CONTROL OF PWM CONVERTERS FOR PMSG WIND TURBINE SYSTEM UNDER GRID VOLTAGE DISTORTION

Tran Trong Hieu, Pham Dinh Tiep, Van Tan Luong*

Ho Chi Minh City University of Food Industry

*Email: *luongvt@hufi.edu.vn*

Received: 25 December 2019; Accepted: 21 February 2020

ABSTRACT

This paper proposes a control method of pulse-width modulation (PWM) converters for permanent magnet synchronous generator (PMSG) small wind turbines under distorted grid voltages. The DC-link voltage can be controlled at the machine-side converter (MSC), while the grid-side converter (GSC) controls the grid active power for a maximum power point tracking (MPPT). With the proposed method, the control performance of the DC-link voltage is improved since it is not directly affected from the grid voltage distortion. Also, the grid current is controlled to be sinusoidal, based on the excellent proportional-resonant (PR) controllers. The validity of the control algorithm has been verified by the simulation of the 2.68 kW-PMSG wind turbine system.

Keywords: Current control, DC-link voltage, distorted voltage, PMSG, wind turbine.

1. INTRODUCTION

Recently, the wind power generation has been considered as one of the most rapidly growing energy sources in the world since the natural resources are becoming exhausted. In the variable-speed wind turbine (WT) systems, a direct-drive wind energy conversion system based on PMSGs has a lot of advantages such as no gearbox, high precision, high power density, and simple control method, except initial installation costs [1-2]. For the grid interface, the PWM inverters with the *LCL* (inductor-capacitor-inductor) filters are commonly applied, which gives many benefits such as low filter size, high dynamic performance of the current control, and lower cost, in comparison to only *L* filter [3-6].

Various control methods for a single-phase PWM inverter have been suggested, in which the grid current control is performed, based on the PR or the proportional-integral (PI) regulators [7-12]. With these methods, however, regulating the fundamental component of the grid current has been done without considering the mitigation of the current harmonics [7-9]. Synchronizing the single-phase inverters with the grid is performed, where a phase locked-loop (PLL) based on multi-harmonic decoupling cell was applied [10-11]. However, this method is complex and the execution time is so long. Another method employing a repetitive controller was introduced in [12], where the distorted grid current caused by the nonlinear loads is suppressed by an active power filter. Nevertheless, the case of the grid voltage distortion has not been considered in the research. Also, the implementation of the repetitive controller in the practical system requires a high number of repetitive taps and a long computation time.

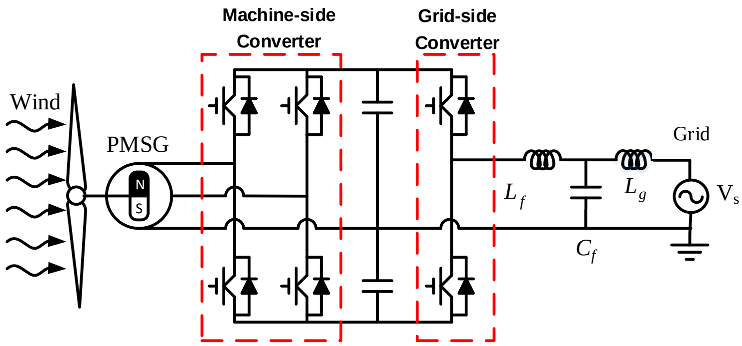

Figure 1. Schematic of small wind turbine system equipped with PMSG.

In the PMSG wind turbine system, the generator is connected to the grid through the PWM converters, of which configuration is shown in Figure 1. Conventionally, DC-link voltage is controlled to be a constant at the grid-side converter, while the machine-side converter controls the active power for MPPT. In the case of the grid voltage distortion, the GSC in the conventional control method may be out of control. When the grid fault happens, the DC-link voltage is excessively increased due to the continuous operation of WT and generator. However, the overall generated output power cannot deliver to the grid fully.

A method is proposed that the DC-link voltage control schemes are employed at the machine-side converter instead of the grid-side converter. Also, the grid current control based on the proportional-resonant controllers is regulated to be sinusoidal. The simulation results for the 2.68 kW-PMSG wind turbine system are provided to verify the effectiveness of the proposed method.

