International Journal of Smart Grid and Clean Energy

Optimal Efficiency Analysis of MW-Level Direct-Drive Wind Generation System

Jingyuan Yin*, Xinmin Jin, Xuezhi Wu

School of Electrical Engineering, Beijing Jiaotong University, Haidian District 100044, Beijing, China

---

Abstract

Given the MW-level direct-drive wind generation system, the optimal efficiency of generators and converters is analyzed. The loss model of the generators including iron loss and the neutral point clamping three-level converters is established. Based on the loss model and the voltage, current limit, the generators and converters, optimal efficiency analytic expressions of direct current are obtained by analyzing the relationships of direct current and loss under given torque, and then optimal efficiency solution of the wind system is got. Finally, Simulation and experiment results on a 2MW "back to back" PWM converter prototype indicate: in the fixed torque and speed condition, such optimal efficiency control is more efficient than the traditional control strategy not only on the generator or converter efficiency but also on the wind generation system.

Keywords: Wind generation system, permanent magnet synchronous generator, three-level converter, optimal efficiency

---

1. Introduction

Direct-driven wind generation system is considered to be an important research direction in wind generation technology area due to its superiorities of being gearless, no slip rings and brushes, flexible power control ability, etc. [1-3].

By the "back to back" PWM converter, PMSG connects to the grid. Generator-side converter responds the torque command from the wind turbine main control, realizing the maximum power pursuit tactic. The frequently-used vector control on generator-side converter includes zero d-axis current vector control, constant mutual flux linkage control and field weakening control [4-6]. Different control strategy response the different stator voltage, current and power factor which influence the efficiency of the generator and converter, so the optimal efficiency analysis for the wind power system exist significance.

The power losses in PMSG are copper and iron losses in the stator, mechanical losses and additional losses. The copper losses which are caused by the fundamental harmonic component of the stator current, and the iron losses, which are caused by the fundamental harmonic components of the air gap linkage flux, belong to the controllable losses. The mechanical and additional losses are uncontrollable. Using the control algorithms of maximum torque per ampere line (MTPA) and field-weakening can separately reduce the copper and iron losses [6-7]. Reference [8] proposed a loss model including the iron losses and develop the loss minimizing algorithm on the PMSG, but it ignore the mechanical losses. Reference [9] analyzed the speed factor for generator efficiency which is not satisfied on the requirement of the wind power. Reference [10] established an on-line optimal efficiency strategy based on a new loss model.

Actually, the wind generation system includes two parts which are the generator and convertor. However the previous papers all ignore the convertor losses when they considered the optimal efficiency on PSMG. Adopting the traditional efficiency-optimization control raises the converter losses and makes the system efficiency down. Reducing losses not only improves the efficiency but makes the heat sink

---

* Manuscript received July 14, 2012; revised August 15, 2012.

Corresponding author. Tel.: +86-10-51684337; *E-mail address*: 10117339@bjtu.edu.cn.

cost down. In engineering application, because of the design defect of heat sink, leads the system can not reach the heat stability and changing the hest sink increases the research cost. This condition needs the appropriate and flexible control to achieve the different aim on the generator and convertor losses. In the [11][12], a practical loss calculation method is derived based on the analysis of the conduction and switching principles of the neutral point clamping three-level converter. The converter losses have the direct relationship with modulation, stator current and power factor. So when consider the optimal efficiency, the generator, converter and system losses should all be forced.

Initially, based on the [9] [11], the generator loss model including the iron losses and the converter loss model for the SPWM modulation are established. Then with the given torque command, the relationship between generator or converter efficiency and direct axis current components is deeply analyzed, thus get the direct current analytic expression of the each optimal efficiency. Finally, together with two loss models, the optimum method of the system efficiency is found. The computer simulations and experimental results verify the validity of efficiency optimization.

