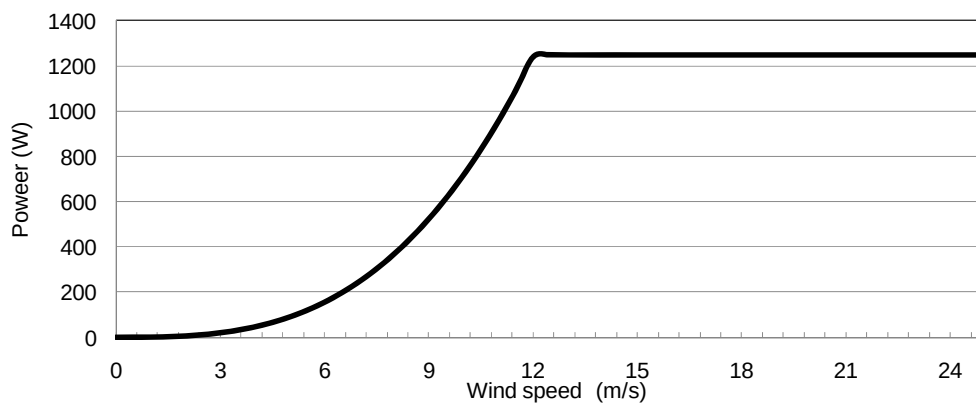


Fig. 1.5. Output power of PMSG based VSWT

The rotation speed dependence on wind velocity of the generator and its voltage characteristics is illustrated in Fig. 1.6. It clearly demonstrates the wide range of generators output voltage and wind turbine operation modes (at maximal turbine power in variable speed mode).

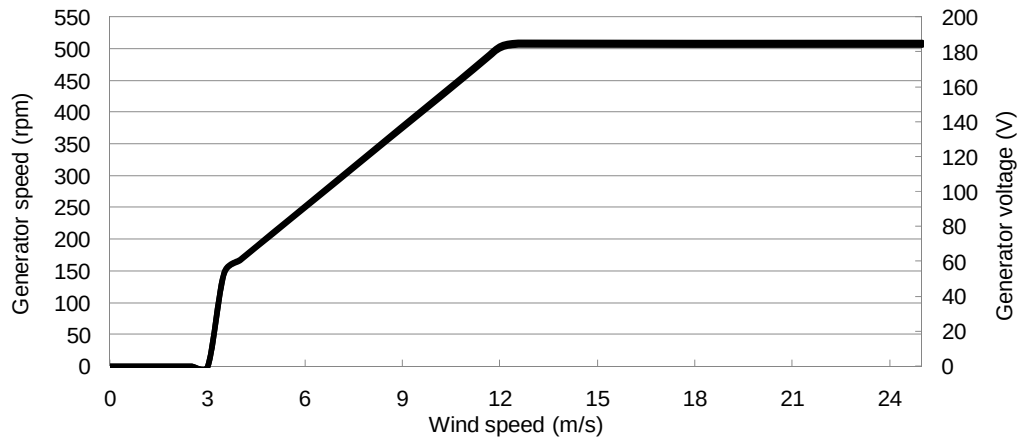


Fig. 1.6. Generator speed and voltage vs. wind speed

The generator operation modes (Table 1.2) were defined depending on its rotation speed and turbines captured energy. The rated speed corresponds to wind speed with maximum captured energy (Fig. 1.3.) and are close to nominal speed of generator. Such energy and corresponding time distribution indicates that energy produced by wind turbine can be fully utilized together with utility power supply. This is the reason for popularity of grid connected or grid-tied systems and the main reason for research in this field. Such distribution of wind energy illustrates another feature of wind power utilization that should be considered in interface converter design: converter operates at partial loads for long. It means that converter efficiency should be high at wide power range to improve the base load energy demand satisfaction. There are no any other opportunities for wind energy since its unpredictable nature.

Table 1.2

Generator operation modes

	No speed	Slow speed	Rated speed	High speed
Wind velocity range	0 – 3 m/s	3.5 – 6.5 m/s	7 – 8.5 m/s	9 – 25 m/s
Operation time at this mode	25 %	46%	17%	12%
Captured energy at this mode	0%	22%	27%	51%
Power range at this mode	0%	3 – 16 %	16 – 35 %	35 – 100 %
Generator speed	0	147 – 273 rpm	273 – 357 rpm	357 – 510 rpm

Topology analysis of interface converters for WSVT

There are a lot of interface converter topologies without galvanic isolation studied in literature, but only few researches are devoted to topologies with high frequency isolation for micro and small wind applications [9,14,16]. In [9] the authors have proposed a buck type isolated DC/DC converter (Fig. 1.7.)

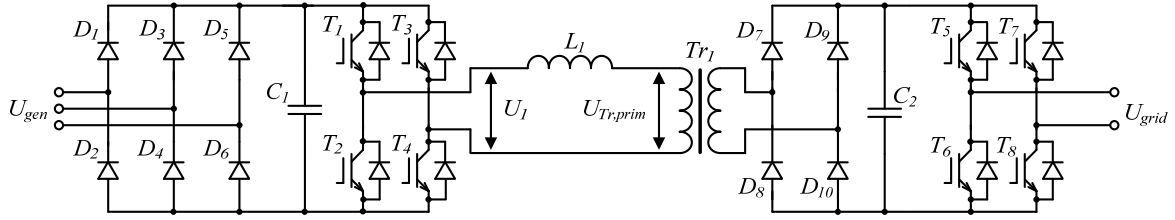


Fig. 1.7. Buck type isolated DC/DC converter

Stabilization of the second DC link voltage is obtained with the buck type isolated DC/DC converter by means of duty cycle variation. The main drawback of buck type converter utilization in wind applications is high currents in the transformer's primary winding and HF inverter switching devices at rated wind speeds. Moreover such topology does not offer possibility to use low voltage transistors: they should withstand the maximal voltage of the first DC link voltage U_{C1} (Fig. 1.8). Fig. 1.8. illustrates the simulation results of buck type interface converter at 1250 W load. One can see that inductor current I_{L1} is enormous for 1.3kW converter and will lead to high power losses in HF inverter switches, inductor and

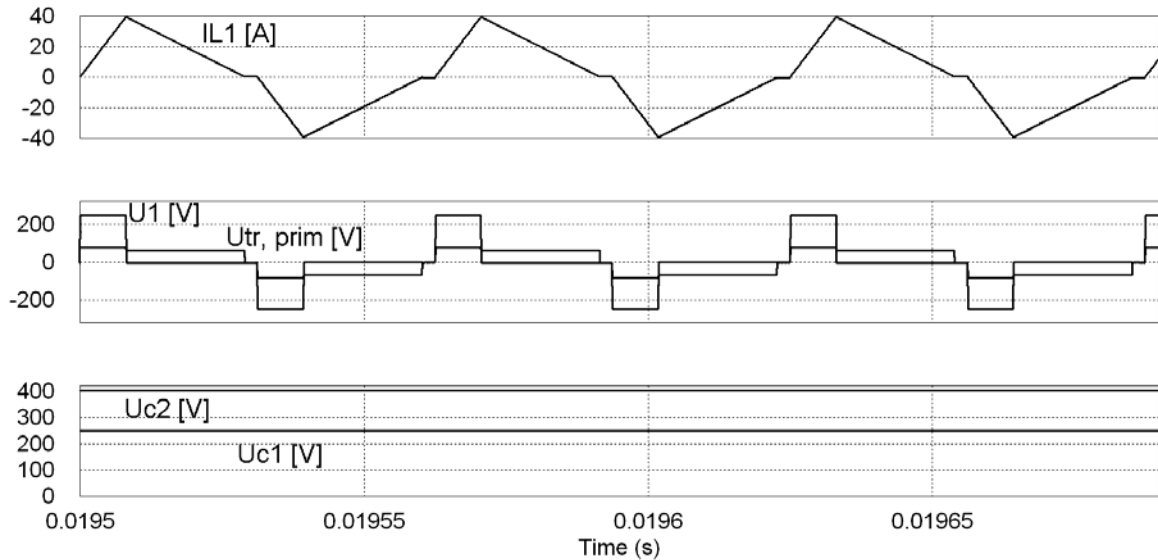


Fig. 1.8. The main current and voltage waveforms of buck type isolated DC/DC interface converter at 1250 W load

transformer primary windings. On the other hand there will be high switching losses at cut-in conditions due to high power transistor utilization in HF inverter. The inductor current I_{L1} , HF inverter output voltage U_1 and transformer primary voltage $U_{Tr,prim}$ and both DC link voltage U_{C1} , U_{C2} waveforms of buck type interface converter at 40 W load are demonstrated in Fig. 1.9. Previously mentioned disadvantages make this topology unattractive for wind applications.

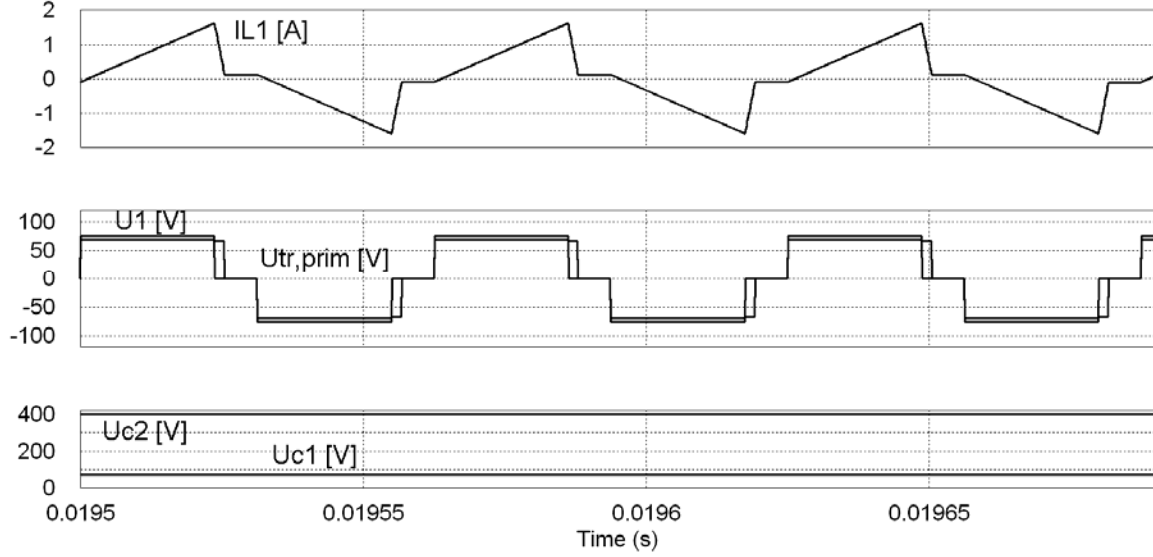


Fig. 1.9. The main current and voltage waveforms of buck type isolated DC/DC interface converter at 40 W load

In [16] the authors have proposed a one-phase soft-switched dual LCL DC/AC converter (Fig. 1.10.).