2. PROPOSED CONTROL SCHEME

2.1. Grid-side converter control for MPPT

2.1.1. Power reference

The mechanical power, P_t, captured by the wind turbine is expressed as [13]

$$P_t = 0.5\rho\pi R^2 C_p(\lambda) v_w^3 \qquad (1)$$

Where ρ is the air density [kg/m^3], R is the radius of the turbine blade [m], v_w is the wind speed [m/s], and $C_p(\lambda)$ is the power coefficient which can be expressed as a function of the tip-speed ratio λ. The tip-speed ratio is defined as

$$\lambda = \frac{\omega_r R}{v_w} \qquad (2)$$

Where ω_r is the generator speed.

The maximum power coefficient, C_{pmax}, corresponds to the optimal tip-speed ratio λ_{opt}. Hence, the turbine speed should be changed with the wind speed so that the optimum tip-speed ratio is maintained.

The power reference, P_t^* can be expressed as [13]

$$P_t^* = K_{opt} \cdot \omega_r^3 \qquad (3)$$

Where $$K_{opt} = 0.5\rho\pi C_{p\max}\frac{R^5}{\lambda_{opt}^3}$$

Figure 2 shows the characteristics of wind turbine, in which the relationship among the mechanical power, rotor speed and the wind speed is illustrated. The MPPT curve in Figure 2 is obtained when the grid power reaches the power reference given in (3) with the converters loss neglected. The MPPT control is performed by the grid converter, as shown in Figure 3.

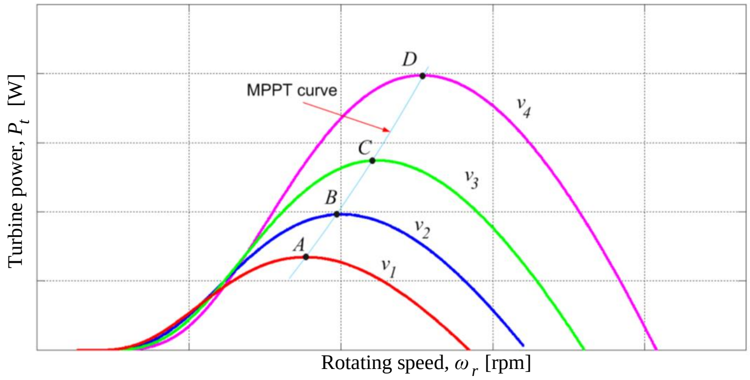

Figure 2. Characteristics of the wind turbine.

2.1.2. Current controller under distorted grid voltage

The grid-side converter should operate to deliver the active power from the turbine to the grid with the sinusoidal grid current even at the distorted grid voltage condition. First of all, the grid voltage is used for the PLL algorithm to detect the phase angle, θ_e. The amplitude of the grid current, I_{amp}^*, is decided by the reference power, P_t^*, from the MPPT control scheme, which is expressed as [4, 5]

$$I_{amp}^* = \frac{2P_t^*}{E_{mag}} \quad (4)$$

where E_{mag} is the magnitude of the fundamental component of the grid voltage.

Then, the grid current reference, i_s^{1st*} is generated as

$$i_s^{1st*} = I_{amp}^* \sin(\theta_e) \quad (5)$$

A multi-PR controller is utilized for regulating the grid current, where the PR^3, PR^5,…, PR^n with cut-off frequencies corresponding to the 3rd, 5th, and nth order harmonics are used to eliminate the harmonic components of the grid current, and the PR^{res} is utilized to damp the resonance in the inverter current.

The grid voltage usually contains the harmonic components due to a presence of the nonlinear loads. In this work, the effect of the low-order harmonics, that is 3rd, 5th and 7th order harmonics, is only taken into account.

