Application of Simplified Neutral Point Clamped Multilevel Converter in a Small Wind Turbine

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Abstract – **In low power distributed generation systems low cost together with the energy quality requirements are a key element. It is known that quality of voltage waveforms generated from multilevel converters is better in comparison with those from two-level. Due to advancements in power electronics and microcontrollers, multilevel converters are being built with the use of integrated power modules thus this type of converters are getting more compact in size. This paper investigates performance of a derivation from the most popular multilevel topology – a neutral point clamped converter (NPC). Applying the idea for simplifying the topology by reducing the number of switches (what came from drives) this NPC converter is capable of bidirectional AC/DC/AC operation. For the AC/DC part two schemes are tested: Direct Torque Control Space Vector Modulated and Field Oriented Control but for the DC/AC part a control scheme utilizing the proportional-resonant controller was chosen. Laboratory setup was based on a permanent magnet synchronous generator with control and acquisition completed with the help of dSpace 1005 control box. Experimental verification shows that system operates properly.**

Keywords – **AC-DC power converters; Power conversion harmonics; Wind energy generation; Bidirectional power flow.**

I. INTRODUCTION

Cost optimization of a power converter based on the idea of replacing one of the semiconductor branches with a split capacitor bank and connecting a phase wire to its middleproposed in [1]. It gives lower number of switching devices comparing to a classical 2-level AC-DC-AC converter which corresponds to reduced number of control channels, IGBT driver circuits etc. Despite above advantages of a 2-level simplified converter for obtaining sinusoidal current there is a necessity to maintain higher DC voltage, that gives higher voltage stress of converter semiconductor devices [2]-[4]. This problem can be solved by application of a 3L-NPC power modules with clamping diodes. New compact devices make it easier to improve the topology with a split capacitor in DC-link that is shown in Fig. 1 [5], [6].
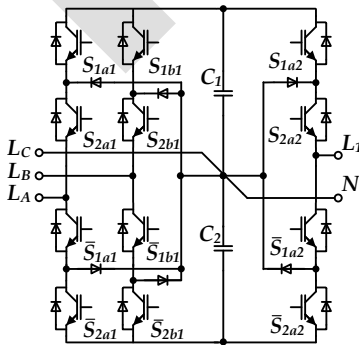
Fig. 1. Simplified AC/DC/AC multilevel NPC converter.

Content of the paper is the following. The second section describes the chosen modulation algorithms for the AC/DC/AC. The third section describes the two control methods implemented for the AC/DC part of converter connecting to PMSG and a proposed control utilizing a proportional-resonant (PR) controller for the grid side DC/AC converter. Section four is dedicated to experimental results. The last closing section is left for conclusion.

II. MODULATION

Modulation for simplified back-to-back converters is realized separately for the DC/AC and AC/DC stage with the use of switching states depicted in Fig.2 and Fig.3. It can be utilized using a universal concept of time-domain duty-cycle computation technique for single-phase multilevel converters described as one dimensional modulation (1DM) technique presented in Fig. 2 [7].
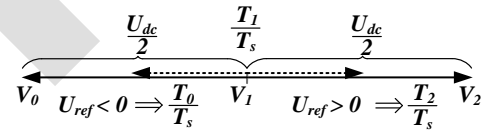
Fig. 2. Vector plane for 1-DM modulation of single-phase DC/AC converter.

For the single phase converter calculating durations of vectors are described as:

$$T_2 = \frac{\left|U_{ref}\right|}{0.5U_{DC}}T_s; \quad T_1 = T_s - T_2; \quad \mathrm{Re}(\underline{U}_{ref}) \geq 0 \quad \text{and}$$