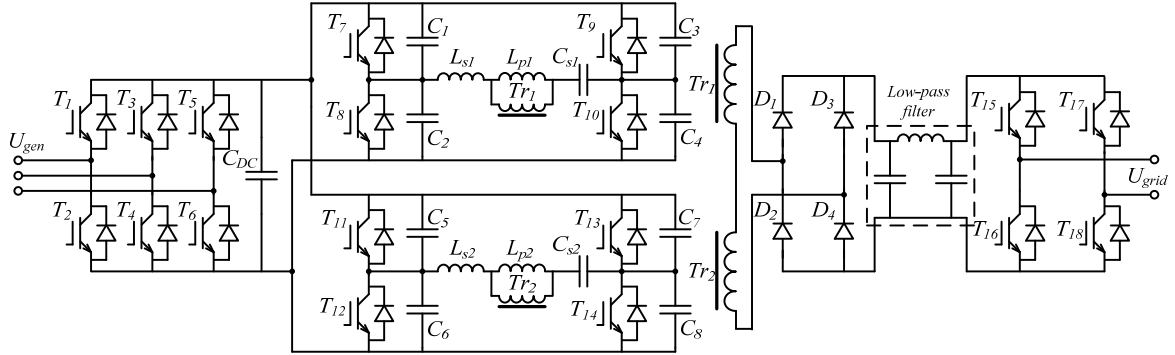


Fig. 1.10. A HF isolated dual-bridge LCL resonant converter

This converter utilizes a controlled rectifier for generator voltage rectification and DC link voltage stabilization. The output voltage of series connected HF transformers is rectified into DC voltage with diode bridge. This rectified voltage (HF transformer output voltage too) contains ripple with grid frequency. The switching frequency of grid side inverter is reduced in

such way. This pulsating voltage is filtered by low pass LCL filter and after is inverted with line connected inverter (LCI) The switches of LCI is commutated when line voltage cross the zero point. High switching frequency of the HF inverter (100 kHz) helps to reduce the low pass LCL filter size, but low switching frequency of LCI eliminates the switching loss in this converter part.

The main disadvantage of dual-bridge LCL resonant converter is big amount of controlled switches (Table 1.3) that needs driver circuits and appropriate control unit. Another disadvantage is reported efficiency of proposed converter prototype: only 90 % at 500 W (nominal load) and 83 % at 250 W load [34]. Reduced efficiency at partial load will significantly reduce the total energy transmitted to the grid that can be the worst case for wind turbine applications.

Analysis of two topologies with HF isolation studied in literature for VSWT applications shows the significant disadvantages in terms of efficiency issues and complexity. Buck type isolated interface converter has relative simple circuit, but high current stress on semiconductor devices in HF inverter and primary winding of transformer can lead to big converter size and high price. Dual bride LCL resonant converter offer soft switching approach at HF isolation and LCI stages, but still has high circuit complexity and low reported efficiency. For these reasons the new HF isolated converter topology for wind applications is proposed. Due to voltage and power characteristics of the PMSG based VSWT an interface converter topology utilizing converters with boost properties seams the most suitable solution for this application.

Table 1.3

Component count in two reviewed topologies

Topology Elements	Buck type converter	Dual bridge LCL resonant converter
Transistors	8	18
Diodes	10	4
Transformers	1	2
Inductors	1	2
Capacitors	2	3

2. NEW ISOLATED CONVERTER TOPOLOGY

To improve the overall performance of the PMSG based VSWT system a new converter topology is proposed in [5], and is presented in Fig. 2.1. It consists of a three-phase full bridge controlled rectifier (generator side inverter) with PFC functionality and a quasi-Z-source (qZS) DC/DC converter with an HF transformer for galvanic isolation and voltage level adjustment. The HF voltage of transformer is rectified by voltage doubler rectifier. The full bridge inverter with LC filter is used for interface converter connection with grid.

The proposed interface converter utilizes the multistage energy conversion. First, the controlled rectifier converts the variable voltage with the variable frequency 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. Utilization 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 stabilized grid side DC link voltage U_{DC2} . Stabilized DC link voltage U_{DC2} can be inverted into the grid current by an appropriate inverter. The modulated output voltage of the inverter is smoothed by output LC filter to obtain purely sinusoidal voltage U_{grid} .

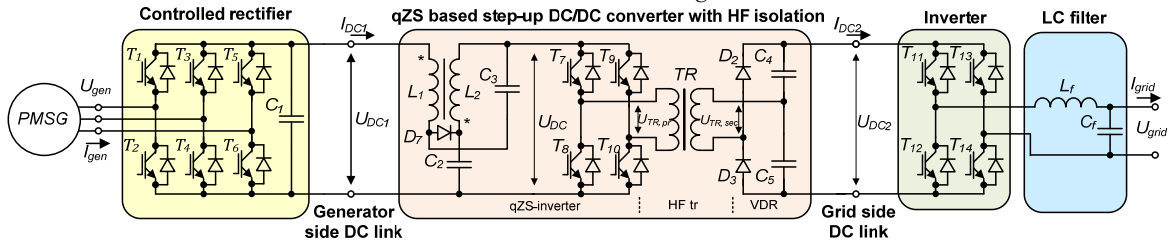


Fig. 2.1. Power circuit of proposed interface converter

Converter operation modes at different wind speeds for the particular application with 1.3 kW PMSG are illustrated in Fig. 2.2. It is seen that the demanded voltage boost could be obtained in two steps. First, the controlled rectifier stabilizes the generator side DC link voltage U_{DC1} to a 150 V level. The generator-side rectifier works as an uncontrolled rectifier when the PMSG voltage U_{gen} is above 112 V. In this mode the voltage U_{DC1} is changing proportionally to the PMSG voltage, from 150 V in the rated speed conditions up to 250 V near the cut-off point. After the rectifier, the qZS based step-up DC/DC converter finally stabilizes the grid side DC link voltage U_{DC2} at 400 V DC despite variations in the generator side DC link voltage U_{DC1} in the range from 150 V to 250 V and also provides the demanded galvanic isolation.

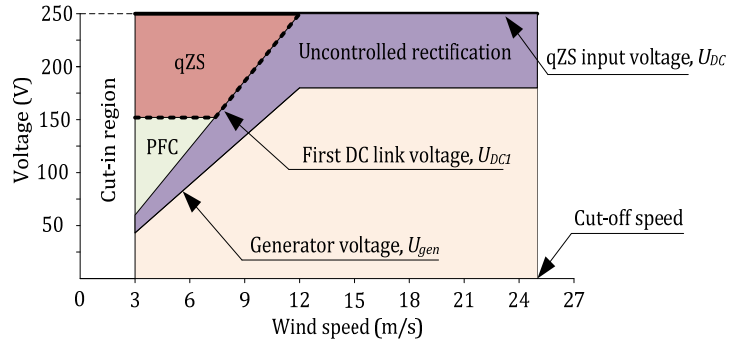


Fig. 2.2. General operation modes of the interface converter

The series of simulations are carried out to validate the proposed operation modes. The theoretical assumptions are experimentally validated by help of the 1.3 kW test setup (Fig. 2.3.) assembled in accordance with schematics presented in Fig. 2.1. The generator side rectifier was powered with 1.3 kW PMSG with 8 pole pairs and loaded with electronic load. The qZS DC/DC converter was tested with fixed input voltages and fixed loads.

A general specifications of experimental setup is collected in Table 2.1.

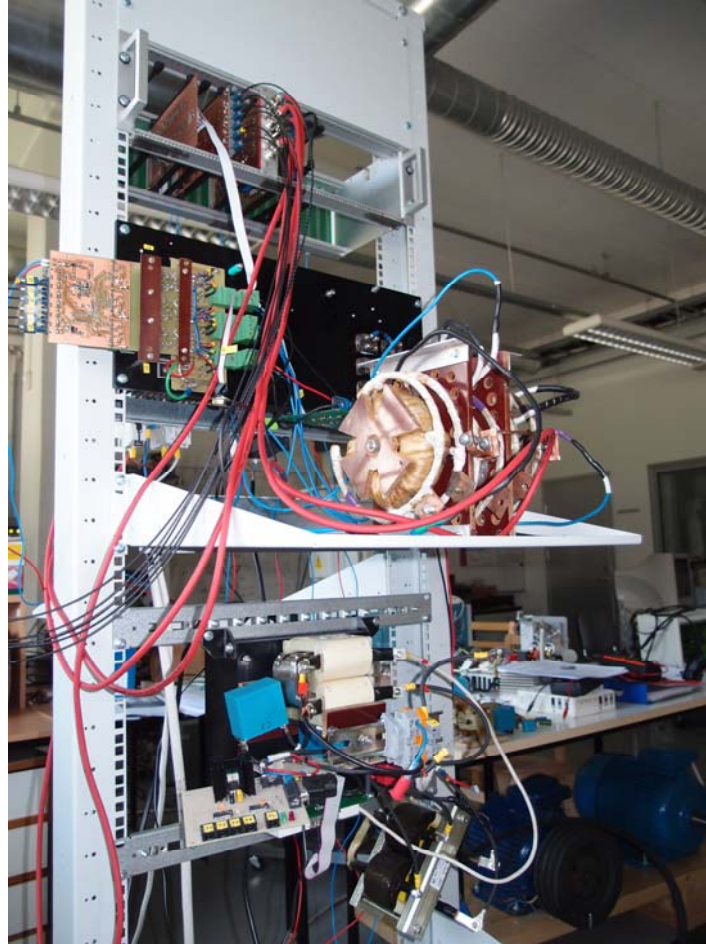


Fig. 2.3. Laboratory test setup of interface converter

General specifications of test setup

Generator side converter

The diagram illustrates a control system for a power converter. It features a reference voltage U_{C_ref} and a DC input U_{DC1} . These inputs are combined at a summing junction. The resulting signal passes through a Low-Pass Filter (LPF) and an integrator block. The output of the integrator is then multiplied by a gain $k2$. This signal is added to the output of a gain $k1$ block, which receives the LPF output. The sum of these signals is then passed through a saturation block (represented by a square with a diagonal line). The output of the saturation block is multiplied by U_{gen} to produce the final output I_{gen} . The system also outputs $T1$ and $T2$ signals.

Fig. 2.4. Control system of generator side inverter (for one phase)

The input values of regulator enter the instantaneous value of generator side DC link voltage U_{DC1} and the reference voltage U_{C_ref} , equal to the necessary voltage level. In order to escape pulsations of voltage across capacitors, only constant component of voltage is used. Further voltage error is feed to the PI regulator, whose output determines the amplitude of reference current. The form of reference current is determined by supply voltage, as a result the current is in-phase to the voltage. Nonlinear element of the type “saturation” is used for limiting the amplitude of current. Further reference current will be given to the controller of the commutation of power switches. The unit of the commutation of power switches is built according to the method of vector control of power switches. In Fig. 2.4b the scheme of controller is represented.

The flowchart of the control algorithm (Fig. 2.5) illustrates the control process of the generator side inverter.

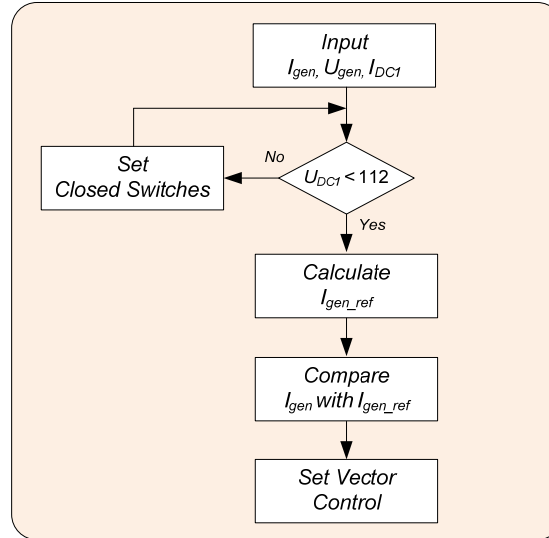


Fig. 2.5. Flowchart of the control algorithm for the generator side inverter

The controlled rectifier operates in the PFC mode and boosts the generator voltage to 150 V level when the line voltage of the generator is below the level of 112 V. The PFC signal generation is stopped and the uncontrolled rectification mode takes place, when the generator line voltage is higher than 112 V.

