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Monitoring and Control Algorithms Applied to Small Wind Turbine with Grid-Connected/Stand-Alone Mode of Operation

Abstract. *This paper presents control of a three-phase DC/AC converter with grid monitoring algorithm applied to Small Wind Turbine (SWT). Monitoring through voltage amplitude and frequency measurement detect electrical grid faults and automatically change the grid-connected/stand-alone mode of operation. Inverse transition stand-alone/grid-connected is preceded by synchronization of DC/AC converter to electrical grid with the help of special Phase Locked Loop (PLL) block.*

Streszczenie. *Poniższy artykuł opisuje sterowanie trójfazowym przekształtnikiem DC/AC z algorytmem monitorowania sieci elektroenergetycznej do zastosowania w Małej Elektrowni Wiatrowej (MEW). Algorytm monitorujący amplitudę oraz częstotliwość napięcia sieci wykrywa awarię sieci elektroenergetycznej i automatycznie przełącza tryb pracy elektrowni z pracy z siecią elektroenergetyczną do pracy autonomicznej. Natomiast przełączenie z pracy autonomicznej do pracy elektrowni z siecią elektroenergetyczną następuje po uprzedniej synchronizacji przekształtnika DC/AC z siecią elektroenergetyczną za pomocą pętli synchronizacji fazowej (PLL). (**Sterowanie trójfazowym przekształtnikiem DC/AC z algorytmem monitorowania sieci elektroenergetycznej**)*

Keywords: Small wind turbine, synchronization, stand-alone mode, grid-connected mode
Słowa kluczowe: Mała elektrownia wiatrowa, synchronizacja, praca autonomiczna, praca z siecią elektroenergetyczną

Introduction

Renewable energy sources are playing an important role in modern distributed generation system. Among them one of most attractive from efficiency point of view (no long distance energy transfer) are Small Wind Turbines, which can be installed in rural or other low density population areas. Therefore number of SWT installations, where area swept by rotor blades reach 200m^2, is constantly growing, what is a very promising supplement to high power commercial WT applications [1-2]. However in some countries grid codes determines operation of SWT in stand-alone and grid-connected mode. The main challenge to fulfill these requirements is proper fault detection and synchronization algorithm, allowing to disconnect/connect DC/AC converter to electrical grid without large shock.

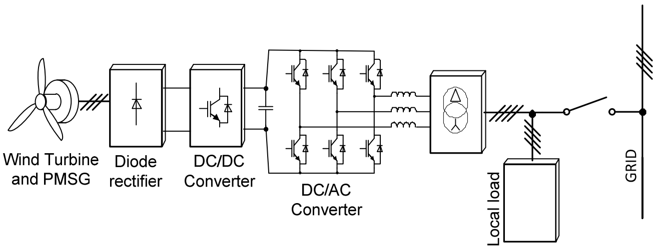

Fig. 1. Block scheme of a small wind turbine

Figure 1 presents a configuration of a typical SWT, which consists of:

- Permanent Magnet Synchronous Generator (PMSG) driven by wind rotor (without a gearbox) [3],
- 6-pulse diode rectifier with a DC/DC boost converter for utilization of Maximum Power Point Tracking (MPPT) [4],
- three-phase DC/AC converter with mandatory delta-star transformer for stand-alone mode of operation.

Last block is very important, because provides uninterruptable supply of symmetrical and asymmetrical local loads during electrical grid faults. Therefore universal control scheme of SWT for grid-connected/stand-alone mode of operation and grid monitoring algorithm are presented in this paper. Proposed solution was verified experimentally in lab setup controlled by DSP platform.

Control Algorithms of DC/AC converter

Figure 2 shows block scheme of proposed control algorithm for DC/AC converter used in SWT, which is divided into three parts [5]:

- Direct Power Control with Space Vector Modulator (DPC - SVM) in grid connected mode of operation,
- voltage control in stand-alone mode of operation,
- grid monitoring and DC/AC converter synchronization.

A. DC-AC converter in Grid Connected Mode of operation

The DC/AC converter in grid-connected mode of operation use DPC-SVM method bases on controlling instantaneous active and reactive powers [6]. Control scheme of this algorithm is marked by red dashed line in figure 2.