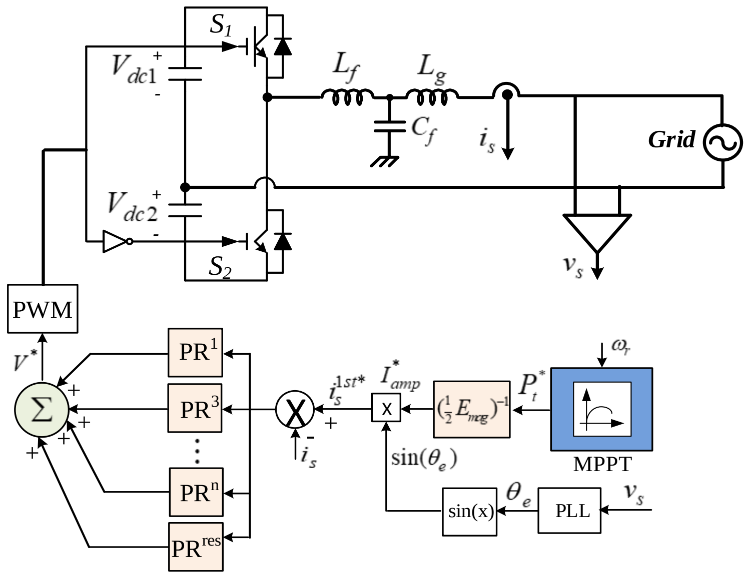

Figure 3. Control block diagram of the grid-side converter.

2.2. Machine-side converter control for DC-link voltage

The control loop of the pulse-width modulation (PWM) converter usually consists of the outer DC-link voltage controller and inner AC input current controller. The integral-proportional (IP) DC-link voltage controller is preferred since it gives less overshoot than the PI-type [14]. The output of the DC-link voltage controller is given by

$$I_{qs}^{*} = \left[-K_p V_{dc} + K_i \int \left(V_{dc}^{*} - V_{dc} \right) dt \right] + P_{out} / \left(1.5 V_{qs} \right) \qquad (6)$$

where V_{dc} and V_{dc}^{*} are the measured DC-link voltage and its reference value, respectively, P_{out} is the output power of the PWM converter, and V_{qs} is the q-axis stator voltage.

The last term in (6) is a feed-forward control component for the output power (P_{out}). The power balance of the input and output of the DC-link is expressed as

$$\frac{C}{2}\frac{dV_{dc}^{2}}{dt} = P_{in} - P_{out} \qquad (7)$$

where C is the DC-link capacitance and $P_{in} = 1.5\, V_{qs} I_{qs}$ is the input power of the PWM converter, which is obtained from (7).

Substituting (6) into (7), equation is rewritten as

$$\frac{C}{2}\frac{dV_{dc}^{2}}{dt} = 1.5 V_{qs} \left[-K_p V_{dc} + K_i \int \left(V_{dc}^{*} - V_{dc} \right) dt \right] \qquad (8)$$

Expanding Taylor series of the DC-link voltage at operating point (V_{dc0}) and neglecting higher-order terms,

$$V_{dc}^{2} = V_{dc0}^{2} + 2\left(V_{dc} - V_{dc0} \right) \qquad (9)$$

From (8) and (9), the transfer function of the DC-link voltage and its reference can be derived from power balance of the input and output of the DC-link as [14]

$$\frac{V_{dc}(s)}{V_{dc}^*(s)} = \frac{\frac{1.5V_{qs}K_i}{CV_{dc}^*}}{s^2 + \frac{1.5V_{qs}K_p}{CV_{dc}^*}s + \frac{1.5V_{qs}K_i}{CV_{dc}^*}} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (10)$$

where $V_{qs}=V_{max}$ is the q-axis generator output voltage, ω_n is the undamped natural frequency and ξ is the damping ratio. From (10), the proportional and integral gains are obtained as

$$K_p = 2\xi\omega_n \frac{CV_{dc}^*}{1.5V_{qs}} \quad (11)$$

$$K_i = \omega_n^2 \frac{CV_{dc}^*}{1.5V_{qs}} \quad (12)$$

The control structure of the machine-side converter consisting of the outer DC-link voltage control loop and the inner current control loop are illustrated in Figure 4. The control of the two-leg three-phase PWM converter has been described in details [15-17].