2. Loss Model Of Direct-Drive Wind Generation System

2.1. Loss model of PMSG

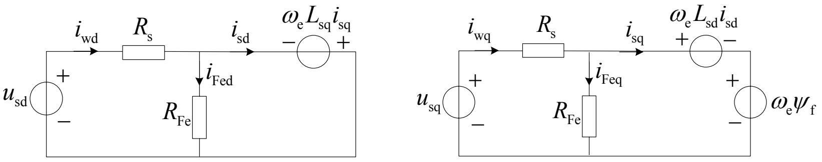
The voltage and electromagnetic torque equations for a PMSM in the synchronous frame are given by

$$\begin{cases} u_{\mathrm{sq}} = R_{\mathrm{s}} i_{\mathrm{sq}} + L_{\mathrm{sq}} \dfrac{di_{\mathrm{sq}}}{dt} + \omega_{\mathrm{e}} L_{\mathrm{sd}} i_{\mathrm{sd}} + \omega_{\mathrm{e}} \psi_{\mathrm{f}} \\ u_{\mathrm{sd}} = R_{\mathrm{s}} i_{\mathrm{sd}} + L_{\mathrm{sd}} \dfrac{di_{\mathrm{sd}}}{dt} - \omega_{\mathrm{e}} L_{\mathrm{sq}} i_{\mathrm{sq}} \end{cases} \tag{1}$$

$$T_{\mathrm{e}} = 1.5p[\psi_{\mathrm{f}} i_{\mathrm{sq}} + (L_{\mathrm{sd}} - L_{\mathrm{sq}}) i_{\mathrm{sd}} i_{\mathrm{sq}}] \tag{2}$$

where u_{sd}, u_{sq} are direct and quadrature axis terminal voltage; i_{sd}, i_{sq} are the torque current in the direct and quadrature axis components; L_{sd}, L_{sq} are direct and quadrature axis inductances; R_{s} is stator resistance; ω_{e} is electrical angular speed; p *is* generator pole pairs; ψ_{f} is permanent magnet rotor flux.

The controllable losses are copper losses and iron losses. The basic hypotheses of the PMSG are that both the spatial distribution of the magnetic flux in the air gap is sinusoidal and the magnetic circuit is linear. Moreover, a dedicated parameter has been considered to account for the losses in the stator. In particular, the iron losses are modelled by a resistance R_{Fe} and the copper losses are R_{s} which are inserted in the traditional equivalent circuits of a synchronous machine so that the losses depend on the air-gap linkage flux and stator current. The quivalent circuit of PMSG in d-q reference frame considering iron loss is shown in Fig.1[9].Where i_{Fed}, i_{Feq} are d- and q-axis iron loss current and expressed as (3); i_{wd}、i_{wq} are d- and q-axis terminal current, given by (4).



(a) d-axis equivalent circuit (b) q-axis equivalent circuit

Fig.1. Equivalent circuit of PMSG in d-q reference frame considering iron loss.

$$\begin{cases} i_{\mathrm{Fed}} = -\omega_{\mathrm{e}} L_{\mathrm{sq}} i_{\mathrm{sq}} / R_{\mathrm{Fe}} \\ i_{\mathrm{Feq}} = \omega_{\mathrm{e}} (L_{\mathrm{sd}} i_{\mathrm{sd}} + \psi_{\mathrm{f}}) / R_{\mathrm{Fe}} \end{cases} \tag{3}$$

$$\begin{cases} i_{\mathrm{wd}} = i_{\mathrm{sd}} + i_{\mathrm{Fed}} = i_{\mathrm{sd}} - \omega_{\mathrm{e}} L_{\mathrm{sq}} i_{\mathrm{sq}} / R_{\mathrm{Fe}} \\ i_{\mathrm{wq}} = i_{\mathrm{sq}} + i_{\mathrm{Feq}} = i_{\mathrm{sq}} + \omega_{\mathrm{e}} L_{\mathrm{sd}} i_{\mathrm{sd}} / R_{\mathrm{Fe}} + \omega_{\mathrm{e}} \psi_{\mathrm{f}} / R_{\mathrm{Fe}} \end{cases} \tag{4}$$