Reference value of active power p_{ref} is calculated by outer dc-link controller and reactive power is set as constant $q_{ref}=0$, what lead to unity power factor. Reference values are compared with estimated described as:

$$p_x = \omega \cdot (u_{L\alpha} i_{L\alpha} + u_{L\beta} i_{L\beta}) \quad (1)$$

$$q_x = \omega \cdot (u_{L\alpha} i_{L\beta} - u_{L\beta} i_{L\alpha}) \quad (2)$$

where:
u_{dc} - dc link voltage; $i_{L\alpha}$, $i_{L\beta}$ - phase currents in *α-β* coordinate system; $u_{L\alpha}$, $u_{L\beta}$ - phase voltages in *α-β* coordinate system.

Instantaneous active and reactive power errors are input values of PI controllers. Their outputs generate signals in *d-q* coordinate system that represent given voltages for Space Vector Modulator (SVM) [7], which is common part for grid-connected and stand-alone mode of operation.

B. DC-AC converter in Stand-alone Mode of operation

The converter in stand-alone mode of operation can be implemented using simple algorithm based on voltage oriented control. Subsystem shown in figure 2 (blue dashed line) contains inner ac voltage control loops in *d-q* coordinate system and outer dc voltage control loop [8-9].

Outer control loop is in charge to maintain U_{dc} voltage at constant, given level. Output signal from PI controller has limitation block because it is mandatory according to grid code to keep phase voltage of DC/AC converter in range 210 V_{rms} - 250 V_{rms} (out of this range converter should be switched off).

Reference value u_{d_ref} is calculated as:

$$u_{d\_ref} = u_{d\_nom} - u_{d\_ocl} \quad (3)$$

where: u_{d_nom} – nominal amplitude of local voltage, u_{d_ocl} – output value from outer control loop.