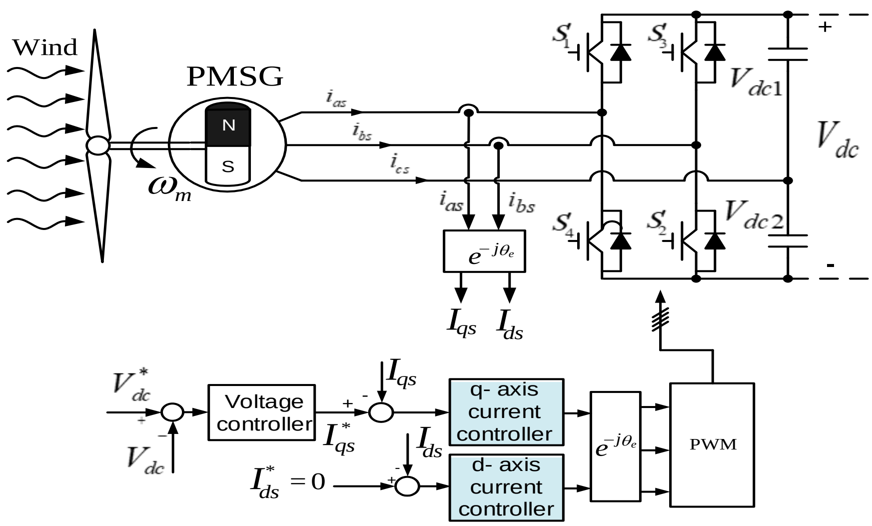

Figure 4. Control block diagram of the machine-side converter.

3. SIMULATION RESULTS

The PSIM simulation for a 2.68 kW-PMSG wind turbine system has been carried out to verify the validity of the proposed control scheme. The system parameters are listed in Table 1.

Table 1. System parameters for simulation

Parameter	Value
PMSG	2.68 kW, 6 poles R_s = 0.49 Ω, L_s = 5.35 mH, J = 0.00331 kg.m^2
Single-phase PWM converter	110 V, 60 Hz, 540 V_{DC} L_g = 0.3 mH, L_f = 3 mH, C_f = 4.75 μF
Switching frequency	10 kHz (both converters)

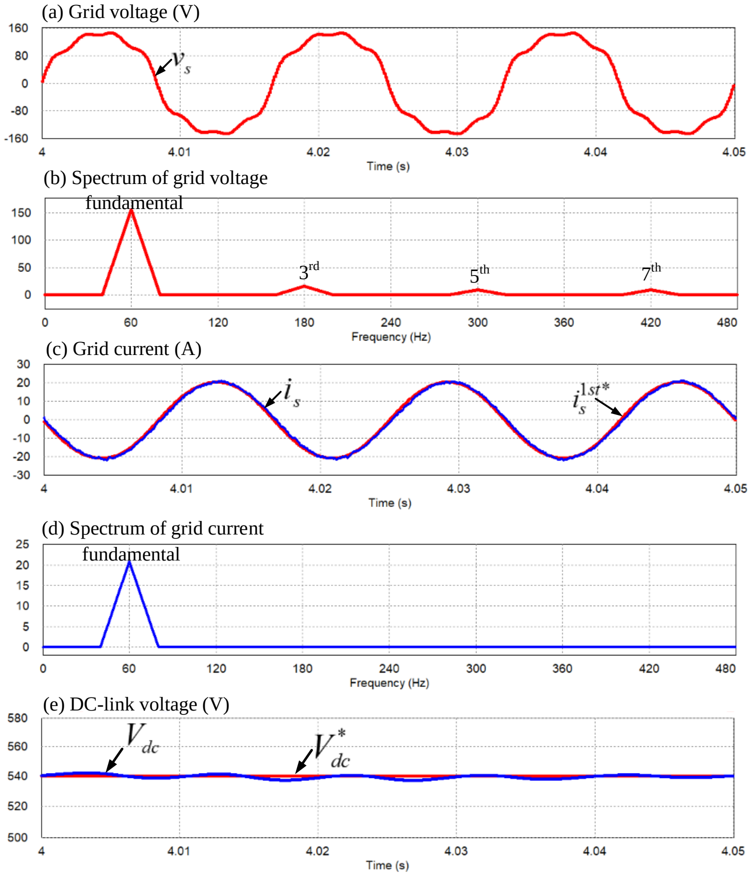

Figure 5. Control performance of single-phase converter at distorted grid voltage.