From Fig. 1, the copper loss P_{Cu} and the iron P_{Fe} loss are expressed by

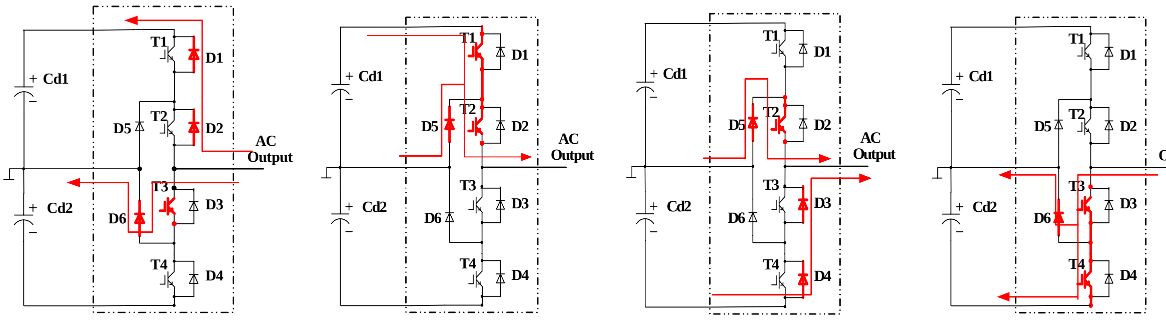
$$\begin{cases} P_{\mathrm{Cu}} = 1.5R_{\mathrm{s}}(i_{\mathrm{wd}}^2 + i_{\mathrm{wq}}^2) \\ P_{\mathrm{Fe}} = 1.5R_{\mathrm{Fe}}(i_{\mathrm{Fed}}^2 + i_{\mathrm{Fed}}^2) = \dfrac{1.5}{R_{\mathrm{Fe}}}\omega_{\mathrm{e}}^2[(L_{\mathrm{sq}}i_{\mathrm{sq}})^2 + (L_{\mathrm{sd}}i_{\mathrm{sd}} + \psi_{\mathrm{f}})^2] \end{cases} \tag{5}$$

By adding P_{Cu} and P_{Fe} the total electrical losses P_{loss} are calculated:

$$P_{\mathrm{loss}} = P_{\mathrm{Cu}} + P_{\mathrm{Fe}} = 1.5R_{\mathrm{s}}(i_{\mathrm{wd}}^2 + i_{\mathrm{wq}}^2) + \frac{1.5}{R_{\mathrm{Fe}}}\omega_{\mathrm{e}}^2[(L_{\mathrm{sq}}i_{\mathrm{sq}})^2 + (L_{\mathrm{sd}}i_{\mathrm{sd}} + \psi_{\mathrm{f}})^2 \tag{6}$$

2.2. The loss model of power device

The converter losses mainly reflect in power semiconductor losses which can be classified as conduction losses, turn-on switching losses, and turn-off switching losses. They are related to the static parameter of device, output current, and power factor and modulation depth. The conduction loss is calculated in a straightforward manner as the product of the device current and the forward saturation voltage and switching losses are the turn on switching energy and turn off switching energy which is got from the device datasheet. Single phase topology of the NPC three-level converter is analyzed as the converter loss model. With the sinusoidal pulse width modulation, the analytic expression of power device losses can be calculated.



(a) $-\theta$~0 (b) 0~$\pi-\theta$ (c)$\pi-\theta$~π (d)π~$2\pi-\theta$

Fig.2. Commutations in different switching states.

The commutations in different switching states are shown in Fig. 2, where the load current $i_{\mathrm{L}}=I_{\mathrm{M}}\ sin(wt)$ and modulation voltage $U_{\mathrm{S}}=U_{\mathrm{M}}\ sin(wt+\theta)$. The load current is positive when it outflows the converter and is negative when flows into converter. When the converter is working in the area of ($-\theta$~0) as shown Fig. 2 (a), the modulation voltage change the states between +1/2 U_{dc} and 0. The load current flows into converter through the D1 and D2 when the voltage is +1/2 U_{dc} and the T3 and D6 when the voltage is 0. Other three areas of switching states are shown in Fig. 2 (b) (c) (d). So based on the commutation process the conduction losses and switching losses of T1 in fundamental period are expressed by