$$T_0 = \frac{\left|U_{ref}\right|}{0.5U_{DC}}T_s; \quad T_1 = T_s - T_0; \quad \mathrm{Re}(\underline{U}_{ref}) < 0 \quad . \quad (1)$$
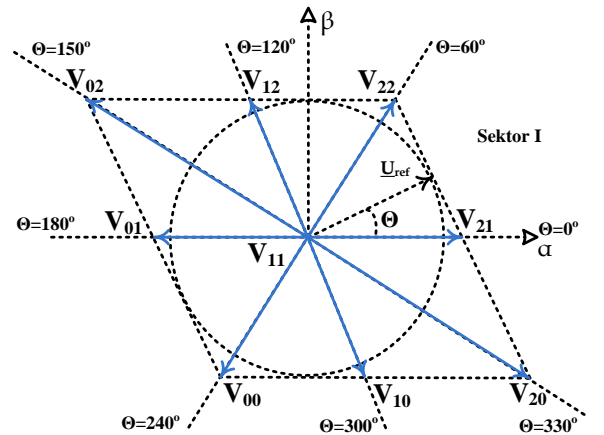
Fig. 3. Possible voltage vectors generated by the simplified three-phase DC/AC converter.
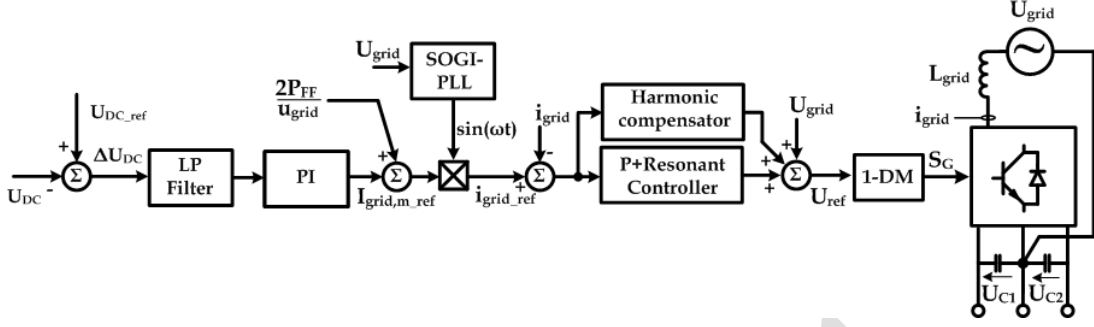
Fig. 4. Single-phase DC/AC converter control scheme.
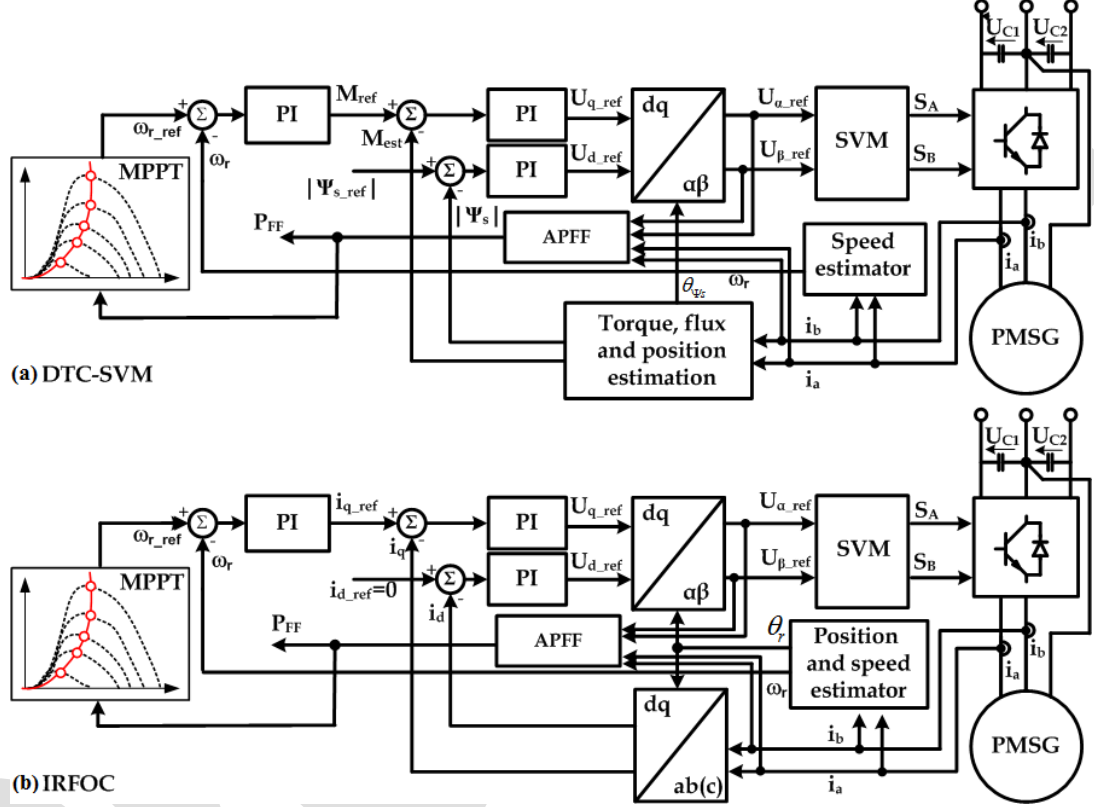

