Modeling and simulation of a brushless DC permanent-magnet generator-based wind energy conversion system

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Abstract— **This paper deals with a brushless DC (BLDC) generator-based wind energy conversion system (WECS) for distributed electric power generation. Three-phase PWM rectifier and maximum-power-point-tracking algorithm are used for controlling the BLDC generator speed to achieve optimum energy output from the wind turbine. A PWM voltage-source inverter is connected to the DC bus for voltage and frequency regulation of AC supply to consumer loads. The BLDC generator-based WECS is modeled by sub-systems, and its dynamic behavior is simulated in MATLAB/SIMULINK environment for different wind-speed conditions and consumer loads.**

Keywords— brushless DC permanent-magnet generator, wind energy conversion system, simulation model, MPPT control, trapezoidal back-EMF.

I. INTRODUCTION

Brushless DC (BLDC) permanent-magnet machines operating in generator mode offer several advantages, such as high efficiency over a wide speed range, low maintenance, greater durability, compactness, and higher power density. Moreover, due to the trapezoidal phase back-EMF of the BLDC generator, the rectified DC output voltage has reduced pulsations. Such positive features prompt the BLDC generator for use in small-scale wind energy conversion systems (WECSs) [1], [2].

Few papers in the literature treat the problem of simulations in the wind energy conversion systems of an entire system consisting of direct driven BLDC-generator with trapezoidal back-EMFs, back-to-back PWM converters with their control, inductive filter and utility grid.

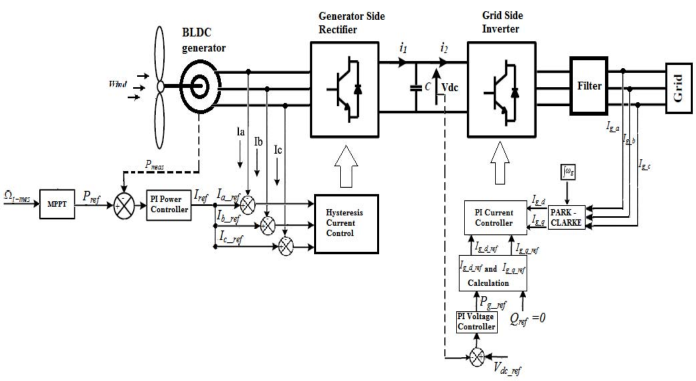

Fig.1. Schematic representation of the direct-driven BLDC generator-based WECS under study.

This paper proposes the modeling and simulation of distributed electric power generation system based on wind-turbine direct-driven three-phase BLDC generator (Fig.1). The output terminals of the BLDC wind generator are connected to a controlled PWM rectifier and the maximum-power-point tracking (MPPT) control is based on determining the maximum available power from the wind turbine. A DC-link capacitor allows the decoupling of the PWM rectifier from the PWM inverter used for grid connection and also for keeping constant the DC-link voltage. The proposed system is simulated using MATLAB/ SIMULINK software.

II. WIND TURBINE MODEL AND MPPT CONTROL

The direct-driven variable-speed wind turbine is modeled by the characteristics of the power coefficient, defined as the ratio of the mechanical power generated by the turbine and the power available in the wind.

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In its turn, the value of the turbine power coefficient varies as a function of the tip-speed ratio, which is dependent on wind speed and angular velocity of turbine blades. Therefore, the mechanical power of the wind turbine extracted from the wind has the following expression [3]:

$$P_t = 0.5 \cdot C_p(\beta, \lambda) \cdot \rho \cdot A \cdot v_w^3 \quad (1)$$

$$C_p(\lambda, \beta) = C1 \cdot \left(\frac{C2}{\lambda_i} - C3 \cdot \beta - C4 \right) \cdot e^{-\frac{C5}{\lambda_i}} + C6 \cdot \lambda \quad (2)$$

where ρ is the air density (kg/m3), A is the area swept by turbine-rotor blades, v_w the wind speed and C_p the power coefficient of the turbine with C1=0.5176, C2=116, C3=0.4, C4=5, C5=-21, C6=0.0068.