Figure 5 shows the control performance of the grid-side converter under the distorted grid voltage, which contains the 10%, 8%, and 6% of the 3rd, 5th, and 7th order harmonic components, respectively, as shown in Figure 5(a). The wind speed is assumed to be 13 m/s. It can be clearly seen that the FFT (fast Fourier transform) spectra of the fundamental and harmonic components from Figure 5(a) are obtained as illustrated in Figure 5(b). Figure 5(c) shows the control performance of the grid current under the distorted grid voltage by applying the multi-PR controller. As can be seen, the grid current is almost sinusoidal. The high-order harmonic components of the grid current have been significantly decreased as shown in Figure 5(d). Figure 5(e) illustrates the DC-link voltage, in which the measured value follows its reference well and its ripples are so low (0.5%).

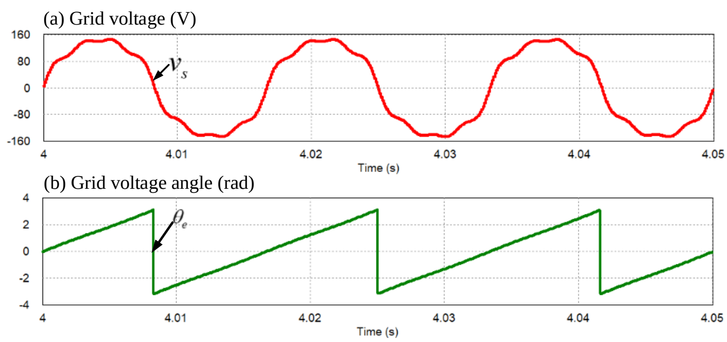

Figure 6. PLL performance in the grid voltage distortion.