(a) DTC-SVM

(b) IRFOC

Fig. 5. Three phase AC/DC converter control schemes of DTC-SVM (a) and IRFOC (b).

Fig.3 shows graphic representation of space vector $\alpha\beta$ voltage plane with nine possible to obtain voltage vectors of three-phase three-level simplified converter. It gives eight active vectors (V_{21}, V_{22}, V_{12}, V_{02}, V_{01}, V_{00}, V_{10}, V_{20},) and one zero vector (V_{11}). Switching times for the Sector I ($0^o \leq \theta < 60^o$) can be computed as:

$$T_{21} = \frac{\sqrt{6}U_\alpha}{U_{DC}}T_s - \frac{\sqrt{2}U_\beta}{U_{DC}}T_s$$
$$T_{22} = \frac{2\sqrt{2}U_\beta}{U_{DC}}T_s$$
$$T_{11} = T_s - T_{21} - T_{22}$$

(2)

III. CONTROL

A. Control of Single-phase Grid Converter

Fig. 4 presents control of single-phase grid side converter based on PR controller firstly proposed in [8]. The ΔU_{DC} voltage is an error calculated by subtraction of measured DC-link voltage (U_{DC}) from DC voltage reference U_{DC_ref}. Error filtered by a low pass filter with a $f_{cut\_off} = 30$Hz is entering a PI controller. Output value from the PI block with addiction of the active power feed-forward signal (APFF) is then multiplied by a sine function of the grid voltage angle, which is calculated by a SOGI-PLL. Resulting outcome becomes reference value for the PR current controller and parallel harmonic compensator block. Resonant part of mentioned PR controller is tuned at the fundamental grid frequency ω for which the highest gain is obtained but harmonic compensator contains resonant part tuned to specific high order harmonics e.g. 5th, 7th [9]-[10].
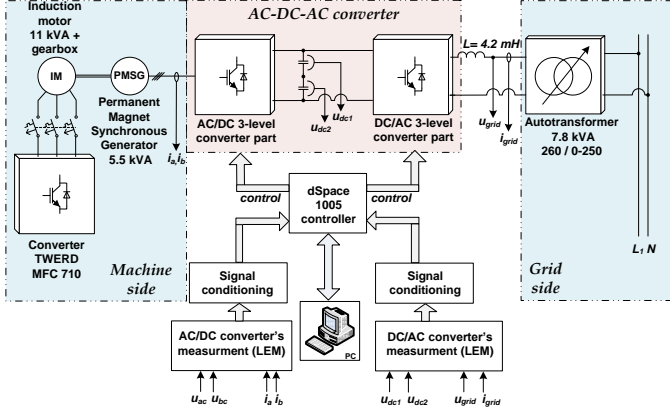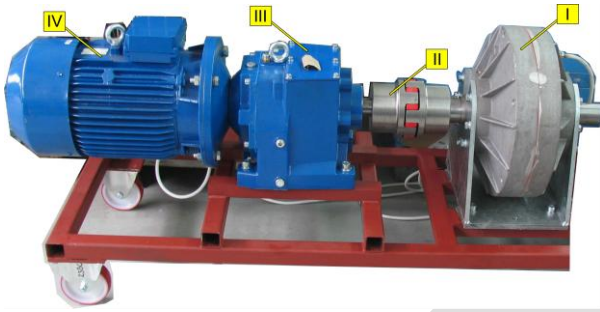
Fig. 6. Block scheme of laboratory setup.