The normal start-up of a wind turbine is for a wind speed of 2.5-5 m/s. Until the wind reaches its nominal speed of 9-15 m/s (depending on the generator power) the turbine operates under the MPPT (maximum power point tracking) control, in order to maximize the power extracted from the wind. For speeds exceeding this nominal value, the turbine operates at nominal power, i.e. the wind generator rated power, to prevent the overload of the conversion system. For the proposed system, the start-up wind speed is at 3 m/s, and the generator reaches its rated power of 3 kW at 11.3 m/s. For a wind speed less than 25 m/s, the wind turbine operates at rated power, and, finally, if the speed of the wind is higher than the admissible one, the wind turbine is stopped (Fig.2). The pitch angle for the proposed system is set to zero.

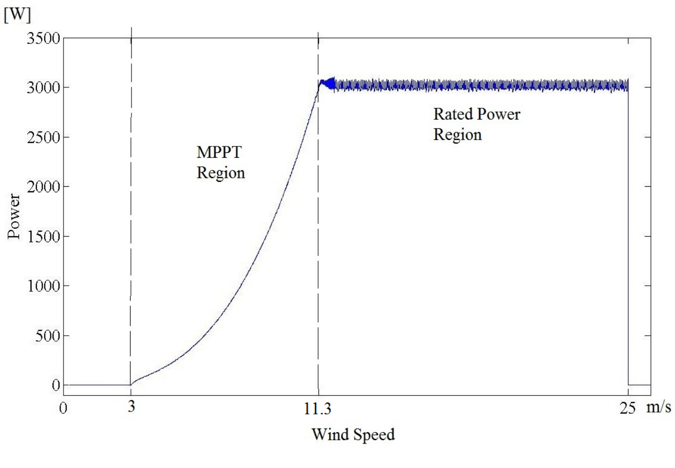

Fig.2. Generated power vs. wind speed for the proposed system

The MPPT control algorithm is based on computing the optimal rotational speed of the wind generator (ω_r) from the wind speed measurements, and further determining the maximum power that can be extracted from the wind. The equations for the optimal rotational speed and maximum power are as follows [4]:

$$\omega_r = \frac{\lambda\_opt}{Rt} \cdot v_w \quad (3)$$

$$P_{\max} = \frac{1}{2} \cdot \pi \cdot R_t^5 \cdot \rho_{air} \cdot \frac{C_{p\_\max}}{\lambda_{\_opt}^3} \cdot \omega_r^3 \quad (4)$$

$$P_{\max} = K_{optim} \cdot \omega_r^3 \quad (5)$$

where R_t is the radius of the turbine-rotor blades and λ_opt is the optimal tip speed ratio.

III. Brushless DC Permanent-Magnet Generator Model and Control

The simulation model of the three-phase star-connected BLDC wind generator is built in MATLAB/ SIMULINK, considering identical resistances and inductances for the three stator-phase windings [5]:

$$v_{ab} = R \cdot (i_a - i_b) + (L - M) \cdot \frac{d(i_a - i_b)}{dt} + e_a - e_b \quad (6)$$

$$v_{bc} = R \cdot (i_b - i_c) + (L - M) \cdot \frac{d(i_b - i_c)}{dt} + e_b - e_c \quad (7)$$

$$i_a + i_b + i_c = 0 \quad (8)$$

where R and L are phase resistance and inductance, M is the mutual inductance, i_k and e_k are the phase currents and the induced back-EMFs, with k being the a, b or c phase .

The motion equation is expressed as:

$$T_e = T_L + J \cdot \frac{d\omega_r}{dt} + B \cdot \omega_r \quad (9)$$

where T_e is the electromagnetic torque developed by the generator, T_L is the load torque given by the wind turbine, J and B represent the rotor inertia and the viscous friction coefficient.

The trapezoidal back-EMF is a function of rotor position, and has the amplitude:

$$E = k_e \cdot \omega_r \quad (10)$$

with k_e being the back-EMF constant.

Considering that back-EMF waveforms are identical in all three stator phases, the back-EMF expression for phase a is [5]:

$$e_a = \begin{cases} (\frac{6 \cdot E}{\pi}) \cdot \theta_r, & 0 < \theta_r < \frac{\pi}{6} \\ E, & \frac{\pi}{6} < \theta_r < \frac{5 \cdot \pi}{6} \\ -(\frac{6 \cdot E}{\pi}) \cdot \theta_r + 6 \cdot E, & \frac{5 \cdot \pi}{6} < \theta_r < \frac{7 \cdot \pi}{6} \\ -E, & \frac{7 \cdot \pi}{6} < \theta_r < \frac{11 \cdot \pi}{6} \\ (\frac{6 \cdot E}{\pi}) \cdot \theta_r - 12 \cdot E, & \frac{11 \cdot \pi}{6} < \theta_r < 2 \cdot \pi \end{cases} \quad (11)$$

The expressions for stator-phases *b* and *c* can be expressed according to (11), knowing that each phase has 120-degree phase shift from the other two phases.