$$\begin{cases} P_{on-T1} = \dfrac{1}{2\pi}\int_0^{\pi-\theta}(V_{T1} + i_L r_{T1}) i_L M \sin(wt+\theta) dwt \\ P_{sw-T1} = (E_{on-T1} + E_{off-T1}) f_S \dfrac{1}{2\pi}\int_0^{\pi-\theta} \sin wtdwt \end{cases} \tag{7}$$

where (V_{T1} $+i_{\mathrm{L}}$ r_{T1}) are forward saturation voltage; $E_{\mathrm{on}\text{-}T1}$ and $E_{\mathrm{off}\text{-}T1}$ which are directly proportional to the current are turn on switching and turn off switching energy for the peak current of the device. Fig. 2 shows that the working condition of T1 is the antithesis to T4, similarly T2 to T3, D1 to D2, D3 to D4, D5 to D6. So the conduction losses and switching losses for other power device are expressed as

$$\begin{cases} P_{on-T2} = \dfrac{1}{2\pi}\int_0^{\pi-\theta}(V_{T2}+i_L r_{T2})i_L dwt + \dfrac{1}{2\pi}\int_{\pi-\theta}^{\pi}[V_{T2}+i_L r_{T2}]i_L[1+M\sin(wt+\theta)]dwt \\ P_{sw-T2} = (E_{on-T2}+E_{off-T2})f_S\dfrac{1}{2\pi}\int_{\pi-\theta}^{\pi}\sin(wt)dwt \end{cases} \tag{8}$$

$$\begin{cases} P_{on-D3} = \dfrac{1}{2\pi}\int_{\pi-\theta}^{\pi}[V_{D3}+i_L r_{D3}]i_L[-M\sin(wt+\theta)]dwt \\ P_{sw-D3} = E_{off-D3}f_S\dfrac{1}{2\pi}\int_{\pi-\theta}^{\pi}\sin(wt)dwt \end{cases} \tag{9}$$

$$\begin{cases} P_{on-D5} = \dfrac{1}{2\pi}\int_0^{\pi-\theta}(V_{D5}+i_L r_{D5})i_L[1-M\sin(wt+\theta)]dwt + \\ \qquad \dfrac{1}{2\pi}\int_{\pi-\theta}^{\pi}[V_{D5}+i_L r_{D5}]i_L[1+M\sin(wt+\theta)]dwt \\ P_{sw-D5} = E_{off-D5}f_S\dfrac{1}{2\pi}\int_0^{\pi}\sin(wt)dwt \end{cases} \tag{10}$$

From the conduction loss expressions, following conclusion can be reached [13]: 1) the conduction loss is approximately linear relationship with load current; 2) the conduction loss of anti-parallel diode can be ignored.

3. Optimal Efficiency Analysis of Wind Generation System

3.1 The analytic expression of direct axis current for PSMG optimal efficiency

From (6), a simple consideration can be drawn: at fixed values of both torque and speed, the total controllable losses depend only on the i_{sd} value, then P_{loss} can be minimized by controlling the current space vector. The relationship between P_{loss} and i_{sd} can be got by uniting the equation (3)~(6). Take the derivative of P_{loss} and considering the i_{sd} is a variable that is $dP_{\mathrm{loss}}/di_{\mathrm{sd}}=0$. In this condition the i_{sd} expression satisfies the optimal control for PMSG efficiency. Then take the i_{sd} into (2), the i_{sq} command is acquired. As follows (11) (12):

$$\frac{dP_{\mathrm{loss}}}{di_{\mathrm{sd}}} = 3R_{\mathrm{s}}i_{\mathrm{sd}} + 3\frac{R_{\mathrm{s}}+R_{\mathrm{Fe}}}{R_{\mathrm{Fe}}{}^{2}}\omega_{\mathrm{e}}^{2}L_{\mathrm{sd}}(L_{\mathrm{sd}}i_{\mathrm{sd}}+\psi_{\mathrm{f}}) - \frac{R_{\mathrm{s}}}{R_{\mathrm{Fe}}}\omega_{\mathrm{e}}i_{\mathrm{sq}}(L_{\mathrm{sq}}-L_{\mathrm{sd}}) = 0 \tag{11}$$