Fig. 7. PMSG based wind turbine laboratory model: I – low speed PMSG, II –clutch, III – gearbox, IV – high speed induction motor.
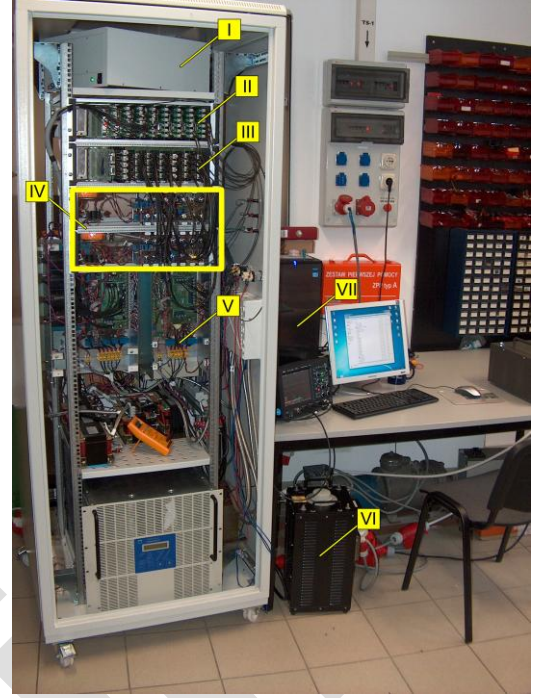

Fig. 8. Laboratory control setup: I – dSpace 1005 system, II – PWM control signal interface, III – signal conditioning, IV – LEM based measure circuits, V – AC/DC/AC converter, VI – autotransformer, VII – PC class computer.

B. Control of Three-phase Generator Side Converter

For controlling the machine side converter two popular control strategies are investigated. The first shown in Fig. 5(a) is the Direct Torque Control with Space Vector Modulation (DTC-SVM) [11]. It consists of a torque M, stator flux Ψ_s and speed ω control loops. Reference value for torque is provided by an outer PI speed controller. Reference value of flux is subtracted from estimated and the error is an input for a PI flux controller. From outputs of PI torque and flux controllers converter voltage in dq coordinates is (after transformation to stationary coordinate system) a reference for modulation algorithm based on space vector representation (SVM) shown in Fig. 3.

Second viable control scheme is based on Indirect Rotor Field Oriented Control – IRFOC, Fig. 5(b). In this scheme reference speed denoted as ω_{r_ref} is compared with estimated angular speed ω_r. Obtained error is an input for a PI speed controller that calculates the reference for the current i_{q_ref} (responsible for electromagnetic torque). Reference current i_{d_ref} is set to be zero. PI current controllers set voltage values of U_{d_ref} and U_{q_ref}, which after transformation to stationary $\alpha\beta$ coordinate system are needed for space vector modulation (SVM). Active power feed forward (APFF) is calculated in both schemes Fig. 5(a) and Fig. 5(b) to improve dynamic performance and stabilize dc-link. APFF is delivered to the DC/AC converter as shown in Fig.4 [12]-[15].

IV. EXPERIMENTAL RESULTS

General idea of the laboratory setup of a simplified multilevel AC/DC/AC converter for SWT is presented in Fig.6 and Fig. 8.