In order to check the control algorithm simulation has been carried out. The first simulation was performed at the generator voltage $U_{gen} = 53$ V and 40 W load (Fig. 2.6.). At the time moment $t=0.1$ s, the regulator is switched on and the capacitor voltage level is gradually increased up to reference level 150 V. The amplitude of current is simultaneously raised up to the level that corresponds to the consumed power in this case. It is evident that current shape follows generation voltage. THD is about 31%. There are

high frequency ripple that can be reduced by additional serial inductance or increased switching frequency of power switches.

The second simulation was performed at rated generator speed conditions, with the generator speed at 315 rpm and turbine power at 330 W. At this point the amplitude of the generator voltage U_{gen} is 150 V and boost control are not needed (Fig. 2.7). At the time moment $t=0.1$ s, the regulator is switched on. The generator current doesn't follow the voltage shape in this mode that can be considered as a disadvantage. Such situation is caused by relative low voltage difference between DC link and generator voltage. THD is improved from 41% to 31%.

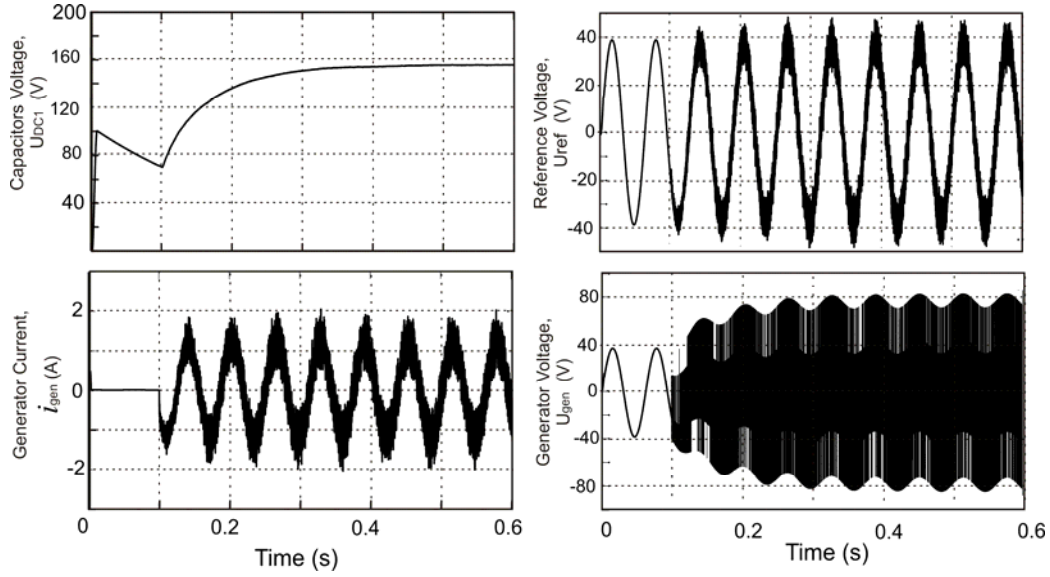


Fig. 2.6. Generator side DC link voltage U_{DCI} , PMSG current i_a , and voltage U_{gen} and filtered generator voltage U_{ref} at 40 W

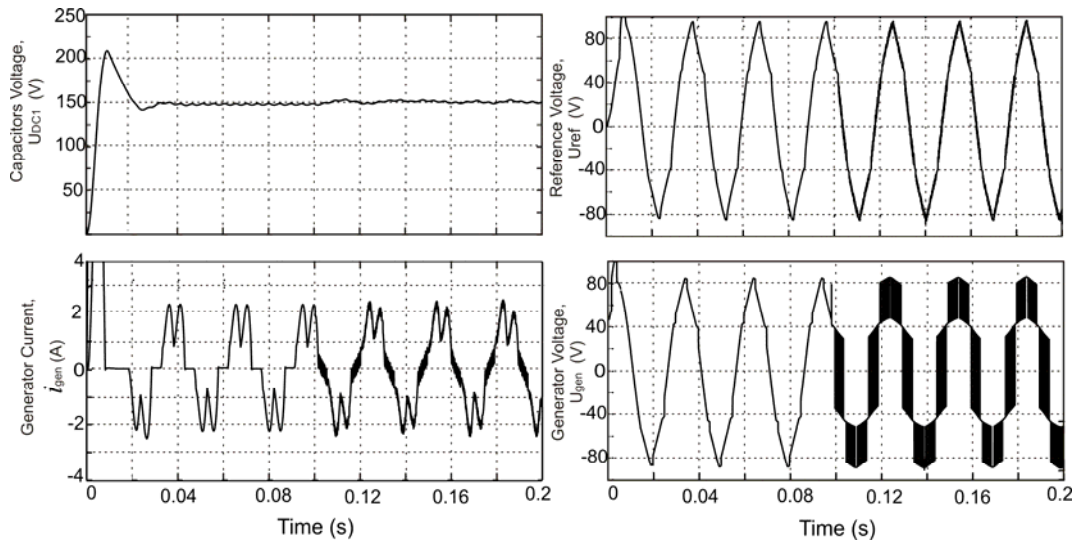


Fig. 2.7. Generator side DC link voltage U_{DCI} , PMSG current i_a , and voltage U_{gen} and filtered generator voltage U_{ref} at 330 W

The third simulation was performed at maximal speed and power of the PMSG: 510 rpm and 1250 W, respectively (Fig. 2.8). Since the nominal speed of the generator is 375 rpm, it was required to verify the generator's ability to produce the power necessary at that speed. The amplitude of the generator's output voltage U_{gen} reaches 250 V. PFC control is not used in this mode and THD of generator current is about 28%.

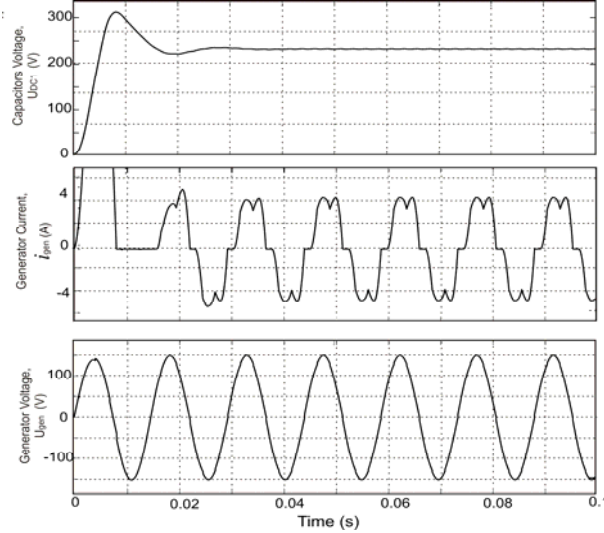


Fig. 2.8. Generator-side DC link voltage U_{DC} , PMSG current i_a and voltage U_{gen} , at 1250 W

A series of experiments were performed to verify the proper operation of the PMSG with the controller. Control was realized by controlling six transistors with a fixed duty cycle at 20 kHz switching frequency. It should be noted, that additional serial inductance was added in order to smooth output voltage of generator. It is necessary for proper measurement of voltage that is used as reference signal in control system. Additionally the inductors ensure lower current ripple.

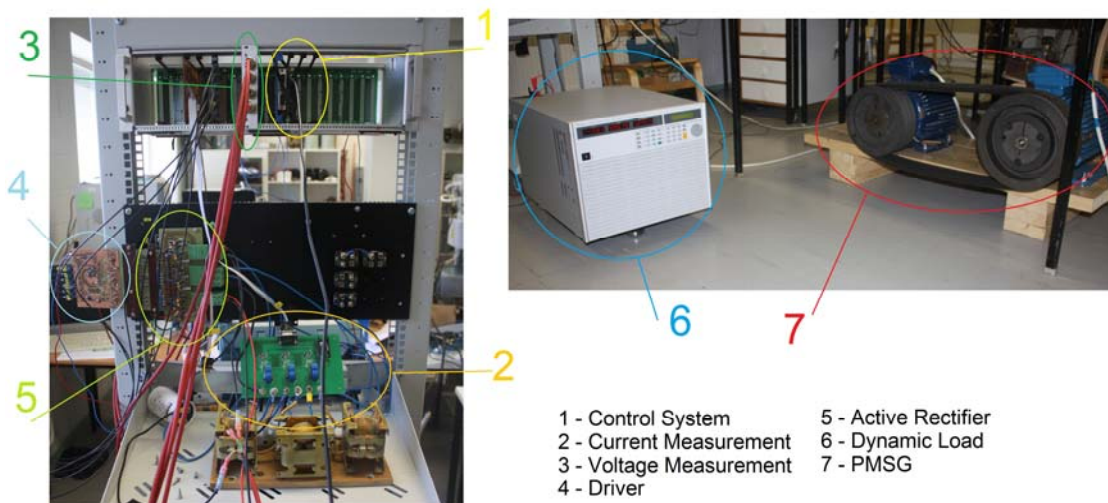


Fig. 2.9. Laboratory test setup for generator side inverter tests

The first experimental test was performed at rated speed conditions, with the generator speed at 315 rpm and turbine power at 330 W. At this point the amplitude of the generator voltage U_{gen} is 150 V and boost control are not needed (Fig. 2.10.). Opposite site of this situation is current shape that doesn't coincident with voltage shape.

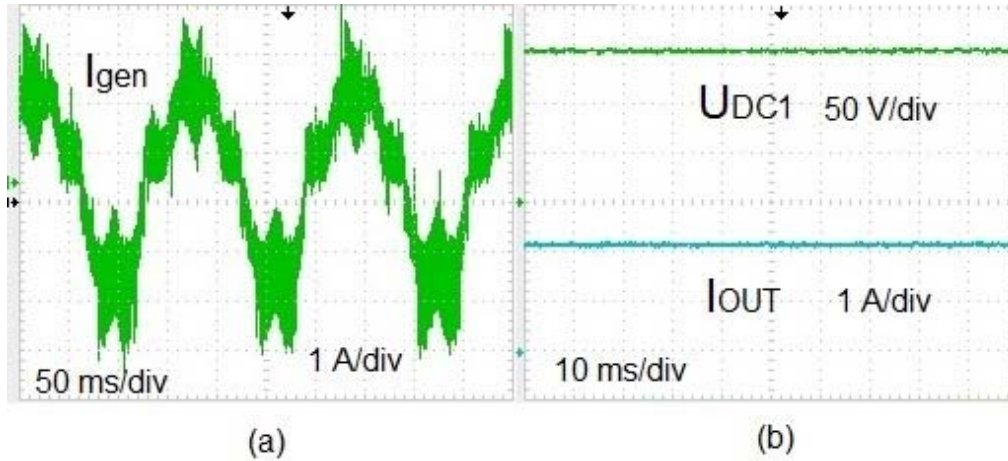


Fig. 2.10. Experimental results: PMSG current (a) and generator side DC link voltage and current (b) at 330 W

The second test was performed at maximal speed and power of the PMSG: 510 rpm and 1250 W, respectively (Fig. 2.11.). Since the nominal speed of the generator is 375 rpm, it was required to verify the generator's ability to produce the power necessary at that speed. The amplitude of the generator's output voltage reaches 250 V. PFC control is not possible in this mode.