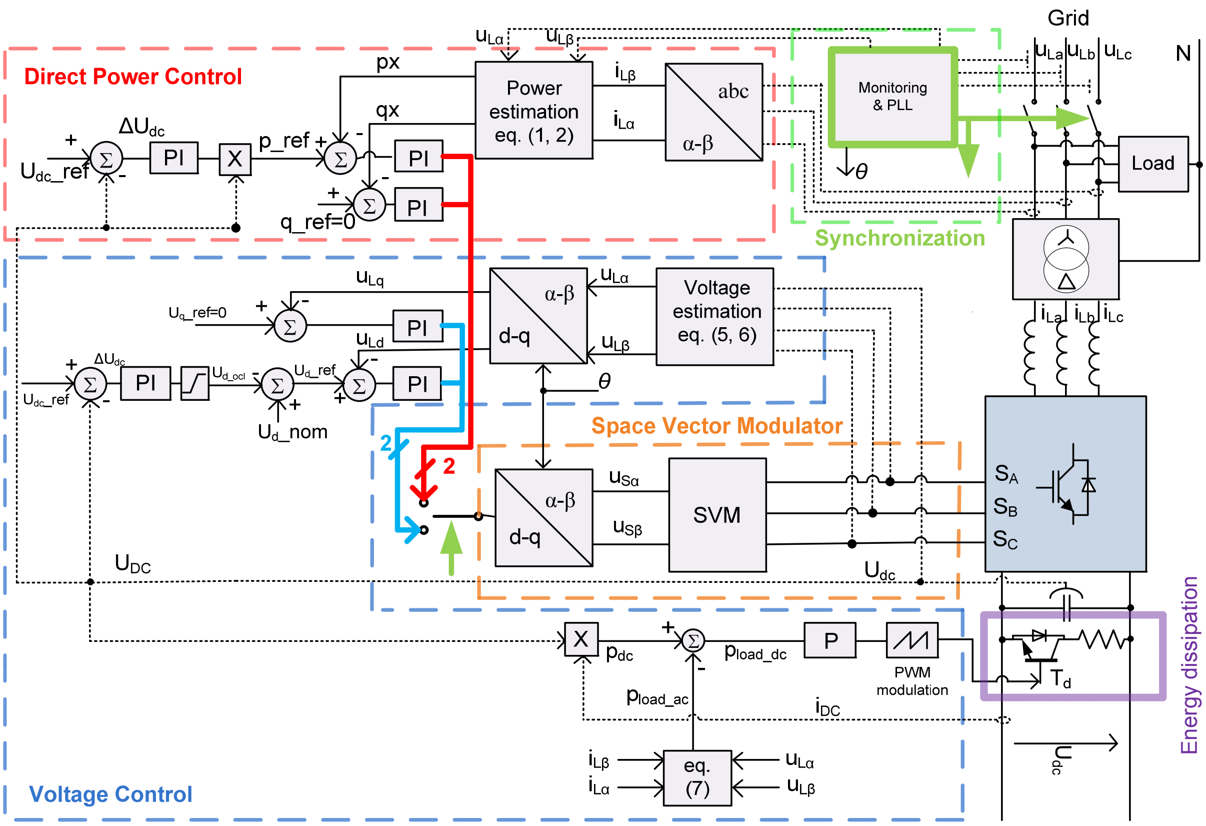

Fig. 2. Control scheme of DC/AC converter in grid-connected (red block) and stand-alone (blue block) modes of operation

Amplitude of output AC voltage in DC/AC converter depend on u_{d_ref} only because reference value in *q*-axis denoted as u_{q_ref} is equal zero, what cause that converter voltage vector is aligned with *d*-axis. Signals u_{d_ref} and u_{q_ref} compared with measure values u_{Ld} and u_{Lq} become input for PI regulators.

Output signals from inner PI regulators after transformation:

$$(4)\qquad \begin{bmatrix} u_{S\alpha} \\ u_{S\beta} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} u_{Sd} \\ u_{Sq} \end{bmatrix}$$

are given values for SVM.

Important part of the control algorithm in stand-alone mode of operation is energy dissipation block, activated when power consumed by local load is lower than generated by turbine. It helps maintain dc voltage at a constant level as well as AC voltage in given safety range. Simple energy dissipation circuit consists of a single transistor and a resistor (water boiler can be used instead of resistor), which is able to consume all produced electrical energy by generator during nominal conditions.

Control algorithm for power dissipation base on following equations:

$$(5)\qquad \mathrm{u_{L\alpha}} = \frac{\mathrm{U_{dc}}}{3}(2\mathrm{D_A} - \mathrm{D_B} - \mathrm{D_C})$$

$$(6)\qquad \mathrm{u_{L\beta}} = \frac{\sqrt{3}\cdot \mathrm{U_{dc}}}{3}(\mathrm{D_B} - \mathrm{D_C})$$

$$(7)\qquad \mathrm{p_{load\_ac}} = \frac{3}{2}(\mathrm{u_{L\alpha} i_{L\alpha} + u_{L\beta} i_{L\beta}})$$

$$(8)\qquad p_{dc} = \mathrm{U_{dc}} \cdot \mathrm{i_{dc}}$$

$$(9)\qquad p_{load\_dc} = p_{dc} - p_{load\_ac}$$

where: $u_{L\alpha}$, $u_{L\beta}$ - estimated values of output voltage in *αβ* coordinate system based on duty cycles of converter's control pulses and dc-link voltage, p_{load_ac} - instantaneous power of the three-phase local load, p_{dc}– instantaneous power generated by SWT, p_{load_dc} - instantaneous power dissipated on resistor.

Then p_{load_dc} is used to determine duty cycle of transistor

$$(10)\qquad D_{dc} = \frac{p_{load\_dc}}{P_N} \cdot T_s$$

where: P_N – nominal generated power by SWT, T_s – sampling time.

Monitoring algorithm With Automatic Transient of grid-connected/stand-alone mode of operation

Main goal of grid monitoring algorithm is to detect fault or recover of electrical grid and make final decision about mode of DC/AC converter operation. This process can be generally divided into three tasks:

- grid voltage/frequency measurement and fault detection,
- synchronization of DC/AC converter to electrical grid by Phase Locked Loop (PLL),
- transient of DC/AC converter between stand-alone /grid-connected modes of operation.

The monitoring algorithm is checking all the time, if angular frequency, voltage amplitude and zero component of grid voltage are in the permissible range described in standards PN-EN 50160:2008 [10-11]. When electrical grid faults are detected then DC/AC converter is switched to stand-alone mode of operation.

If electrical grid recovers, then PLL start synchronization process, which is used to determine grid and converter voltage frequency. Block scheme of PLL is shown in figure 4.

Idea based on assumption, that converter can be connected to the grid if *ΔΘ* described by equations (11-12) [6] is equal zero.