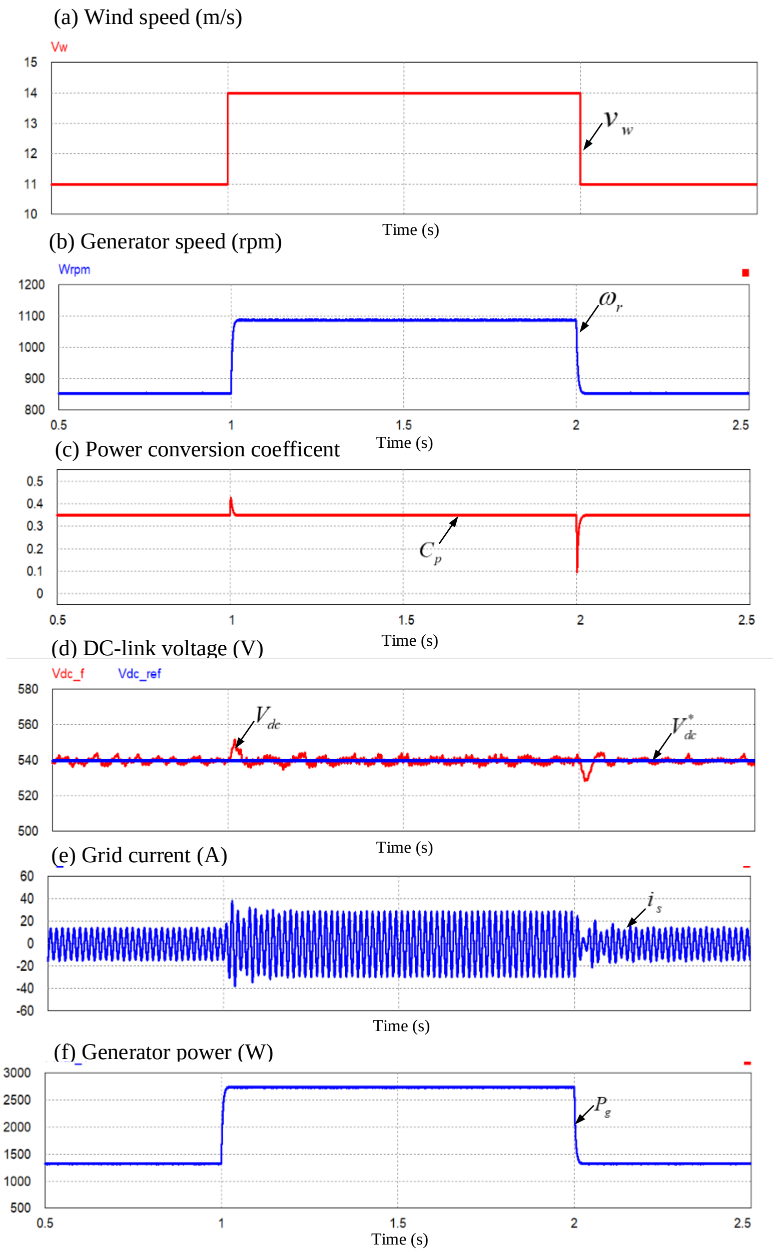

Figure 7. Control performance of system at stepwise change of wind speed.

The single-phase PLL performance under the grid voltage distortion is shown in Figure 6. Even the grid voltage contains the harmonic components as shown in Figure 6(a), the PLL method still gives good performance. As illustrated in Figure 6(b), the phase angle is satisfactory.

The response of the whole system in the machine and grid sides for a stepwise change of the wind speed was investigated in Figure 7. The wind speed pattern applying to the turbine blade is shown in Figure 7(a), where the wind speed is increased from 11 m/s to 14 m/s at the moment of 1 s and reduced to 11 m/s at 2 s. The generator speed in Figure 7(b) is varied according to the wind speed, by which the tip-speed ratio is optimized and the maximum value of the power conversion coefficient is kept at 0.4 in the steady state condition as shown in Figure 7(c). With the wind speed pattern in Figure 7(a) and under grid voltage distortion, the DC-link voltage is controlled to follow its reference value (540 V) well in the steady and transient states, as shown in Figure 7(d). Also, the current flowing into the grid (see 7(e)) is also varied according to the wind speed change and this grid current is still sinusoidal in the steady state. Likewise, the active power produced from the generator is changed. As can be clearly seen in Figure 7(f), the generator power can reach 1300 W and 2680 W at the wind speeds of 11 m/s and 14 m/s, respectively.

6. CONCLUSION

This paper has proposed a control method of the small wind turbine using PMSGs for the grid voltage distortion. In this method, the DC-link voltage control is performed by the MSC, not by the GSC which is usually used. The GSC controls the grid power according to the MPPT strategy. For distorted grid voltage conditions, the grid current control based on PR controllers has been applied for the high-order harmonic components of the grid current. The validity of the control algorithm has been verified by simulation results for a 2.68 kW PMSG wind power system.

REFERENCES

1. Chinchilla M., Arnaltes S., and Burgos J. C. - Control of permanentmagnet generators applied to variable-speed wind-energy systems connected to the grid, IEEE Transactions on Energy Conversion **21** (1) (2006) 130-135.
2. Polinder H., A van der Pijl F. F., and Tavner P. - Comparison of direct-drive and geared generator concepts for wind turbines, IEEE Transactions on Energy Conversion **21** (3) (2006) 543-550.
3. Liserre M., Blaabjerg F., and Hansen S. - Design and control of an LCL-filter-based three-phase active rectifier, IEEE Transactions on Industrial Application **41** (5) (2005) 1281-1291.
4. Balasubramanian A. K., John V. - Analysis and design of split-capacitor resistive-inductive passive damping for LCL filters in grid-connected inverters, IET Power Electronics **6** (9) (2013) 1822-1832.
5. Mukherjee N., De D. - Analysis and improvement of performance in LCL filter-based PWM rectifier/inverter application using hybrid damping approach, IET Power Electronics **6** (2) (2013) 309-325.
6. Heo H. J., Im W. S., Kim J. S., and Kim J. M. - A capacitance estimation of film capacitors in an LCL-filter of grid-connected PWM converters, Journal of Power Electronics **13** (1) (2013) 94-103.
7. Song H. S., Keil R., Mutschler P., Weem V., Nam K. - Advanced control scheme for a single-phase PWM rectifier in traction application, Industry Applications Society Annual Meeting (IAS), (2003) 1558-1565.
8. Nguyen T. H., Lee D. C., Lee S. G. - Sinusoidal current control of single-phase PWM converters under voltage source distortion using composite observer, Transactions of KIPE **16** (2011) 466-476.
9. Lumbreras C., Guerreo J. M., Garcia P., Briz F., and Reigosa D. D. - Control of a small wind turbine in the high wind speed region, IEEE Transactions on Power Electronics **31** (10) (2016) 6980-6990.