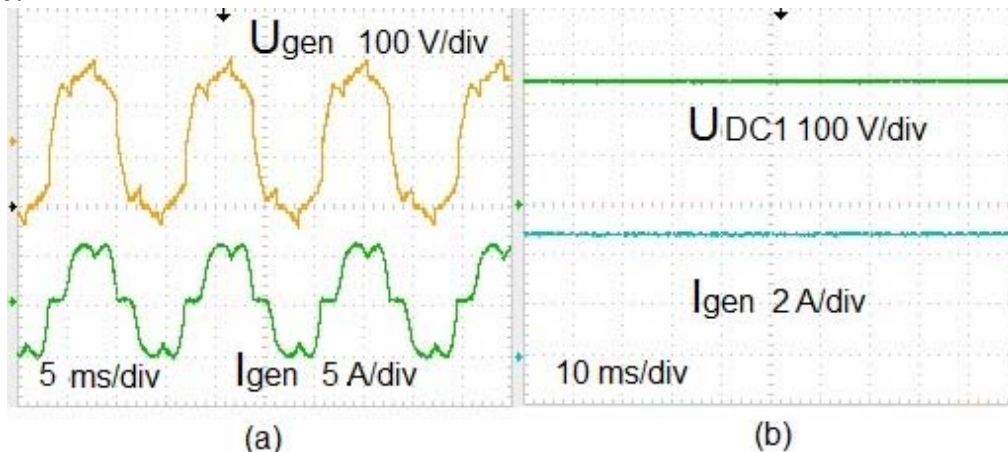


Fig. 2.11. Experimental results: PMSG voltage and current (a) and generator-side DC link voltage and current (b) at 1250 W

From experimental results is concluded that the controlled rectifier operates in close to expected mode. Limitations connected with voltage distortion during transistor switching can be eliminating by improvement of signal filtering.

qZS based DC/DC converter with HF isolation

The qZSI is derived from a traditional Z-source inverter (ZSI) [21] and has two distinctive advantages as compared to ZSI, such as continuous DC current drawn from the source and lower operating voltage of the capacitor C2 [1]. Practically, qZSI is a traditional PWM inverter coupled with a special quasi-Z-source network (qZS-network). As seen from Fig. 2.12., the qZS-network consists of two capacitors C1 and C2, two inductors L1 and L2 and a diode D1.

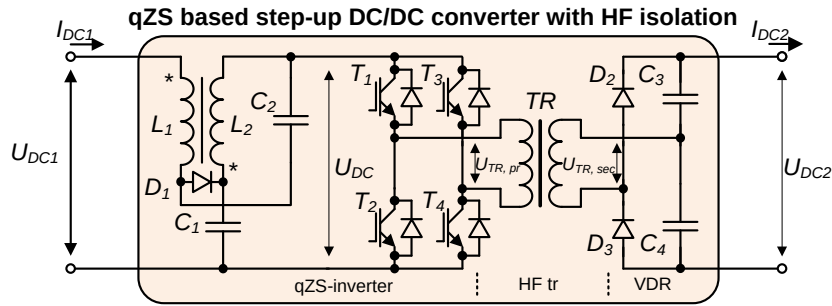


Fig. 2.12. qZS based step-up DC/DC converter with HF isolation

The high-frequency step-up isolation transformer provides the required galvanic isolation of the input and output sides of the converter. Transformer's primary winding is connected to the output terminals of qZSI, while the secondary side is connected to the voltage doubler rectifier (VDR).

The main function of the HF isolation converter is to stabilize the grid side inverter voltage U_{DC2} despite the variations of the first DC link voltage U_{DC1} . By keeping the DC-link voltage constant the PWM inverter could be operated with a fixed duty cycle value, thus ensuring constant volt-second and flux swing of the isolation transformer.

In accordance with the input voltage (generator side DC link voltage) the operating modes of the proposed DC/DC converter could be broadly categorized as *non-shoot-through* and *shoot-through* operating modes (Fig. 2.13).

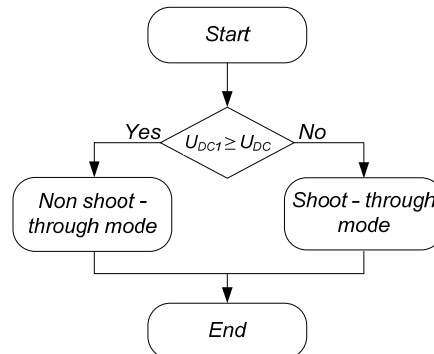


Fig. 2.13. Flow chart of operating modes of qZSI based DC/DC converter

If the voltage is equal or higher than the desired DC-link voltage, the converter starts to operate in the non-shoot-through mode. In this mode the qZSI operates as a traditional VSI. The operating period of the qZSI in the non-shoot-through mode consists of the combination of active and zero states. During active (energy transfer) states the power switches of the inverter bridge are gated alternately in pairs (T1, T4 and T2, T3) and power is transferred from the DC-link to the isolation transformer (Fig. 2.14.). During zero states the primary winding of the isolation transformer is shorted either through the upper switches (T1, T3) or the bottom switches (T2, T4) of the inverter bridge (Fig. 2.15) and the transformer sees no voltage from the inverter.

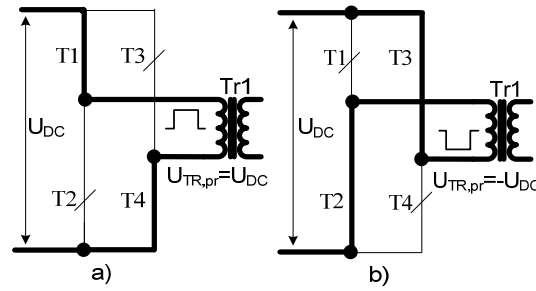


Fig. 2.14. Equivalent circuit during active states: positive (a) and negative (b) half-cycles

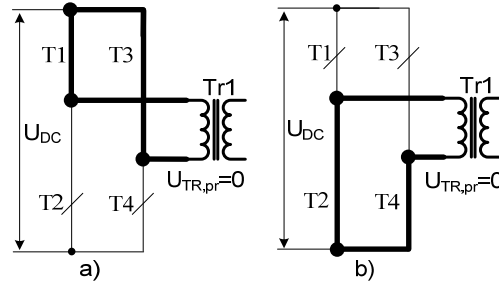


Fig. 2.15. Equivalent circuit during zero-states created by upper (a) and lower (b) switches

The operating period of the PWM inverter during the non-shoot-through mode consists of an active state t_A and a zero state t_Z :

$$T = t_A + t_Z . \quad (3)$$

If the generator side DC link voltage drops below the predefined DC link voltage level U_{DC} the converter begins to operate in the shoot-through mode. The varying voltage of the generator side DC link is preregulated to a desired DC-link voltage level by adjusting the shoot-through duty cycle. Afterwards the isolation transformer is being supplied from the inverter with a voltage of constant amplitude, as described in the previous section.

To boost the input voltage during the shoot-through operating mode the special switching state – shoot-through state - is implemented in the HF inverter control. During the shoot-through states the primary winding of the isolation transformer and the output of qZS network is shorted through both the upper and lower switches of any one phase leg (i.e., both devices are gated on) or both phase legs (Fig. 2.16). This shoot-through state (or vector) is forbidden in the traditional VSIs, because it would cause a short circuit of DC capacitors and destruction of power switches. The unique two-port network – the qZS-network (see Fig. 2.12) – 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_1 and C_2 . This increase in the inductive energy in turn provides the boost of voltage seen on the inverter output during the active states of the inverter.

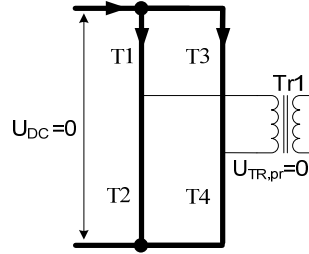


Fig. 2.16. Inverter equivalent scheme during the shoot-through state

The operating period of the PWM inverter during the shoot-through mode consists of an active state t_A , a zero state t_Z and a shoot-through state t_S :

$$T = t_A + t_Z + t_S . \quad (4)$$

To reduce the turns ratio of the isolation transformer the voltage doubler rectifier (VDR) was implemented on the secondary side of the converter.

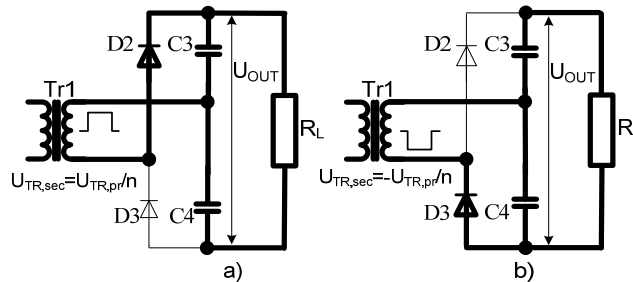


Fig. 2.17. Operation principle of VDR

At every time instant the output voltage (U_{DC2}) from this circuit will be the sum of the two capacitor voltages or twice the peak voltage ($U_{TR,sec}$) of the secondary winding of the isolation transformer:

$$U_{DC2} = 2 \cdot U_{TR,sec} \cdot \quad (5)$$

Operating principle of the qZSI during the shoot-through mode

In the shoot-through operation mode there are two general power conversion states: shoot-through (voltage boost in primary side) and active (power transfer to secondary side) state. The equivalent schemes of the qZSI during the shoot-through and active state are presented in Fig. 2.18.[30]. All the polarities, voltages and currents are defined with arrows and polarity signs.