For $(\gamma - \theta) > \pi$ *(figure 5):*

$$(11)\qquad \Delta\Theta \cong \sin(\gamma - \theta) = \sin\gamma \cdot \cos\theta - \cos\gamma \cdot \sin\theta$$

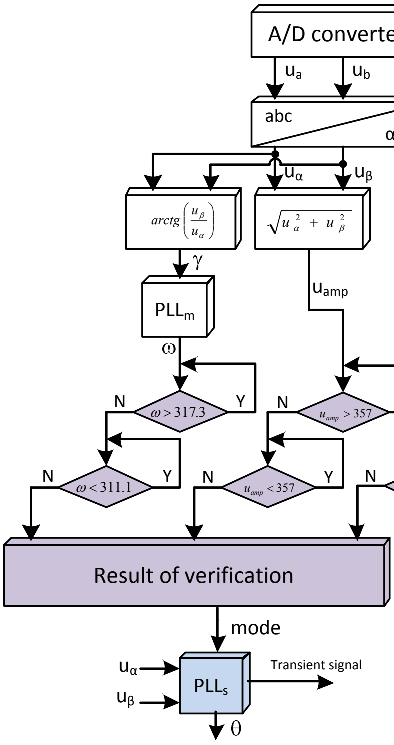

Fig. 3. Flow-chart of monitoring algorithm

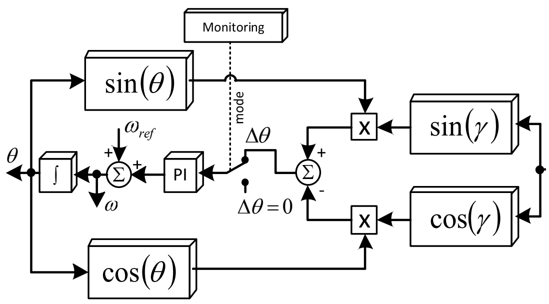

Fig. 4. Implemented PLL's scheme

For $(\gamma - \theta) < \pi$:

(12) $$\Delta\Theta \cong \sin(\theta - \gamma) = \cos\gamma \cdot \sin\theta - \sin\gamma \cdot \cos\theta$$

It can happen twice, when sine argument $(\gamma - \theta)$ is equal "*0*" (correctly) as well as "*π*" (incorrectly). Therefore if $(\gamma - \theta) = \pi$, small value is added to $\Delta\Theta$, to omit this undesirable situation.

When synchronization process is finished, the DC/AC converter is connected back to the electrical grid. Full flow-chart of monitoring algorithm is shown in figure 6.

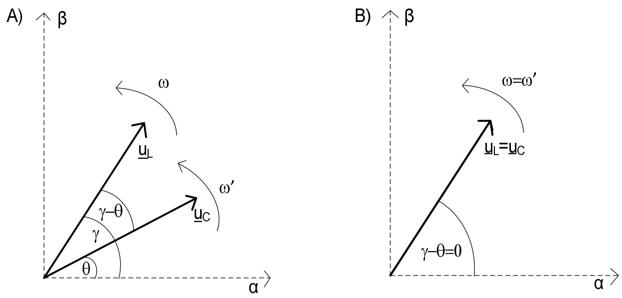

Fig. 5 Phase synchronization process: a) converter not-synchronized, b) converter synchronized [10]

Experimental Results

Laboratory experiment has been performed in order to show the correctness of proposed control and monitoring algorithms. Block scheme, some selected elements and parameters of setup are shown in figures 7 - 8 and table 1.

Proposed algorithms was implemented on Texas Instrument microcontroller, C2000 family, fixed point Piccolo TMS320F28027 (dedicated for power electronics applications [12]).

Table 1 Experimental setup parameters

Generator with gear and motor	
Generator type	PMSG
Nominal power	5.5 kVA
Nominal speed	150 rpm
Number of pole pairs	20
Induction motor nominal power	11 kVA
Induction motor nominal speed	1460 rpm
Gear ratio	9.7/1
Converter with filter	
Nominal power	11 kVA
Number of phases	3
Number of levels	2
Switching frequency	5 kHz
DC voltage	650 V
LC filter (for each phase)	L = 5 mH C = 12 µF
Transformer	
Type	dY11
Nominal power	15 kVA