$$i_{\mathrm{sd}} = -\frac{(R_{\mathrm{s}}+R_{\mathrm{Fe}})\omega_{\mathrm{e}}^{2}L_{\mathrm{sd}}\psi_{\mathrm{f}} + R_{\mathrm{s}}R_{\mathrm{Fe}}^{2}\omega_{\mathrm{e}}i_{\mathrm{sq}}(L_{\mathrm{sd}}-L_{\mathrm{sq}})}{(R_{\mathrm{s}}+R_{\mathrm{Fe}})\omega_{\mathrm{e}}^{2}L_{\mathrm{sd}}{}^{2} + R_{\mathrm{s}}R_{\mathrm{Fe}}^{2}} \tag{12}$$

Let I_{smax} be the maximum current magnitude. Then, the current limit is appeared as a circle. Neglecting ohmic drop across the stator resistance and the cross coupling, the voltage constraint is obtained from (1) such that

$$i_{\mathrm{sd}}{}^{2} + i_{\mathrm{sq}}{}^{2} = I_{\mathrm{smax}}{}^{2} \tag{13}$$

$$(L_{\mathrm{sd}}i_{\mathrm{sd}}+\psi_{\mathrm{f}})^{2} + (L_{\mathrm{sq}}i_{\mathrm{sq}})^{2} \le (U_{\mathrm{smax}}/\omega_{\mathrm{e}})^{2} \tag{14}$$

where U_{smax} is the maximum terminal voltage. The voltage limit (14) appears as an ellipse in the (i_{sd}, i_{sq}) plane. Note that that the ellipse shrinks to($-\psi_{\mathrm{f}}/L_{\mathrm{sd}}$, 0) as the speed increases and the constant torque line of interior PMSM is denoted hyperbolic curve. When considering the generator losses in fixed torque, whether the current command calculated within the voltage and current limit must be noticed [14]. In order to effectively explain how to select optimal solution with the voltage and current limit, a set of parameters for 2WM wind generation system is given by Table 1. The voltage and current limit curve, rated torque curve and optimal efficiency curve of generator are plotted in the same coordinate as Fig. 3.

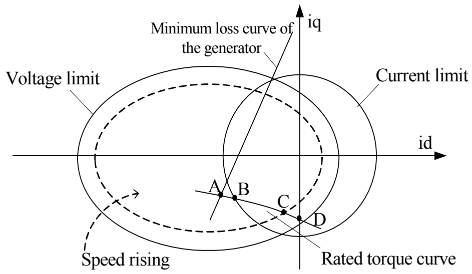


Fig. 3. The voltage and current limit figure with the minimum loss curve of the generator.

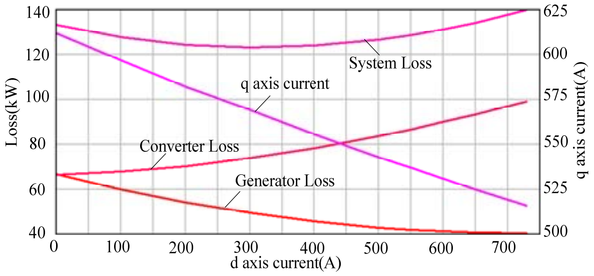


Fig.4. The relationship between losses and d axis current in rated power condition.