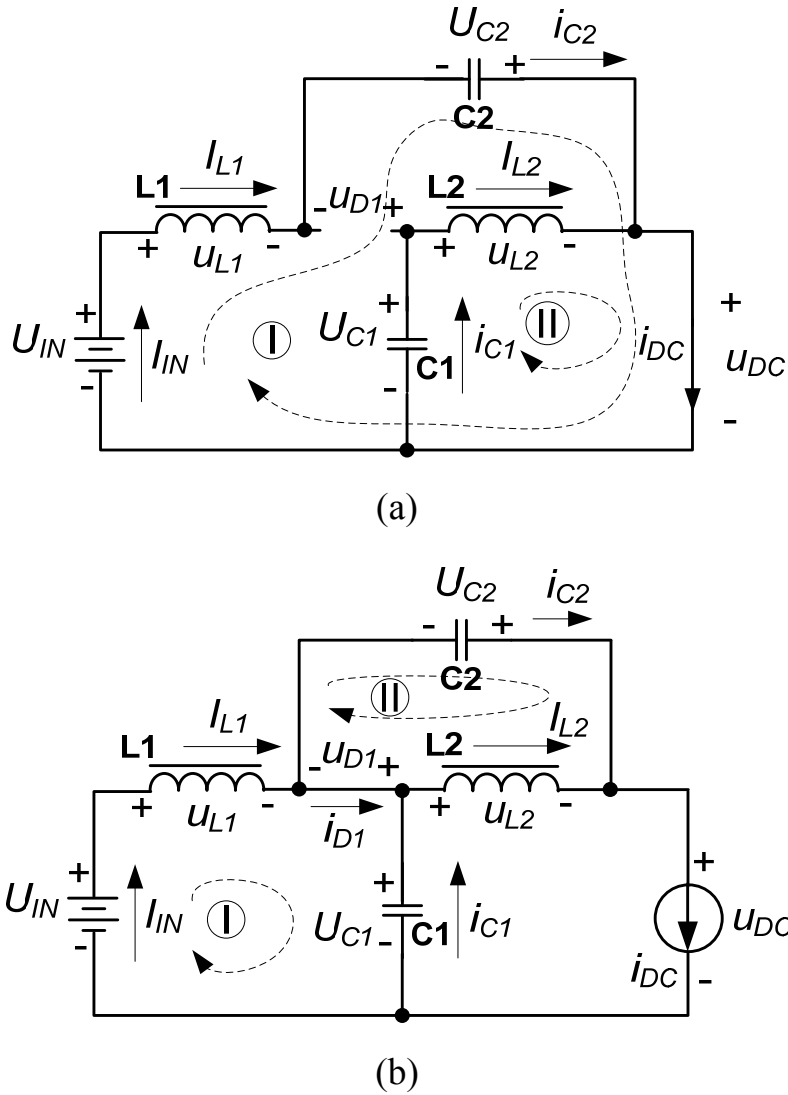


Fig. 2.18. Equivalent circuits of the qZSI during the shoot-through (a) and active (b) states

From Fig. 2.18.a, which represents the shoot-through state of the qZSI with duration t_s , one can obtain

$$u_{L1} = U_{C2} + U_{IN}, \quad U_{L2} = U_{C1}, \quad (6)$$

$$u_{DC} = 0, \quad u_{D1} = U_{C1} + U_{C2}. \quad (7)$$

From Fig. 2.18.b, which represents the active state of the qZSI with the duration of $(T-t_s)$, we can obtain

$$u_{L1} = U_{IN} - U_{C1}, \quad u_{L2} = -U_{C2}, \quad (8)$$

$$u_{DC} = U_{C1} - u_{L2} = U_{C1} + U_{C2}, \quad u_{D1} = 0. \quad (9)$$

At the steady state the average voltage of the inductor over one switching period is zero. Thus, from equations (6) and (8) we can obtain

$$\begin{cases} U_{L1} = u_{L1} = \frac{t_s \cdot (U_{C2} + U_{IN}) + (T - t_s) \cdot (U_{IN} - U_{C1})}{T} = 0 \\ U_{L2} = u_{L2} = \frac{t_s \cdot (U_{C1}) + (T - t_s) \cdot (-U_{C2})}{T} = 0 \end{cases}. \quad (10)$$

Accordingly,

$$U_{C1} = \frac{1 - \frac{t_s}{T}}{1 - 2 \cdot \frac{t_s}{T}} \cdot U_{IN} \quad \text{and} \quad U_{C2} = \frac{\frac{t_s}{T}}{1 - 2 \cdot \frac{t_s}{T}} \cdot U_{IN}. \quad (11)$$

The peak DC-link voltage across the inverter bridge is

$$\hat{u}_{DC} = U_{C1} + U_{C2} = \frac{1}{1 - 2 \cdot \frac{t_s}{T}} \cdot U_{IN} = B \cdot U_{IN}, \quad (12)$$

where B - the boost factor of the qZSI:

$$B = \frac{1}{1 - 2 \cdot \frac{t_s}{T}}. \quad (13)$$

The operating voltages and average currents of the qZSI during active and shoot-through states are shown in Table 2.2.

For the better appearance the shoot-through time interval t_s was replaced with the shoot-through duty cycle $D_s = t_s / T$.

Table 2.2

Operating voltages and average currents of the qZSI

State	Active	Shoot-through
Inductor voltage ($u_{L1}=u_{L2}$)	$-\frac{D_S}{1-2 \cdot D_S} \cdot U_{IN}$	$\frac{1-D_S}{1-2 \cdot D_S} \cdot U_{IN}$
DC-link voltage (u_{DC})	$\frac{1}{1-2 \cdot D_S} \cdot U_{IN}$	0
DC-link current ($I_{DC,av}$)	$\frac{P \cdot (1-2 \cdot D_S)}{U_{IN}}$	$\frac{2 \cdot P}{U_{IN}} \cdot D_S$
Diode D1 voltage (u_{D1})	0	$\frac{1}{1-2 \cdot D_S} \cdot U_{IN}$
Capacitor C1 voltage (U_{C1})	$\frac{1-D_S}{1-2 \cdot D_S} \cdot U_{IN}$	
Capacitor C2 voltage (U_{C2})	$\frac{D_S}{1-2 \cdot D_S} \cdot U_{IN}$	
Input current ($I_{IN,av}$)	$\frac{P}{U_{IN}}$	
Inductor current ($I_{L1,av}=I_{L2,av}$)	$\frac{P}{U_{IN}}$	
Capacitor current ($I_{C1,av}=I_{C2,av}$)	$I_{DC,av} - I_{L1,av}$	
Diode current ($I_{D1,av}$)	$2 \cdot I_{L1,av} - I_{DC,av}$	

Discontinuous conduction mode of qZS inverter

As it is seen from Fig. 2.1., the proposed qZS-inverter has the input inductor L_I that buffers the source current. It means that in the continuous conduction mode (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 [8].

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

$$\frac{t_A}{T} + \frac{t_S}{T} + \frac{t_D}{T} = D_A + D_S + D_D = 1, \quad (14)$$

where D_A - duty cycles of active;
 D_S - shoot-through state;
 D_D - discontinuous conduction state.

The equivalent circuit of the discontinuous conduction state is similar to the active states (Fig. 2.18.b), the only difference is that the diode D_I stops conducting at that time interval. The equivalent circuits of the qZS-inverter in the shoot-through and active states remain the same as in Fig. 2.18.

When the converter is in a discontinuous conduction state t_D , the voltages of the inductors $L1$ and $L2$ are equal to zero. For the DCM, Eq. (10) could be extended as follows:

$$\begin{cases} U_{L1} = \bar{u}_{L1} = D_S \cdot (U_{C3} + U_{DC1}) + D_A \cdot (U_{DC1} - U_{C2}) + D_D \cdot 0 = 0 \\ U_{L2} = \bar{u}_{L2} = D_S \cdot (U_{C2}) + D_A \cdot (-U_{C3}) + D_D \cdot 0 = 0 \end{cases}, \quad (15)$$

where D_A - duty cycles of active;
 D_S - shoot-through state;
 D_D - discontinuous conduction state.

In contrast to the CCM the operating voltage of the capacitor C_2 during the DCM will increase:

$$U_{C2} = \frac{1 - D_S - D_D}{1 - 2 \cdot D_S - D_D} \cdot U_{DC1}. \quad (16)$$

That, in turn, will lead to an increased peak value of the DC link voltage during the DCM, causing the “overboost effect” of the input voltage:

$$\hat{U}_{DC(DCM)} = U_{C2} + U_{C3} = \frac{1 - D_D}{1 - 2 \cdot D_S - D_D} \cdot U_{DC1}. \quad (17)$$

Simulation and experimental results.

In the first test the generator-side DC link voltage was set to 150 V that corresponds to the cut-in and rated 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. Since the voltage boost of the qZS based DC/DC converter is higher at

the DCM than at the CCM, the shoot-through duty cycle D_s was set at 0.12 for this mode. Peak DC link voltage U_{DC} is 270 V (Fig. 2.19.) that corresponds to theoretical assumptions stated in [8]. The DCM for low power operation was chosen to reduce the size of the inductors. Transformer voltages (Fig. 2.20) repeat the shape of the intermediate DC link voltage. 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 second test was performed at the same generator-side DC link voltage ($U_{DCI} = 150$ V), but power was raised to 330 W that corresponds to turbine power at the rated wind speed. To boost the input voltage to the desired voltage level of the intermediate DC-link (250 V) the shoot-through duty cycle D_s was set to 0.2. Fig. 2.21. shows that the qZSI operates in the CCM, thus ensuring the demanded gain of the input voltage ($U_{DC} = 250$ V, as expected). Moreover, the voltage doubler rectifier provides the demanded voltage doubling effect of the peak voltage of the secondary winding of the isolation transformer, thus ensuring the voltage of 405 V DC at the grid side DC-link (Fig. 2.21). Transformer voltages (Fig. 2.22) have not any disturbances that verify correct component selection.