The electromagnetic torque expression results as:

$$T_e = \frac{e_a\, i_a + e_b\, i_b + e_c\, i_c}{\omega_r} \quad (12)$$

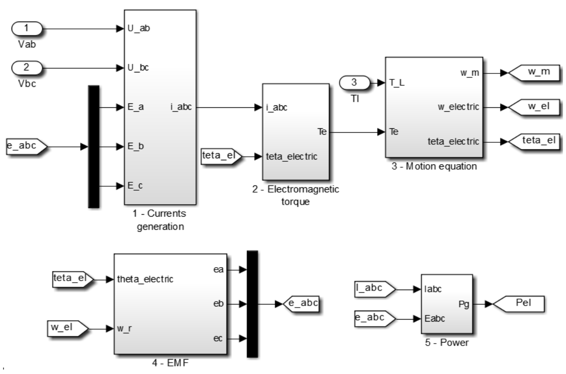

Fig.3 MATLAB/SIMULINK implementation of the BLDC wind-generator model.

The blocks in Fig. 3 represent the implementation of equations (6) to (12) in MATLAB/SIMULINK environment for the BLDC generator model having as main outputs the phase currents, the active power, the back-EMFs, the electromagnetic torque and the speed of the machine. The inputs are represented by the line-to-line stator voltages and the active torque produced by the wind turbine.

The error signal representing the difference between the maximum reference power achieved from the MPPT control and the active power of the generator is processed through PI controller, whose output is then used to obtain the phase reference currents, based on 120°-switching pattern of the generator-side rectifier according to the generator-rotor angular position (Table 1).

TABLE 1: ROTOR ANGULAR POSITION AND CORRESPONDING REFERENCE PHASE CURRENTS

Sector	θ_r	I_{a_ref}	I_{b_ref}	I_{c_ref}
1	330^0-30^0	0	-Ir	Ir
2	30^0-90^0	Ir	-Ir	0
3	90^0-150^0	Ir	0	-Ir
4	150^0-210^0	0	Ir	-Ir
5	210^0-270^0	-Ir	Ir	0
6	270^0-330^0	-Ir	0	Ir

Further, the 'ON/OFF' PWM signals for driving the power devices of the wind generator-side rectifier are achieved from the hysteresis current control after adjusting the generator currents in order to follow the reference ones, as shown in Fig.4. These power electronic devices of the rectifier are considered ideal and without power losses.

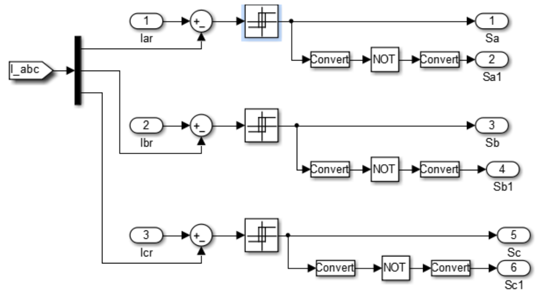

Fig.4. Hysteresis current-control implementation in MATLAB/SIMULINK.

IV. GENERATOR-SIDE PWM RECTIFIER MODEL

The three-phase PWM rectifier connected between the BLDC generator terminals and the DC-link circuit is modeled for six operation states (or sectors), each one (of 60º) consisting of a commutation interval and a conduction interval (Fig.5).

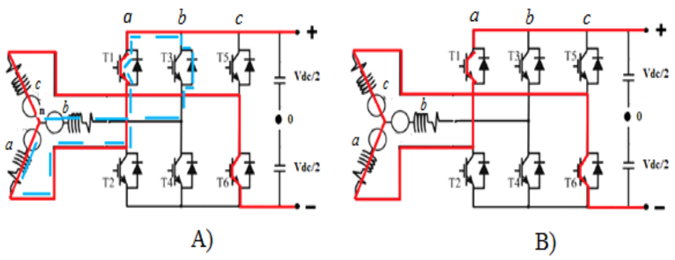

Fig.5. Equivalent circuit and current path corresponding to the commutation interval (A) and conduction interval (B) of one of the six operation states (sectors) of the generator-side three-phase PWM rectifier.