10. Hadjidemetriou L., Kyriakides E., Yang Y., and Blaabjerg F. - A synchronization method for single-phase grid-tied inverters, IEEE Transactions on Power Electronics **31** (3) (2016) 2139-2149.
11. Hadjidemetriou L., Yang Y., Kyriakides E., and Blaabjerg F. - A synchronization scheme for single-phase grid-tied inverters under harmonic distortion and grid disturbances, IEEE Transactions on Power Electronics **32** (4) (2016) 2783-2793.
12. Bojoi R. I., Limongi L. R., Rooiu D., Tenconi A. - Enhanced power quality control strategy for single-phase inverters in distributed generation systems, IEEE Transactions on Power Electronics **26** (3) (2011) 798-806.
13. Akhmatov V. - Analysis of dynamic behavior of electric power systems with large amount of wind power, Ph.D. dissertation, Department of Electrical Power Engineering, Technical University of Denmark, Kongens Lyngby, Denmark (2003).
14. Jang J.-I. and Lee D.-C. - High performance control of three-phase PWM converters under non-ideal source voltage, IEEE International Conference on Industrial Technology (2006) 2791-2796.
15. Lee D. C. and Kim Y. S. - Control of single-phase-to-three-phase AC/DC/AC PWM converters for induction motor drives, IEEE Transactions on Industrial Electronics **54** (2) (2007) 797-804.
16. Park H. G., Jang S. H., Lee D. C., and Kim H. G. - Cost-effective converters for micro wind turbine systems using PMSG, Journal of Power Electronics **8** (2) (2008) 156-162.
17. Nguyen T. H., Jang S.-H., Park H.-G., and Lee D.-C. - Sensorless control of PM synchronous generators for micro wind turbines, in Proceedings of IEEE 2nd International Power Energy Conference (2008) 936-941.

TÓM TẮT

ĐIỀU KHIỂN BỘ CHUYỂN ĐỔI CÔNG SUẤT PWM CHO HỆ THỐNG TUA-BIN GIÓ CÔNG SUẤT NHỎ DÙNG MÁY PHÁT PMSG KHI ĐIỆN ÁP LƯỚI BỊ MÉO DẠNG

Trần Trọng Hiếu, Phạm Đình Tiệp, Văn Tấn Lượng*
Trường Đại học Công nghiệp Thực phẩm TP.HCM
*Email: *luongvt@hufi.edu.vn*

Bài báo này đề xuất một phương pháp điều khiển bộ chuyển đổi công suất PWM cho hệ thống tua-bin gió dùng máy phát điện gió đồng bộ nam châm vĩnh cửu (PMSG) khi điện áp lưới bị méo dạng. Điện áp tụ DC-link có thể được điều khiển bởi bộ chuyển đổi công suất phía máy phát (MSC), trong khi đó bộ chuyển đổi phía lưới (GSC) điều khiển công suất tác dụng lưới bằng phương pháp tìm kiếm điểm phát công suất cực đại (MPPT). Với phương pháp đề xuất, vận hành điều khiển của điện áp tụ DC-link được cải thiện tốt do tụ DC-link không bị ảnh hưởng trực tiếp từ sự méo dạng điện áp lưới. Ngoài ra, dòng điện lưới được điều khiển hình sin nhờ các bộ điều khiển cộng hưởng tỷ lệ (PR). Tính xác thực của thuật toán điều khiển đã được kiểm chứng bằng mô phỏng của hệ thống tua-bin gió dùng máy phát PMSG côngsuất 2,68 kW.

Từ khóa: Điều khiển dòng điện, điện áp tụ DC-link, điện áp méo dạng, tua-bin gió.