Laboratory verification was conducted using a 5.5kW Permanent Magnet Synchronous Generator with 20 pole pairs and nominal speed of 150 rpm (Fig. 7). Generator was connected by a gearbox with an 11kW Induction Motor controlled by a commercial industrial inverter. Chosen experimental results are shown in Fig.9-18 and a list of the laboratory setup parameters is given in Table 1. In Fig.9 a steady state of the single-phase DC/AC converter at grid connected mode of operation is shown. Stand-alone operation at step-change of the load is presented in Fig. 10. Fig.11 and Fig. 14 are also from steady state operation but for the three-phase AC/DC converter using two investigated control methods (DTC-SVM, IFOC). Next oscillograms are showing dynamic responses for step increase and decrease of reference speed, in case of DTC-SVM (Fig. 12- 13), and IRFOC (Fig. 15-16). In both cases dynamic behavior of the system is satisfying. Operation of IRFOC without and with active power feed-forward (APFF) is shown in Fig. 17-20.

TABLE I

PARAMETERS OF THE LABORATORY SETUP

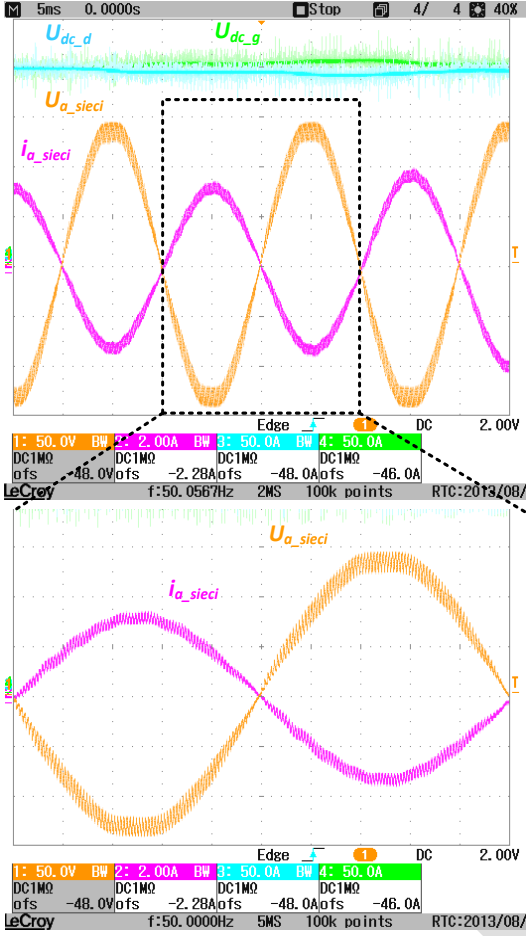|		
Nominal power	5.5kW	PMSG
Pole pairs	20	
Nominal speed	150 rpm	
Nominal voltage	3x380V	
Phase winding resistance	4.4 ohm	
Phase inductance	30mH	
Summary dc-link	1.5μF	AC/DC/AC Converter
Grid side filter inductance	4.2mH	
Control system	dSpace 1005	
Switching frequency	8 kHz	

A. DC/AC Converter Operation

Fig. 9. Steady state of single-phase DC/AC part of converter at grid connected mode of operation. From top: voltage on upper capacitor (U_{dc_g}), voltage on lower capacitor (U_{dc_d}), grid voltage (U_{a_sieci}) and grid current (i_{a_sieci}).
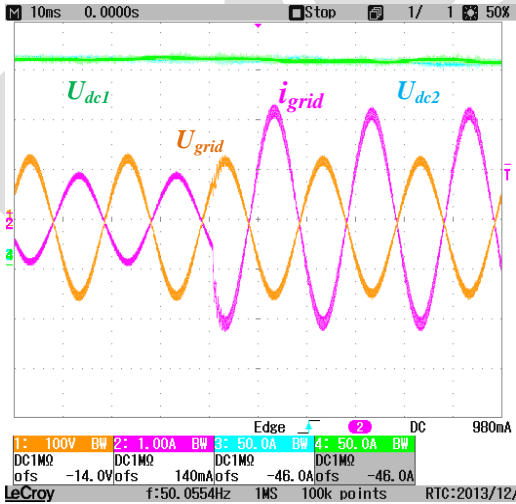