During the commutation interval (Fig.5, *A*) all three phases are active due to the freewheeling current flowing in the phase just switched-off. For example, in Fig. 5, *A*, the main current path is through *a*-phase and *c*-phase windings, allowed by the open upper-side power switch T1 and lower-side power switch T6; the second current path is the freewheeling one through b-phase winding via the upper-side power switch T1 and the upper-side fly-back diode D3. At the end of the commutation interval, the free-wheeling current vanishes and the conduction interval begins (Fig.5,*B*) with only two energized phases, according to the operating states of the PWM rectifier.

TABLE 2: STATOR-PHASE VOLTAGES OF THE BLDC GENERATOR

Sector	θ_r	V_{an}		V_{bn}		V_{cn}	
		Commutation Interval	Conduction Interval	Commutation Interval	Conduction Interval	Commutation Interval	Conduction Interval
1	330^0-30^0	$\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	e_a	$-\frac{2}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Vb01+\frac{(e_b+e_c)}{2}$	$\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Vc0+\frac{(e_b+e_c)}{2}$
2	30^0-90^0	$\frac{2}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Va0+\frac{(e_a+e_b)}{2}$	$-\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Vb01+\frac{(e_a+e_b)}{2}$	$-\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	e_c
3	90^0-150^0	$\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Va0+\frac{(e_a+e_c)}{2}$	$\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	e_b	$-\frac{2}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Vc01+\frac{(e_a+e_c)}{2}$
4	150^0-210^0	$-\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	e_a	$\frac{2}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Vb0+\frac{(e_b+e_c)}{2}$	$-\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Vc01+\frac{(e_b+e_c)}{2}$
5	210^0-270^0	$-\frac{2}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Va01+\frac{(e_a+e_b)}{2}$	$\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Vb0+\frac{(e_a+e_b)}{2}$	$\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	e_c
6	270^0-330^0	$-\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Va01+\frac{(e_a+e_c)}{2}$	$-\frac{1}{3}\cdot Vdc+\frac{e_{sum}}{3}$	e_b	$\frac{2}{3}\cdot Vdc+\frac{e_{sum}}{3}$	$Vc0+\frac{(e_a+e_c)}{2}$

After calculating the stator-phase voltages for commutation and conduction intervals of each of the six operation states of the PWM rectifier, their expressions have been synthesized in Table 2, where $e_{sum}=e_a+e_b+e_c$.

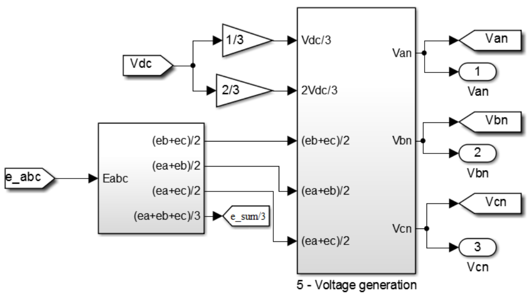

Fig.6. Stator-phase voltage generation block in MATLAB/SIMULINK.

Fig. 6 shows the implementation of Table 2 in MATLAB/SIMULINK environment for the stator-phase voltage determination. This implementation is done for each operation state (sector) of the BLDC generator-side PWM rectifier; detail of one sector is shown in Fig. 7, where V_{ao} and V_{co1} represent the voltages for the upper-side power switch of phase a and the lower-side switch of phase c and S_{ao} and S_{co1} are the corresponding PWM signals. These voltages are obtained as:

$$V_{ao}=\frac{Vdc}{2}*S_{ao}$$
$$V_{co1}=-\frac{Vdc}{2}*S_{co1} \tag{13}$$

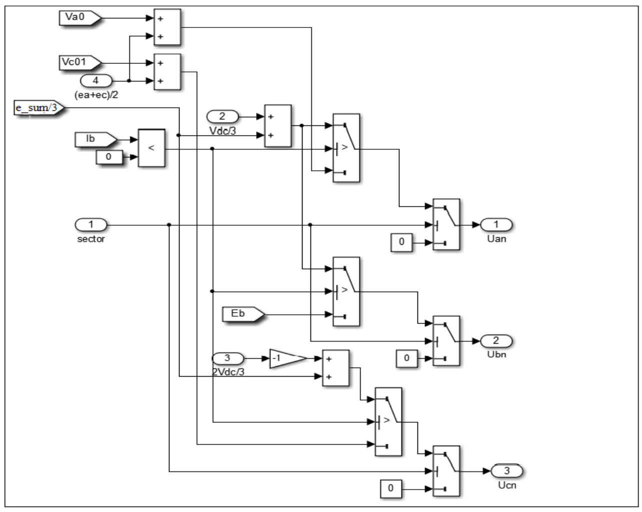

Fig. 7. Scheme of an operation sector of the three-phase PWM rectifier in Matlab/Simulink.

V. CONTROL OF THE GRID-SIDE PWM INVERTER

The electric energy provided by the three-phase BLDC wind generator and transmitted to the DC-link circuit via the PWM rectifier is then applied to a PWM inverter, which is conceived and simulated to keep the DC-link voltage constant at a proper value, and to provide a 50Hz-sinusoidal supply to the consumer loads or utility grid by means of an inductive filter [4] [6].

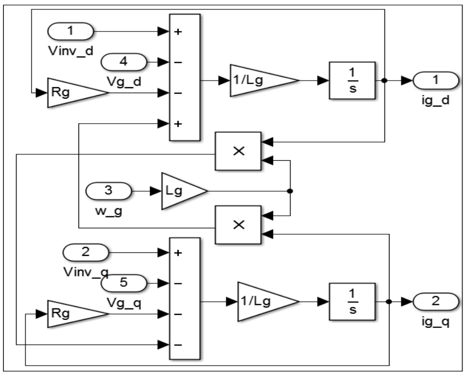

Fig. 8. Grid-connection implementation in MATLAB/SIMULINK.

The dynamic model of the grid connection, developed in the reference frame rotating synchronously with the grid-voltage space vector, is presented in Fig.8.

A. DC-link voltage control

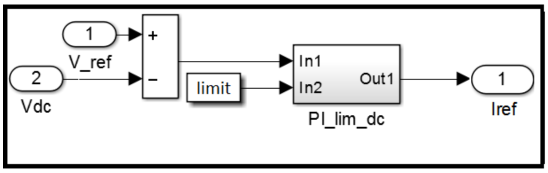

Fig. 9. DC-link voltage control and active reference current value generation.

The measured DC voltage across the capacitor is compared to a reference voltage, as shown in Fig. 9. The DC-link voltage regulation is based on the following equations:

$$\frac{dV_{dc}}{dt} = \frac{1}{C} \cdot (i_1 - i_2) \tag{14}$$

$$i_{dc} = i_1 - i_2 \tag{15}$$

where

$$i_1 = \frac{1}{2} \cdot (S_a \cdot i_a + S_b \cdot i_b + S_c \cdot i_c)$$

$$i_2 = \frac{1}{2} \cdot (S_{ga} \cdot i_{ga} + S_{gb} \cdot i_{gb} + S_{gc} \cdot i_{gc}) \tag{16}$$

with S_i denoting the PWM switching functions for each converter leg of generator-side rectifier and grid-side inverter, respectively.

B. Current control

The currents are controlled using PI controller to provide the reference voltages (Figs. 10 and 11).

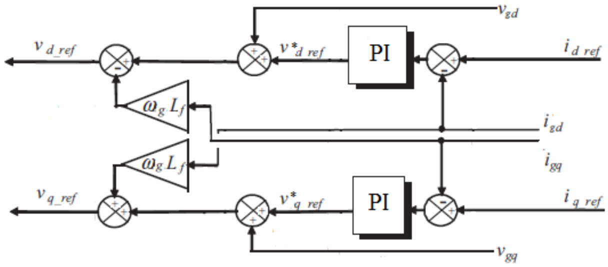

Fig. 10. Block-diagram of the grid-side PWM inverter current control [7].