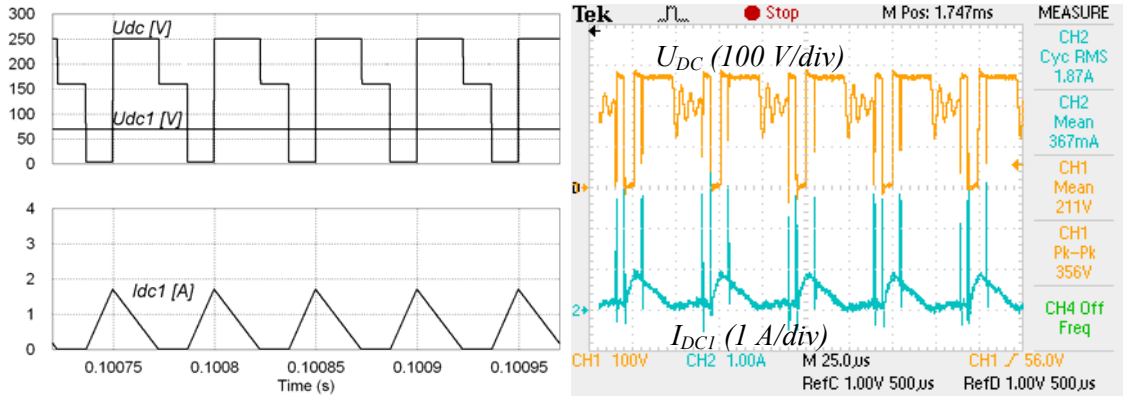


Fig. 2.19. DC link voltage and input current at cut-in conditions

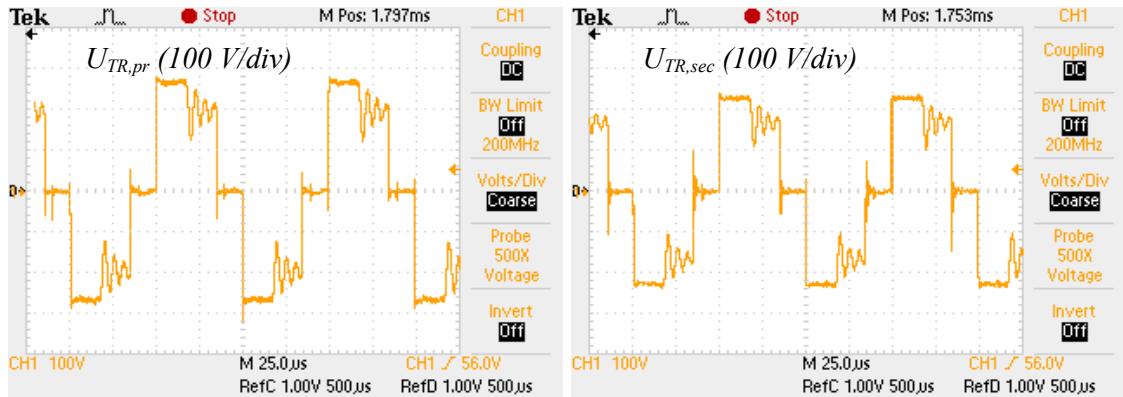


Fig. 2.20. Voltages of transformers primary and secondary windings

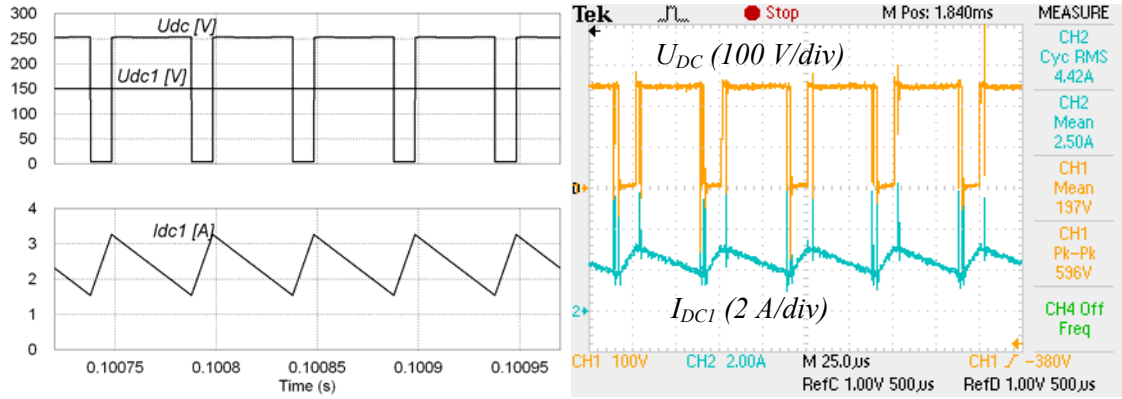


Fig. 2.21. DC link voltage and current at rated speed conditions (330 W)

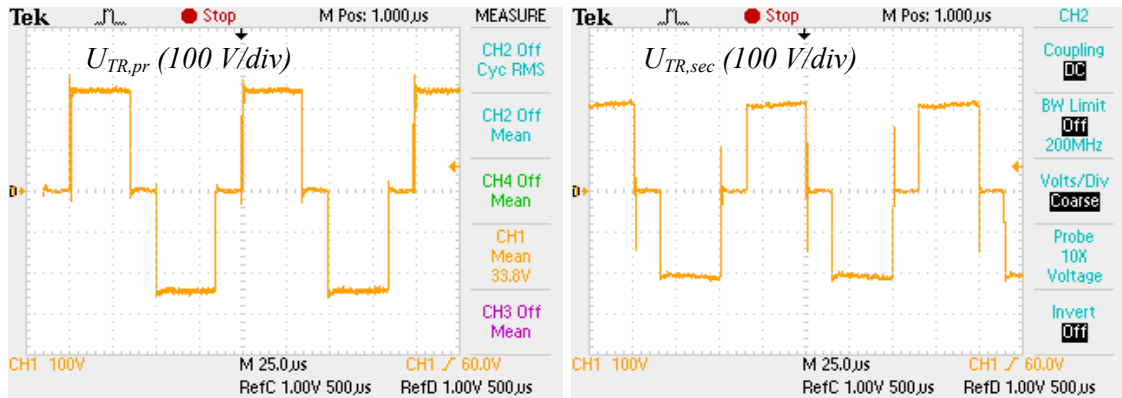


Fig. 2.22. Voltages of transformers primary and secondary windings

The third test was performed at the maximum generator-side DC link voltage ($U_{DCI} = 250$ V), which corresponds to the maximal power of the turbine (1250 W). At this operating point, when the input voltage equals the desired intermediate DC-link voltage ($U_{DCI} = U_{DC} = 250$ V), the shoot-through states were eliminated ($D_S = 0$) and the converter operated as a traditional VSI (Fig. 2.23.). In that case the isolation transformer is supplied with voltage pulses with the amplitude value equal to the generator-side DC link voltage. The voltage waveforms of the isolation transformer in this operation point are similar to those presented in Fig. 2.24.

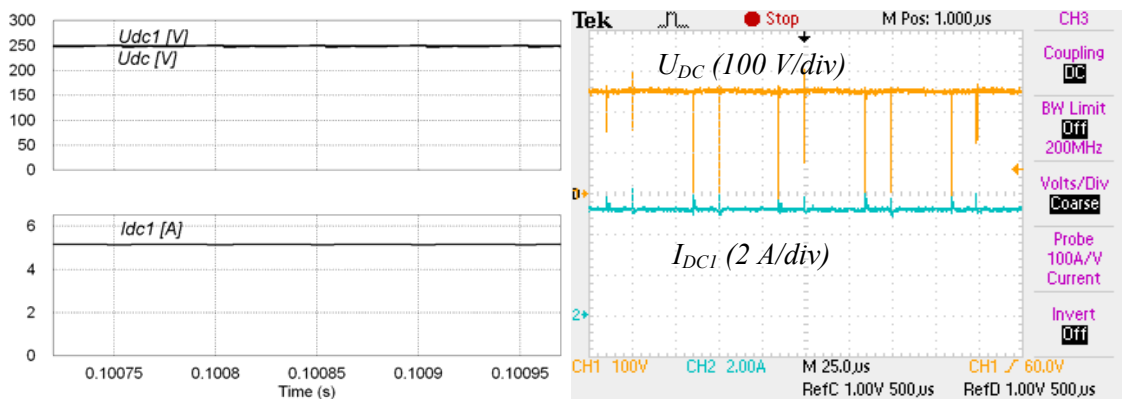


Fig. 2.23. DC link voltage and input current at rated wind speed (1250 W)

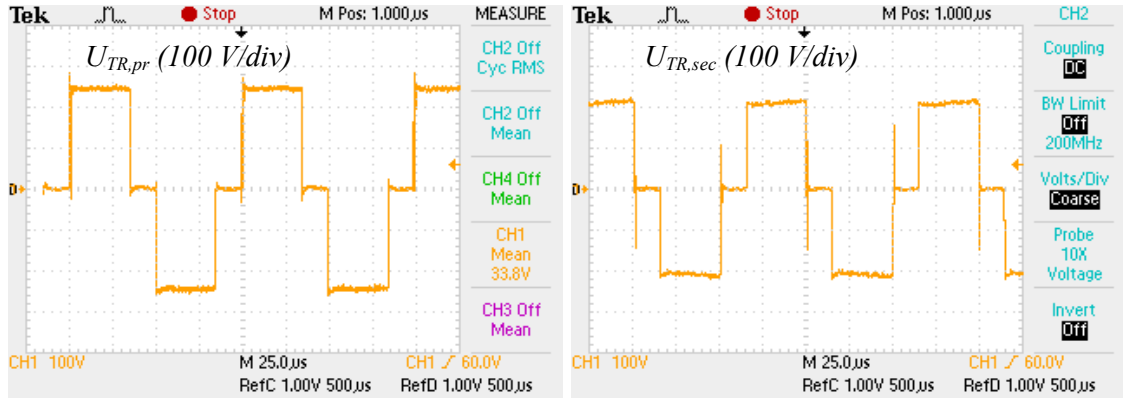


Fig. 2.24. Voltages of transformers primary and secondary windings

Interface converter for micro turbines

To reduce the overall cost of the system and taking into account “overboost” effect of qZS DC/DC converter was offered simplified interface converter (Fig. 2.25.). Elimination of controlled rectifier allows utilization of simpler control circuit.

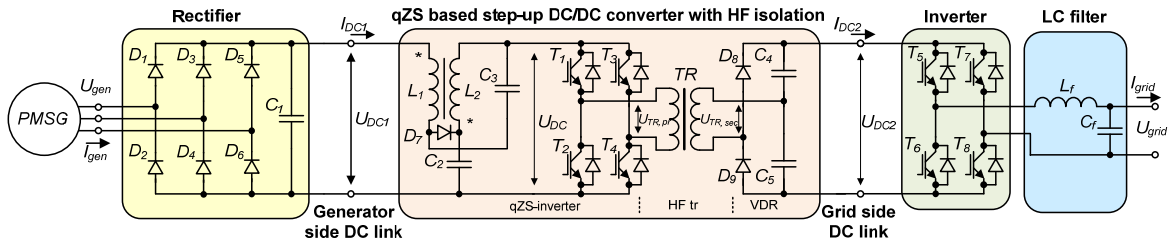


Fig. 2.25. Power circuit for wind turbine systems of micro power level

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. 2.26.

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.

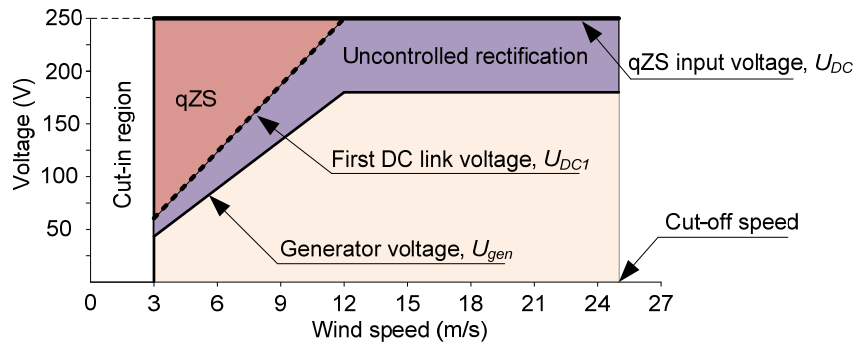


Fig. 2.26. Operation modes of simplified interface converter

The PWM shoot-through control technique [30] was implemented during the tests. The qZS network was operating at 20 kHz frequency, but isolation transformer at 10 kHz.

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. 2.27.) that corresponds to theoretical assumptions stated in. The DCM for low power operation was chosen to reduce the size of the inductors.

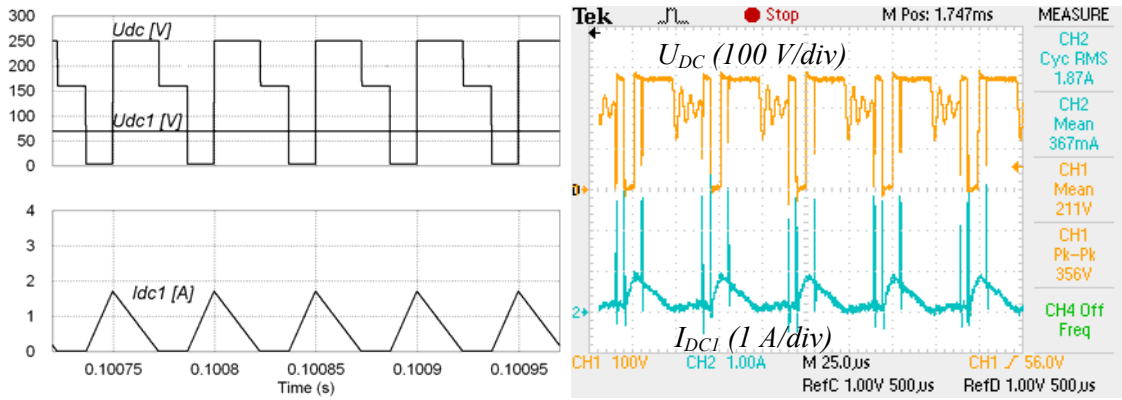


Fig. 2.27. Simulation and experimental results of simplified interface converter

3. QZS DC/DC Converter with improved boost properties

Improved quasi-Z-source based back-to-back interface converter is introduced by the utilization of the switched inductor quasi-Z-source network (Fig. 3.1.). The new topology offers the increased voltage boost capability of the grid-side inverter.