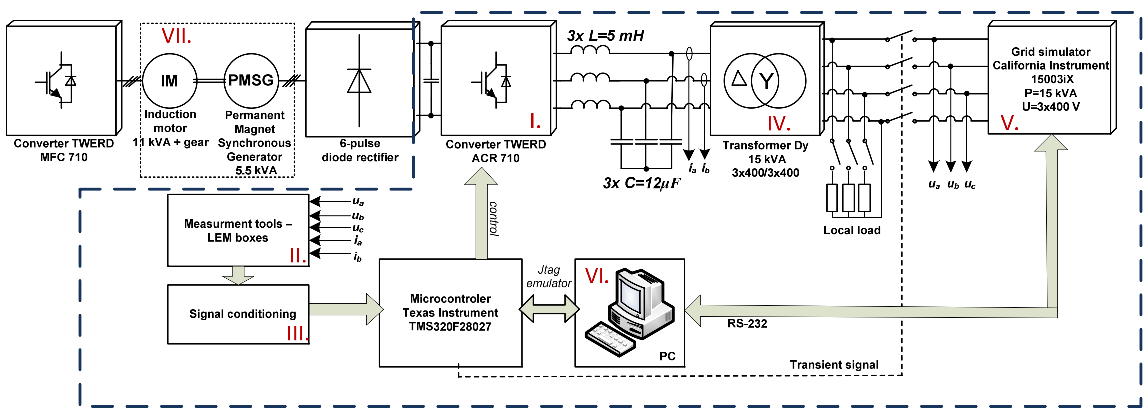

Fig. 7. Block scheme of experimental setup

The waveforms presented in this paper show steady state operation of SWT in grid connected/stand-alone mode of operation as well as transient between them.

Figure 9 shows step change of load from 2 kW to 4 kW in stand-alone mode of SWT operation with symmetrical three-phase load. Note that during transient generated voltages are sinusoidal without significant disturbances.

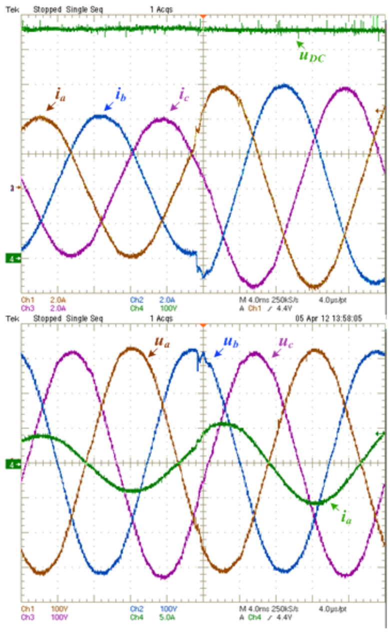

Fig. 9. Step change of the symmetrical three-phase load for DC/AC converter in stand-alone mode of operation. From the top: voltage in dc link u_{DC}, phase currents i_a, i_b, i_c, phase voltages u_a, u_b, u_c, phase current i_a

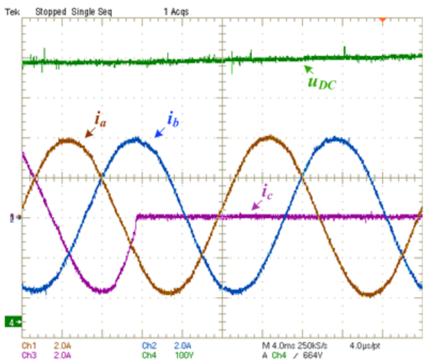

Fig. 10. Transient from three-phases to two-phases load for DC/AC converter in stand-alone mode of operation. From the top: voltage in dc link u_{DC}, phase currents i_a, i_b, i_c

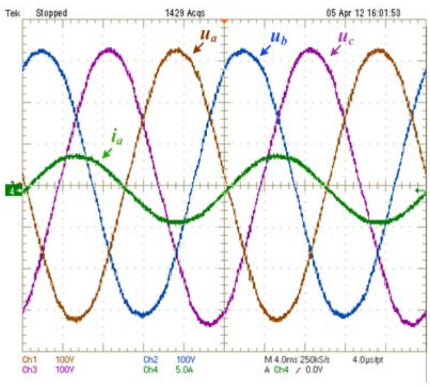

Fig. 11. Steady-state operation of DC/AC converter in stand-alone mode with two-phase load. From the top: phase voltages u_a, u_b, u_c, phase current i_a

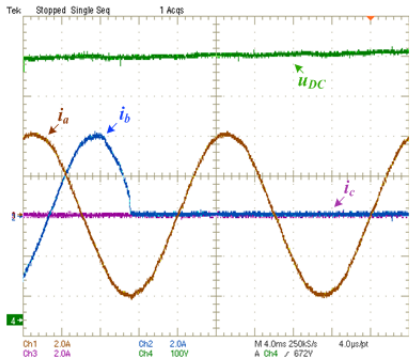

Fig. 12. Transient from two-phase to single-phase load for DC/AC converter in stand-alone mode of operation. From the top: voltage in dc link u_{DC}, phase currents i_a, i_b, i_c.