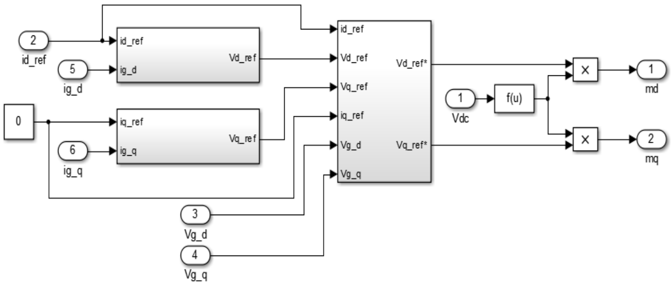

Fig. 11. Grid-side PWM inverter current-control implementation in MATLAB/SIMULINK.

The d-current component is used for DC voltage regulation and the q-current component is used for the reactive power regulation. A zero value was imposed to the q-component of the reference current, in order to maintain a unity power factor.

VI. SIMULATION RESULTS

The overall simulation model of the BLDC generator-based WECS under study is implemented in MATLAB/SIMULINK environment, using a fix-time step solver with a basic time step 10µs.

The active torque on the generator shaft is applied by the wind turbine, and the MPPT control yields the reference power needed to control the BLDC wind generator.

The wind speed profile, shown in Fig. 12, was chosen for simulations in order to analyze the wind turbine performances in MPPT and rated-power regions.

The active power of the BLDC wind generator and the wind turbine power are illustrated in Fig. 13. As it can be seen, starting from 3 m/s wind speed, the turbine is activated and operates under the MPPT region and then at the rated power, when the nominal wind speed is reached.

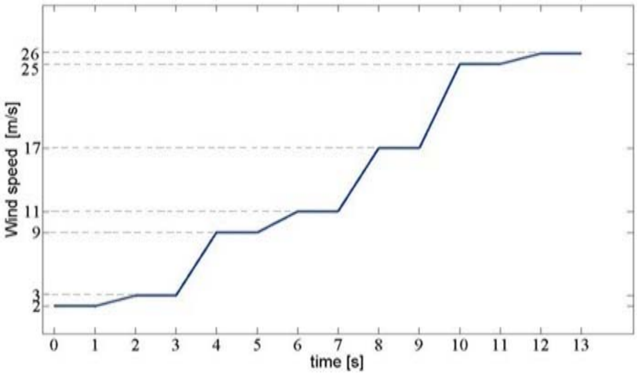

Fig. 12. Wind speed profile.

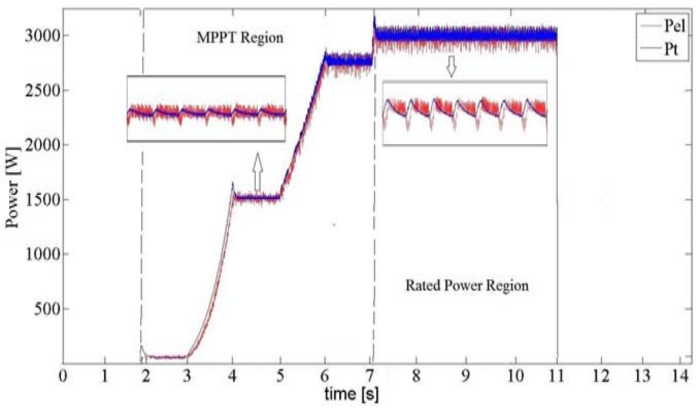

Fig. 13.Wind turbine power and BLDC-generator delivered active power.

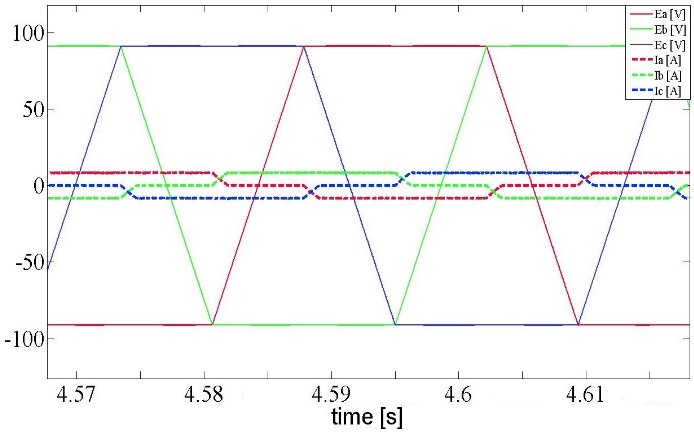

Fig. 14. Three-phase stator currents and back-EMFs of the wind turbine-driven BLDC generator under study.