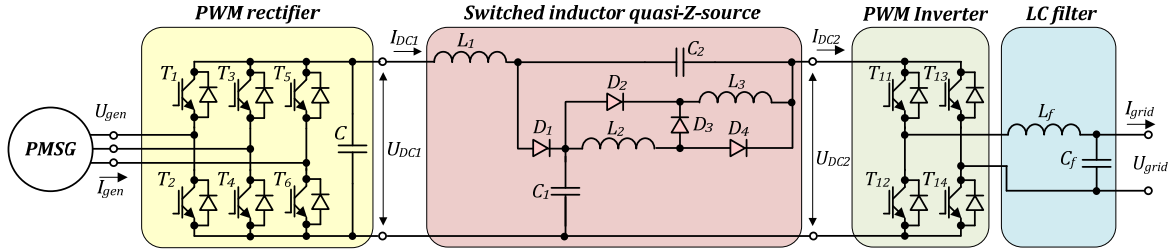


Fig. 3.1. New proposed switched inductor quasi-Z-source based back-to-back converter for VSWTs with PMSG

The proposed SL qZS network consists of three inductors ($L_1 \dots L_3$), four diodes ($D_1 \dots D_4$) and two capacitors (C_1 and C_2). Inductors L_2 and L_3 can be implemented as coupled inductors. Coupled with the grid side PWM inverter, the SL qZS network forms the SL quasi-Z-source inverter (SL qZSI). Similarly to the traditional qZSI [75], the SL qZSI has two main types of operational states at the DC side: non-shoot-through states and shoot-through states. Fig. 3.2. shows the equivalent circuits of the SL qZSI operating in the CCM for the shoot-through (a) and active (b) states.

At the steady state the average voltage of the inductors over one operating period is zero:

$$U_{L1} = \int_t^{t+T} u_{L1} dt = 0; \quad U_{L2} = \int_t^{t+T} u_{L2} dt = 0; \quad U_{L3} = \int_t^{t+T} u_{L3} dt = 0. \quad (18)$$

Based on that fact and defining the shoot-through duty cycle as D_S and the non-shoot-through duty cycle as $(1-D_S)$, the inductors voltages over one operating period could be represented as

$$\begin{cases} U_{L1} = \bar{u}_{L1} = D_S(U_{DC1} + U_{C2}) + (1-D_S)(U_{DC1} - U_{C1}) = 0 \\ U_{L2} = U_{L3} = \bar{u}_{L2} = \bar{u}_{L3} = D_S U_{C1} + (1-D_S)\left(-\frac{U_{C2}}{2}\right) = 0 \end{cases} \quad (19)$$

The peak inverter input voltage U_{DC2} are derived from the steady state analysis.

$$\hat{U}_{DC2} = \frac{U_{DC1} \cdot (1 + D_S)}{(1 - 2 \cdot D_S - D_S^2)} = B \cdot U_{DC1}. \quad (20)$$

The voltage conversion ratio G of the whole inverter can be expressed by

$$G = \frac{U_{gridm}}{U_{DC1}} = M \cdot B, \quad (21)$$

where M - is the modulation index.

The modulation index is connected with the shoot-through duty cycle by the following relation [1]:

$$M \leq 1 - D_S. \quad (22)$$

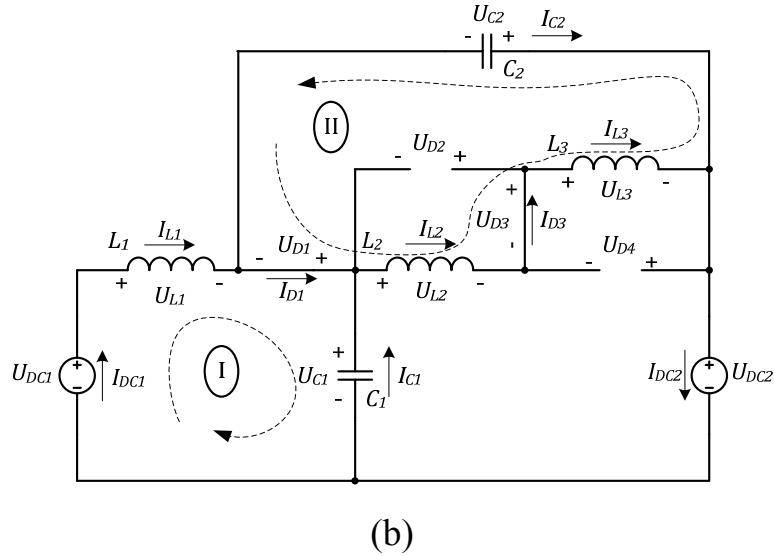
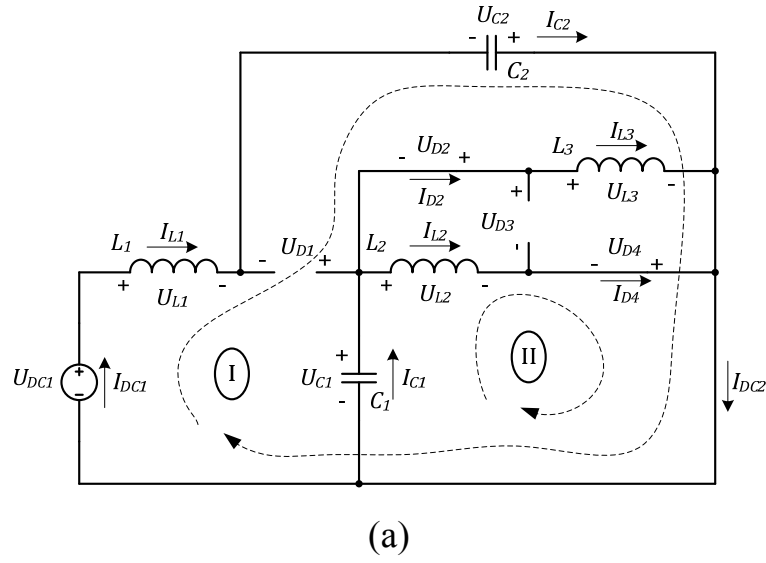
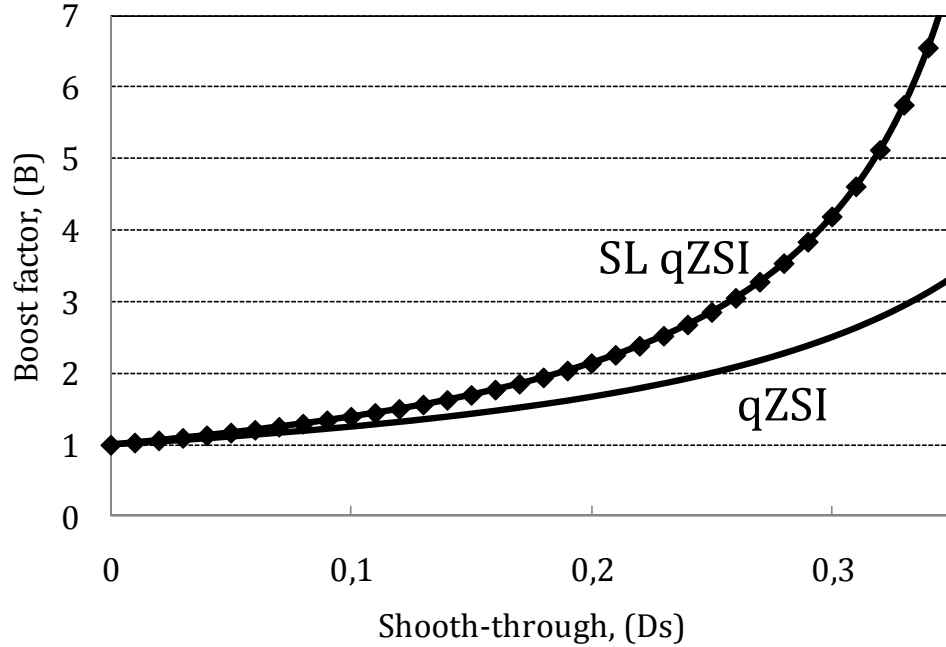


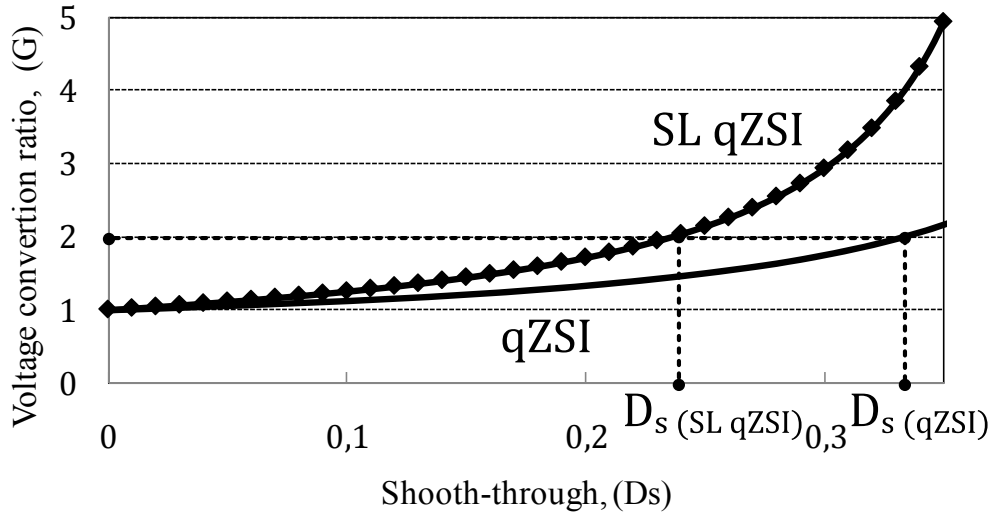
Fig. 3.2. Equivalent circuits of the SL qZSI: during shoot-through state (a) and during active (non-shoot-through) state (b)

In Fig. 3.3. the voltage boost factor B and the voltage conversion ratio G of the traditional qZSI are compared with those of the proposed SL

qZSI. It is seen that the shoot-through duty cycle D_s for the SL qZSI is lower than for traditional qZSI at the same voltage conversion ratio G (Fig. 3.3.b). This is significant feature of the SL qZSI that allows expand the grid voltage regulation possibilities at reduced grid side DC link peak voltage U_{DC2p} .



(a)



(b)

Fig. 3.3. Boost factor B (a) and voltage conversion ratio G (b) as functions of the shoot-through duty cycle for qZSI and SL qZSI

Operation modes of the interface converter

Based on the specifications of the PMSG the operation modes of the proposed back-to-back interface converter are presented in Fig. 8. The necessary voltage boost is obtained in two steps. The PWM rectifier stabilizes the DC link voltage U_{DC1} to a 150 V level when the generator voltage is below 112 V. This operation mode of the converter is called a PWM mode. The transferred power of the converter lies between 40 W and 330 W at this mode.