Fig. 10. Step-change of the load for single-phase DC/AC part of converter at stand-alone mode of operation. From top: voltage on upper capacitor (U_{dc1}), voltage on lower capacitor (U_{dc2}), grid voltage (U_{grid}) and inverted grid current (i_{grid}).
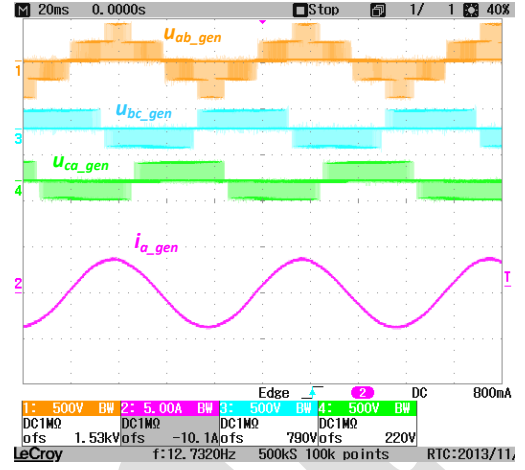
B. AC/DC Control Operation with DTC-SVM

Fig. 11. Steady state of three-phase AC/DC part of converter. From top: phase to phase voltages of converter (u_{ab_gen}, u_{bc_gen}, u_{ca_gen}) and generator phase current i_a.

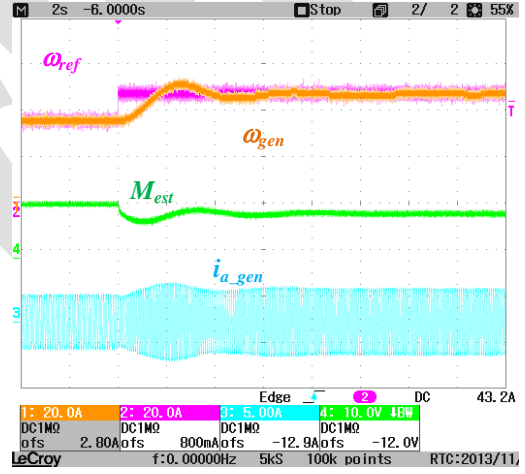Fig. 12. Response for step change of speed. From top: reference speed (ω_{ref}), measured speed (ω_{gen}), estimated torque (M_{est}), phase current (i_{a_gen}).
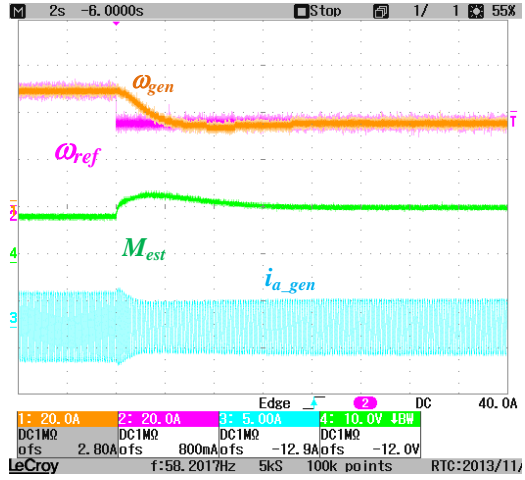