Fig. 14 shows in detail the waveforms of the BLDC wind-generator stator currents and back-EMFs. Due to the generator operating mode, currents and back-EMFs are time-varying in opposite phase.

The line-to-neutral and line-to-line voltages of the BLDC wind generator, determined by using Table 2, are emphasized in Figs. 15 and 16.

Simulation results for the DC-link voltage regulation are presented in Fig. 17, pointing out rather small variations around the preset value of 530 Vcc for wind speed changes.

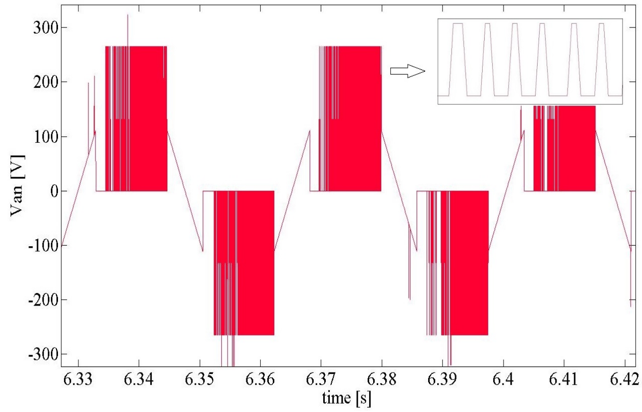

Fig. 15. Line-to-neutral voltage of the wind turbine-driven BLDC generator under study.

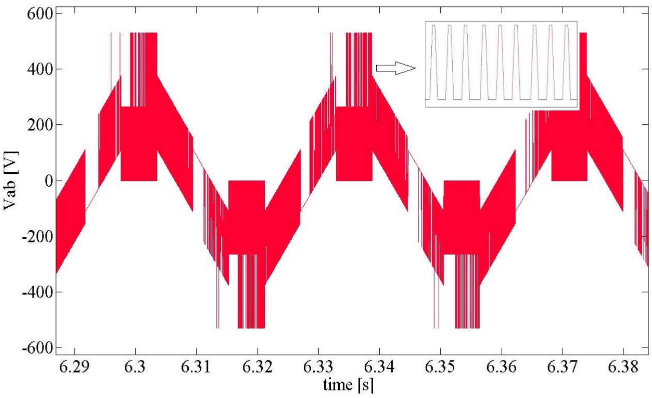

Fig. 16. Line-to-line voltage of the wind turbine-driven BLDC generator under study.

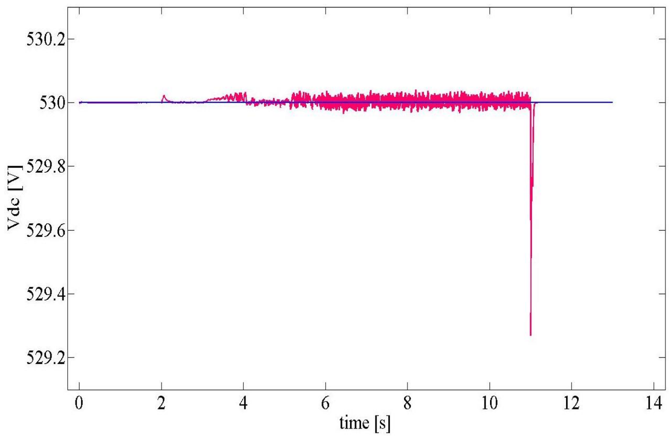

Fig. 17. Simulation results for the DC-link voltage regulation by the grid-side three-phase PWM inverter.

VII. Conclusions

The present paper has proposed and developed in MATLAB/SIMULINK environment a complete simulation model of a small-scale WECS consisting of wind turbine with MPPT control strategy, BLDC permanent-magnet generator, back-to-back PWM converters with their control, inductive filter and utility grid.

Mathematical models and simulation results for all these WECS sub-systems have been given, providing a simulation tool for performance analysis and control design of direct-driven BLDC generator–based WECSs.

A perspective is to use this model in an optimization process to minimize the torque ripple and maximize the energy sent to the grid.

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