The controlled rectifier works as diode rectifier when the generator voltage U_{gen} is above 112 V. In this mode the DC link voltage is changed proportionally to the generator voltage, at the range from 150 V in rated generator speed conditions up to 250 V at the maximal speed.

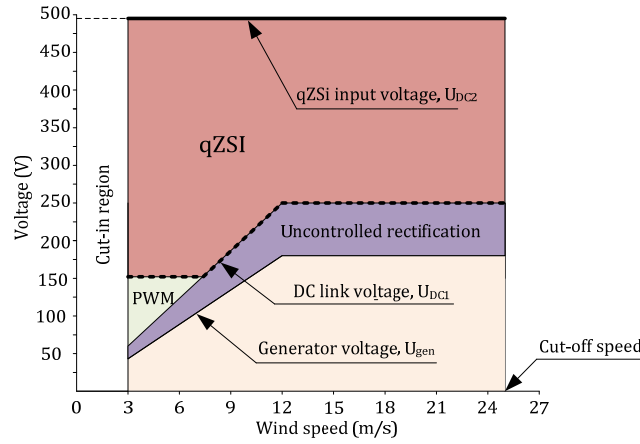


Fig. 3.4. Operation modes of the proposed converter

The SL qZS network with appropriate inverter control is stabilizing the peak value of the inverter side DC link voltage U_{DC2} to 490 V despite the voltage variations on the generator side DC link. The inverter input voltage U_{DC2} regulation is obtained by changing the shoot-through duty cycle D_s [5]. The peak value of the inverter side DC link voltage U_{DC2} is so high due to lower modulation index M if compared with voltage source inverters. Modulation index is limited by shoot-through states implemented in SL qZSI.

The variation range of the voltage conversion ratio G lies between 1.44 and 2.4 that corresponds to the generator side DC link voltage U_{DC1} range from 250 V up to 150 V. Since the modulation index M and the boost factor B are the functions of D_s , the appropriate values of shoot-through can be found for minimum and maximum G values. The variation range of the shoot-through duty cycle D_s is from 0.17 in maximum speed conditions to 0.27 in the cut-in speed conditions.

Analysis of simulation and experimental results

A series of simulations and experiments were performed to verify the proper operation of the proposed SL qZSI based back-to-back 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 [5]. These points are: cut-in speed (low voltage and minimum power), rated speed (corresponds to 7.5 m/s wind speed) and maximum generator speed, power conditions. The operating frequency of the SL qZSI network was 20 kHz and maximal switching frequency of transistors – 40 kHz.

First simulations and tests were performed at the generator side DC link voltage of 150 V. The power rating was 330 W. To boost this voltage to the desired level of the intermediate DC link ($U_{DC2} = 490 \text{ V}_{\text{peak}}$) the shoot-through duty cycle D_s was set to 0.27. Fig. 3.5.. shows that the SL qZSI operates in CCM and ensures the demanded gain of the input voltage ($U_{DC2} = 490 \text{ V}_{\text{peak}}$, as expected).

The simulated and experimental waveforms of the grid voltage and current U_{grid} and I_{grid} of the proposed interface converter at this operation point are presented in Fig.3.6. It is seen that the grid side PWM inverter operates correctly thus ensuring the 230 VAC_{rms} 50 Hz grid voltage.

The second group of simulations and experiments was performed at the generator side DC link voltage of 250 V. The power rating was 1250 W. The shoot-through duty cycle of the SL qZSI was set to 0.17 to ensure necessary voltage boost at this operation point. Both DC link voltages and input current are shown in Fig.3.7. while the grid voltage and current in Fig.3.8. Experimental results clearly demonstrate the converter's ability to ensure the required grid voltage level at all operation modes of the interface converter.

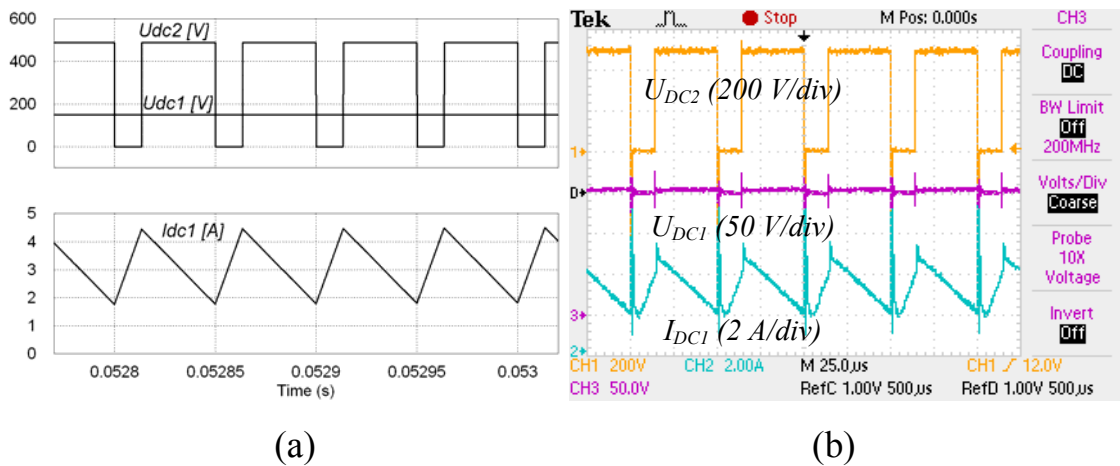
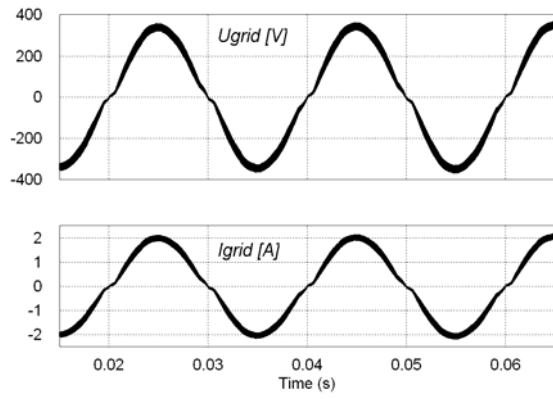
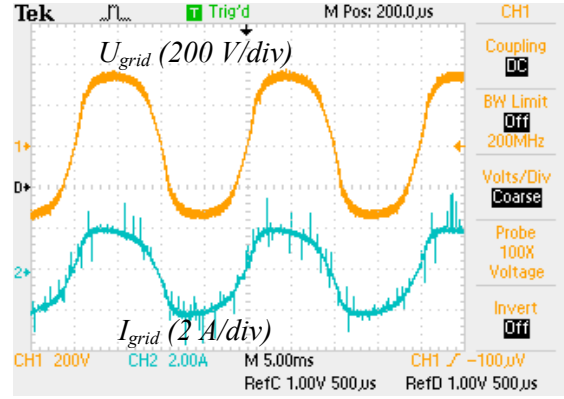


Fig. 3.5. Simulated (a) and experimental (b) waveforms of operating voltages and input current of the SL qZSI at 330 W

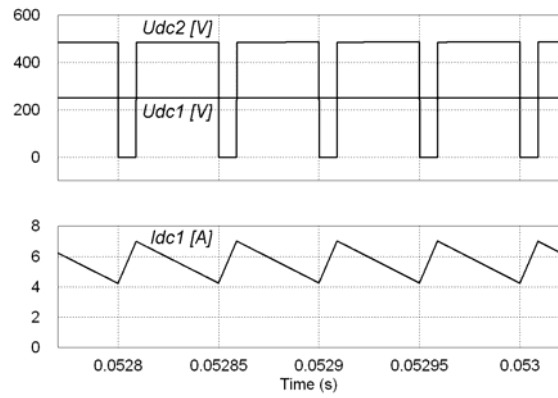


(a)

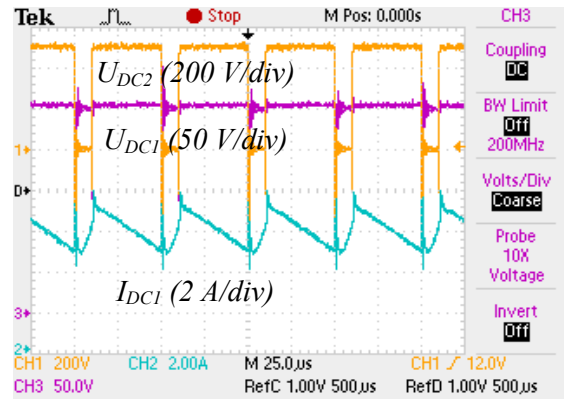


(b)

Fig. 3.6. Simulated (a) and experimental (b) waveforms of the grid voltage and current at 330 W

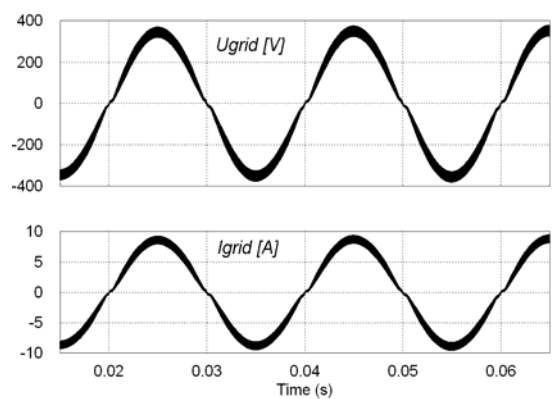


(a)

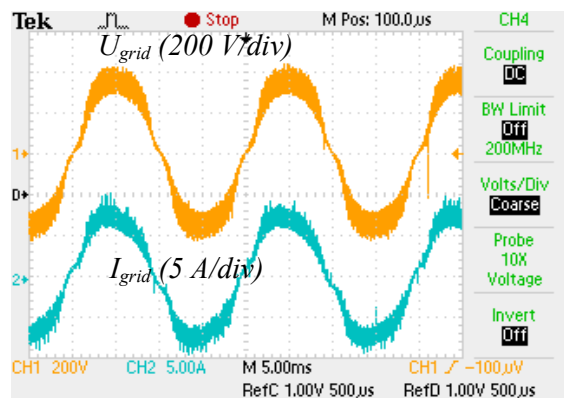


(b)

Fig. 3.7. Simulated a) and experimental b) waveforms of qZSI voltages and current at 1250W load



(a)



(b)

Fig. 3.8. Simulated a) and experimental b) waveforms of SL qZSI output voltage and current at 1250W load

4. CONCLUSIONS AND FUTURE WORK

The family of qZS based interface converters for PMSG based VSWT applications are offered in this thesis. The qZS based interface converter with generator side inverter was offered for PMSG based VSWT systems in small power range, but topology with uncontrolled rectifier for micro power range.

The new topology of qZS converter with switched inductors was offered and analysed. The main target for this topology is converters with ultra wide input voltage range, thanks to enhanced boost performance of this converter. The main advantage of the proposed converter is the enhanced output voltage regulation properties thanks to the new SL qZS network implemented. The proposed topology could be implemented in the residential PMSG based wind turbines with power rating up to 15 kW.

The future work should be concentrated on brand new semiconductor switch utilisation in converters for future efficiency optimization and higher utilization of renewable energy.

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LAURIS BISENIEKS

**RESEARCH AND DEVELOPMENT OF INTERFACE
CONVERTER FOR PMSG BASED WIND GENERATOR**

Summary of doctoral thesis