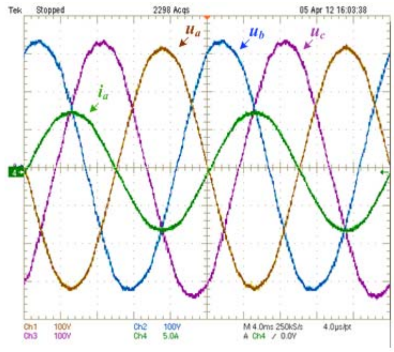

Fig. 13. Steady-state operation of DC/AC converter in stand-alone mode with single-phase load. From the top: phase voltages u_a, u_b, u_c, phase current i_a

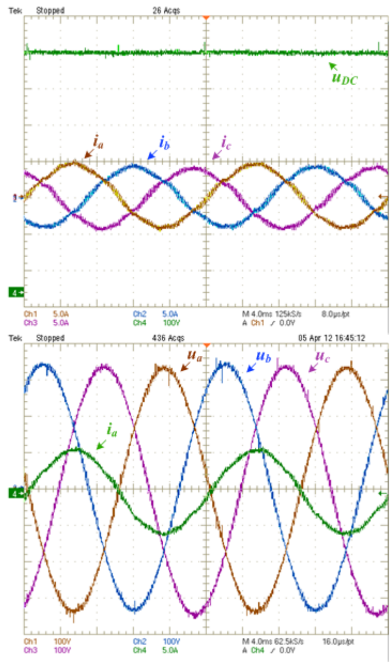

Fig. 14. Steady-state operation of converter in grid-connected mode (DPC-SVM). From the top: voltage in dc link u_{DC}, phase currents i_a, i_b, i_c, phase voltages u_a, u_b, u_c, phase current i_a.

Figure 10 and figure 11 show transition from three-phase to two-phase load for stand-alone mode of operation. Notice that DC/AC converter is working properly not only with two-phase load but even with single-phase load, what is shown in figure 12 and figure 13.

Figure 14 presents correct steady-state operation of converter in grid-connected mode, where active power is transferred to the electrical grid.

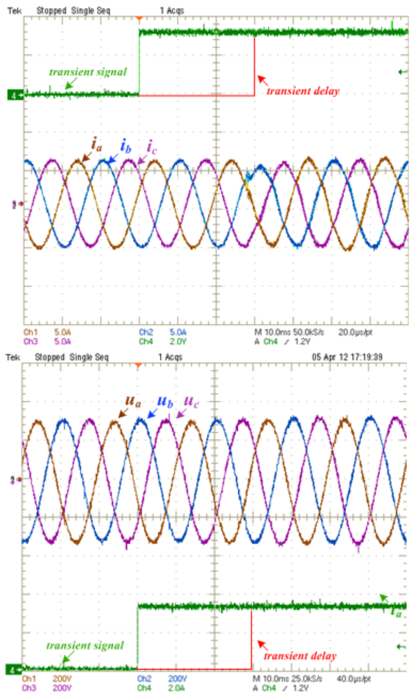

Fig. 15. Transient from stand-alone to grid-connected mode of operation. From the top: transient signal with delay, phase currents i_a, i_b, i_c, phase voltages u_a, u_b, u_c.

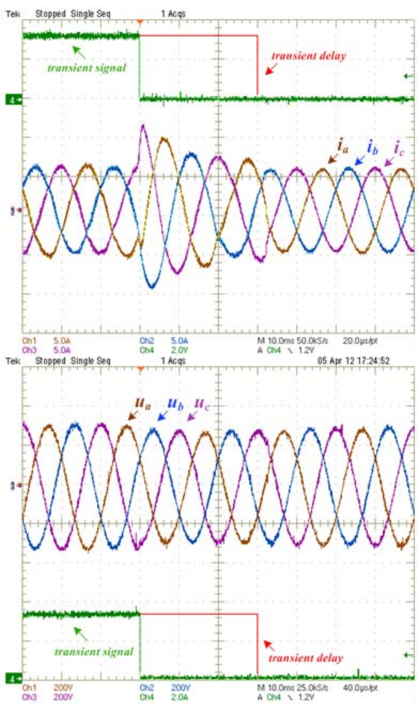

Fig. 16. Transient from grid-connected to stand-alone mode of operation. From the top: transient signal with delay, phase currents i_a, i_b, i_c, phase voltages u_a, u_b, u_c.