Table1: Parameters of PMSG power system based on NPC PWM converter

Parameters	Value	Parameters	Value
Rated speed ω_e / (rad/s)	335	Permanent magnet flux ψ_f / wb	6.5
Number of pole p	8	Voltage limit U_{smax} / V	2600
Stator resistance R_s / Ω	0.01744	Current limit I_{smax} / A	900
Equivalent iron loss resistance R_{Fe} / Ω	204	Rated torque T_e / Nm	5970
q axis inductance L_{sq} / mH	6.35	Switching frequence f_S / Hz	1950
d axis inductance L_{sd} / mH	4.7		

Because the voltage ellipse shrinks as the speed increases, the ellipse of rated speed condition is the maximum voltage limit. When the value of torque increases the torque curve moves down. As shown in Fig. 3, the optimal point A exceeds the current limit in rated torque condition. How to select the optimal point to achieve the minimum loss between B and D is thought about. Take the second derivative of P_{loss} for the i_{sd} , the result expressed as

$$\frac{d^2P_{\text{loss}}}{di_{\text{sd}}{}^2} = 3R_s + 3\frac{R_s + R_{\text{Fe}}}{R_{\text{Fe}}{}^2}\omega_e^2 L_{\text{sd}}{}^2 > 0 \tag{15}$$

Equation (15) shows the optimal point A is the minimal value that means on the right of point A, the more value of d-axis current (negative), the more losses on generator. So in this condition, the point B is the optimal efficiency for generator. According to (2) (13), the threshold torque can be got meaning that when torque command is greater than this, the voltage and current limit must be considered.

3.2 The analytic expression of direct axis current for converter optimal efficiency

By (7)~(10), the single phase NPC converter losses are expressed

$$P_{\text{sw-loss}} = (E_{\text{on-T2}} + E_{\text{off-T2}} + E_{\text{off-D3}})f_{\text{S}}\frac{1}{2\pi}\int_{\pi-\theta}^{\pi}\sin(wt)dwt + E_{\text{off-D5}}f_{\text{S}}\frac{1}{2\pi}\int_0^{\pi}\sin(wt)dwt + k_1 I_M \tag{16}$$

The conduction loss is approximately linear relationship with load current and the k1 is the proportionality factor. Meanwhile $E_{\text{on-T1}}$ and $E_{\text{off-T1}}$ are directly proportional to the stator current, so (16) rewrites as

$$P_{\text{sw-loss}} = k_2 I_{\text{M}} f_{\text{S}}\frac{1}{2\pi}(1-\cos\theta) + k_3 I_{\text{M}} f_{\text{S}}\frac{1}{2\pi} + k_1 I_M \tag{17}$$

$$\cos\theta = 2T_e\omega_e / 3U_s I_{\text{M}} \tag{18}$$

where k2 is the proportionality factor for the sum of $E_{\text{on-T2}}$, $E_{\text{off-T2}}$, $E_{\text{off-D3}}$ and k3 is the proportionality factor for $E_{\text{off-D5}}$. Consider power factor as (18) Where I_{M} and U_s are the stator peak value of the phase voltage and phase current. Take the derivative of $P_{\text{sw-loss}}$ for the variable i_{sd} , the result expressed as

$$\frac{dP_{\text{sw-loss}}}{di_{\text{sd}}}=\frac{(k_2+k_3)i_{\text{sd}}f_{\text{S}}+2\pi k_1 i_{\text{sd}}}{2\pi I_{\text{M}}}+\frac{k_2 T_{\text{e}}\omega_{\text{e}}f_{\text{S}}(L_{\text{sd}}{}^{2}i_{\text{sd}}+L_{\text{sd}}\psi_{\text{f}})}{2\pi U_{\text{s}}{}^{2.5}} \tag{19}$$

The T_e and w_e is fixed and value of T_e is negative. (19) consists of two polynomials and the value of second polynomial is much smaller than the first polynomial, so the value of (19) is the negative no matter what the parameter of the generator and converter. Because of this the converter losses $P_{\text{sw-loss}}$ is a decreasing function for i_{sd} that means the more value of i_{sd}, the fewer converter losses. If the $i_{\text{sd}}=0$ is specified in the voltage and current limit, zero d-axis current vector control is the optimal strategy for converter losses. When $i_{\text{sd}}=0$ exceeds the limit, just like the dash line in Fig.3, point C is the best.