Fig. 13. Response for step change of speed. From top: reference speed (ω_{ref}), measured speed (ω_{gen}), estimated torque (M_{est}), phase current (i_{a_gen}).
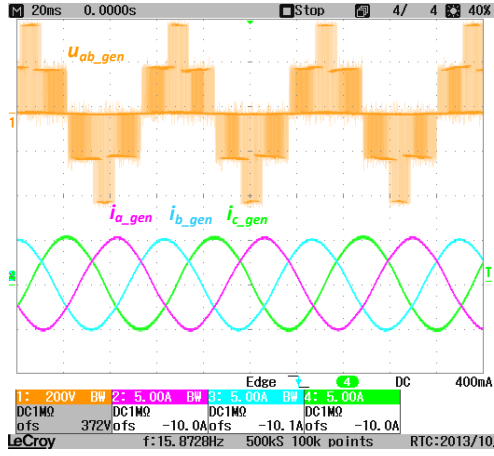
C. AC/DC Control Operation with IRFOC

Fig. 14. Steady state of AC-DC part of converter. From top: phase to phase voltage of converter (u_{ab_gen}) and generator phase currents (i_{a_gen}, i_{b_gen}, i_{c_gen}).

Fig. 15. Response for step change of speed. From top: speed reference (ω_{ref}), estimated speed (ω_{gen}), current in q-axis (i_q), current in d-axis (i_d).

Fig. 16. Response for step change of speed. From top: reference speed (ω_{ref}), estimated speed (ω_{gen}), current in q-axis (i_q), current in d-axis (i_d).
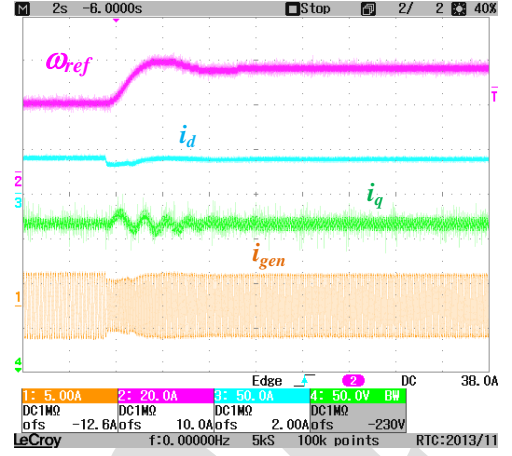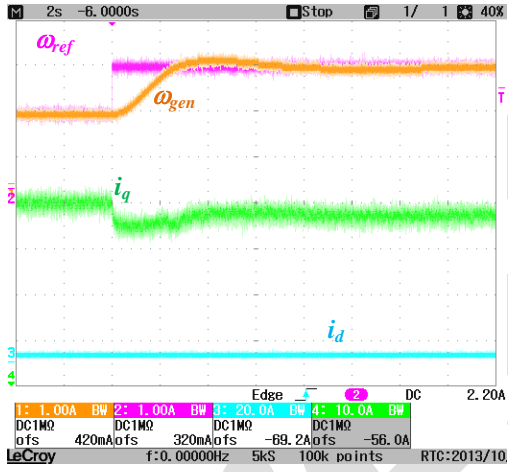
D. DC/AC Control Operation with APFF

Fig. 17. Response for step change of speed without APFF. From top: estimated speed (ω_{gen}), current in d-axis (i_d), current in q-axis (i_q), generator current (i_{gen}).
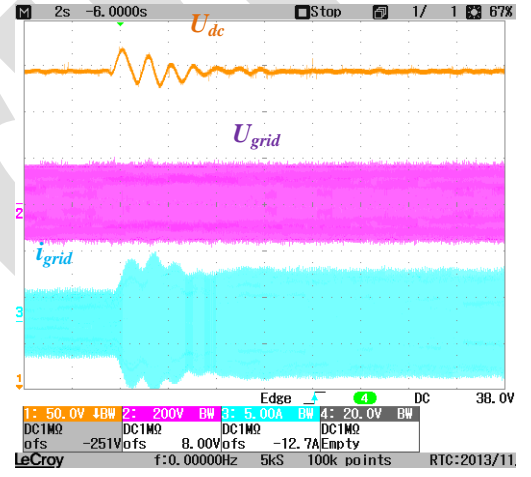

Fig. 18. Response for step change of speed without APFF. From top: dc-link voltage (U_{dc}), grid voltage (U_{grid}), grid current (i_{grid}).