Figure 15 and figure 16 show transient between stand-alone and grid connected mode of operation. Experimental setup was connected to the grid by traditional contactor with additional control electrical circuit, which is not enough fast for this type of application. It causes delay between transient signal and physical transient, what is very dangerous during grid faults. There is necessary to use faster switch (e.g. semiconductor switch) in this kind of application. This problem not exists for transient from stand-alone to grid-connected mode, because transient delay does not matter, when converter is synchronized with the grid.

Conclusions

This paper has presented experimental verification of monitoring and control algorithm for DC/AC converter applied in Small Wind Turbine, which can operate in stand-alone and grid-connected modes. Evaluation shows that proposed solution is working correctly in both mode of operation giving uninterruptable power supply for different kind of local load in case of electrical grid faults. When electrical grid recover DC/AC converter after synchronization process is smoothly connected back to electrical grid.

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REFERENCES

[1] IEC 61400-02 Design requirements for small wind turbines, IEC, (2007)

[2] Spagnuolo G., Petrone G. Araujo S.V. Cecati, C., Friis-Madsen, E., Gubia E., Hissel, D., Jasinski, M., Knapp, W., Liserre, M., Rodriguez, P., Teodorescu, R., Zacharias, P., , "Renewable Energy Operation and Conversion Schemes: A Summary of Discussions During the Seminar on Renewable Energy Systems," *Industrial Electronics Magazine*, IEEE , vol.4, no.1, pp.38-51, (2010)

[3] Z. Goryca, M. Ziolek, M. Malinowski, „Cogging Torque of the Multipolar Generator with Permanent Magnets”, (in Polish) "*Maszyny Elektryczne Zeszyty Problemowe nr 88*", pp. 53-56, (2010)

[4] R. Kot, M. Rolak, M. Malinowski, „”Comparison of Maximum Peak Power Tracking Algorithms for a Small Wind Turbine”, *ELECTRIMACS* 2011, 6-8th June 2011, Cergy-Pontoise, France

[5] Malinowski M., Młodzikowski P., Milczarek A. „Algorytm sterowania przekształtnikiem DC/AC dla małej elektrowni wiatrowej”, *Electrical Review*, ISSN 0033-2097, R. 87 NR 6/2011, pp. 67-72

[6] M. Malinowski, M. Jasinski, M. P. Kazmierkowski, “Simple Direct Power Control of Three-Phase PWM Rectifier Using Space Vector Modulation”, *EPE-PEMC`02*, vol.4, pp. 1114 – 1118, (2002)

[7] M. Malinowski, “Sensorless Control Strategies for Three – Phase PWM Rectifiers”, Ph.D. Thesis, Warsaw University of Technology, (2001)

[8] M. Fatu., L. Tuteaea, R. Teodorescu, F. Blaabjerg, I. Boldea, ”Motion Sensorless Bidirectional PWM Converter Control with Seamless Switching from Power Grid to Stan Alone and Back”, *Power Electronics Specialists Conference*, pp. 1239-1244,(2007)

[9] R. Teodorescu, F. Blaabjerg, “Flexible Control of Small Wind Turbines With Grid Failure Detection Operating in Stand-Alone and Grid-Connected Mode”, *IEEE transaction on power electronics*, vol. 19, pp. 1323-1332, (2004)

[10] Malinowski M., Młodzikowski P., Milczarek A. „Control algorithm of a DC/AC converter applied in a small wind turbine”, *Industrial Electronics (ISIE), 2011 IEEE International Symposium*, 27-30 June 2011, pp. 1006 - 1010

[11] PN-EN 50160:2008, Polish Grid Codes, (2008)

[12] Kazmierkowski, M.P.; Jasinski, M.; Wrona, G.; , "DSP-Based Control of Grid-Connected Power Converters Operating Under Grid Distortions," *IEEE Transactions on Industrial Informatics*, vol.7, no.2, pp.204-211, May 2011

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