Fig. 19. Response for step change of speed with APFF. From top: estimated speed (ω_{gen}), current in d-axis (i_d), current in q-axis (i_q), generator current (i_{gen}).

Fig. 20. Response for step change of speed with APFF. From top: dc-link voltage (U_{dc}), grid voltage (U_{grid}), grid current (i_{grid}).
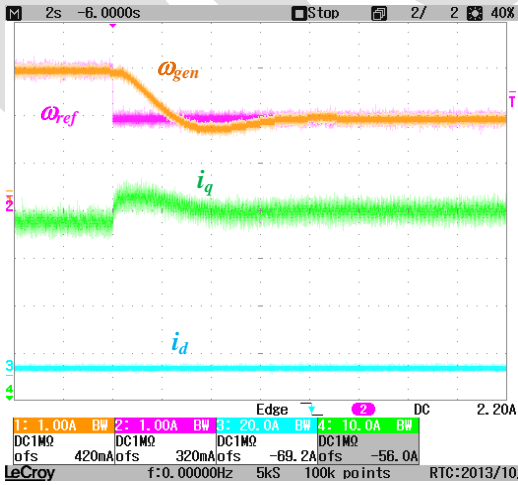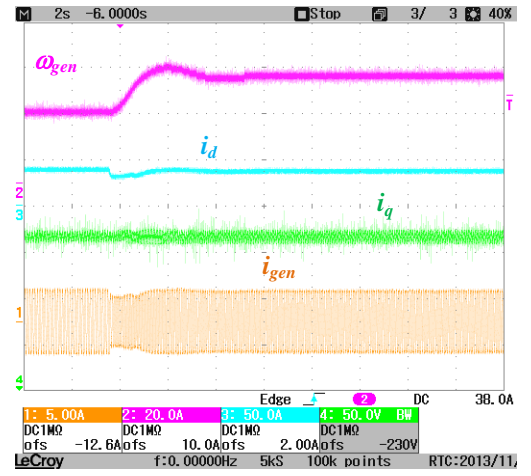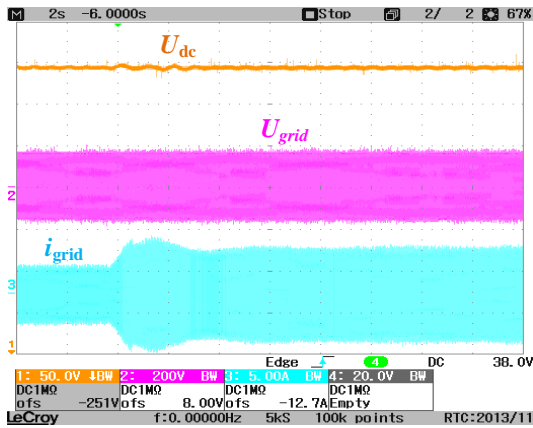
V. CONCLUSION

AC/DC/AC converters recently turned attention for small wind turbine (SWT) applications. Relatively simple control algorithm for the single-phase DC/AC part of converter allows to precisely eliminate higher order harmonic distortion in the grid current. Two possible control schemes for the AC/DC part of converter (DTC-SVM and IRFOC) working with a PMSG are also investigated giving good dynamic response and sensorless operation. Further improvement can be provided with active power feed-forward (APFF) term added to the control system. Experimental validation proved the feasibility of simplified multilevel converter in SWT. Presented system is an interesting alternative for low cost fully controlled AC-DC-AC converters applied to small power generator systems working with permanent magnet synchronous or induction generators interfacing to the single phase grid.
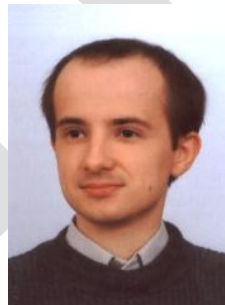
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