3.3 The optimal efficiency analytic expression of direct axis current for the wind generation system

When the efficiency of generation system is pursued, the generator and converter losses are all considered and the optimal d-axis current is calculated. Based on the Tab.1 and (6) (16), the relationship between losses and d axis current in rated 2WM power condition is shown as Fig.4. As shown the more absolute value of d-axis current, the more converter losses and the fewer generator losses, so the curve of system losses presents a concave which means in the fixed power condition, existing a optimal d-axis current makes the system efficiency best. Uniting the equation (11) and (19), the analytic expression (20) between d-axis and q-axis current is obtained. The intersection of (20) and torque curve is the optimal efficiency of the wind generation system.

$$i_{\text{sq}}=-\sqrt{\frac{c^2 i_{\text{sd}}{}^{2}}{a i_{\text{sd}}{}^{2}+2ab i_{\text{sd}}+b^2}-i_{\text{sd}}{}^{2}} \tag{20}$$

where $a=3R_{\text{s}}+3\omega_{\text{e}}^{2}L_{\text{sd}}{}^{2}/R_{\text{Fe}}$, $b=3\omega_{\text{e}}^{2}L_{\text{sd}}\psi_{\text{f}}/R_{\text{Fe}}$, $c=\dfrac{(k_2+k_3)f_{\text{S}}+2\pi k_1}{2\pi}$.

4. Simulation analysis and experimental results

In order to verify the efficiency optimization control strategy, a simulation model of direct-driven wind generation system based on active-rectify topology has been built. At the same time, a 2MW “back to back” NPC PWM converter is researched. The generator-side converter connects the PMSG and the line-side converter connects the grid according to the 3kV/10kV step-up transformer. The system parameter is showed in Table 1. In the experimental control system, one digital signal processor (TMSS320F28335) is employed. With the zero d-axis current control, the relationship between the current and torque is linear, so the current command is easily calculated. But the maximum efficiency control needs calculate the intersection between optimal current and torque curve. Because Dsp can not finish the real-time computation, the optimal d axis current curve of the generator and system losses in different torque condition should be drawn as shown in Fig. 5. Fig. 6 is the stator line-to-line voltage and phase current in rated power condition with the zero d-axis current control. It implements stability of the system.

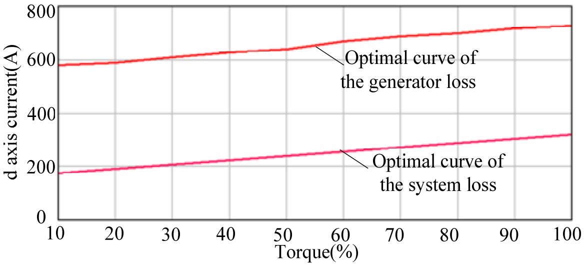


Fig. 5. Optimal d axis current curve of the generator and system losses in different torque condition.

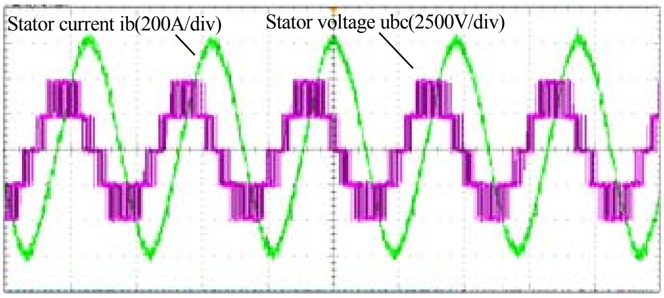


Fig. 6. Stator line-to-line voltage and phase current.

With the constant speed operation (N=400rpm) and the different torque command, the wind system loss, generator loss and converter loss are separately measured in three different kinds of efficiency optimization control. Fig. 7 (a) shows the system loss obviously declines in the full-scale range by the proposed the system efficiency control compared with zero d-axis current control. The system efficiency can be improved 1% in rated power condition. Fig. 7 (b) is the generator loss which is reduced 25kW still compared zero d-axis current control. Fig. 7 (c) is converter loss which includes power device loss and filter loss. The device loss of generator-side converter is controllable. So the loss minimization control of converter is effective.

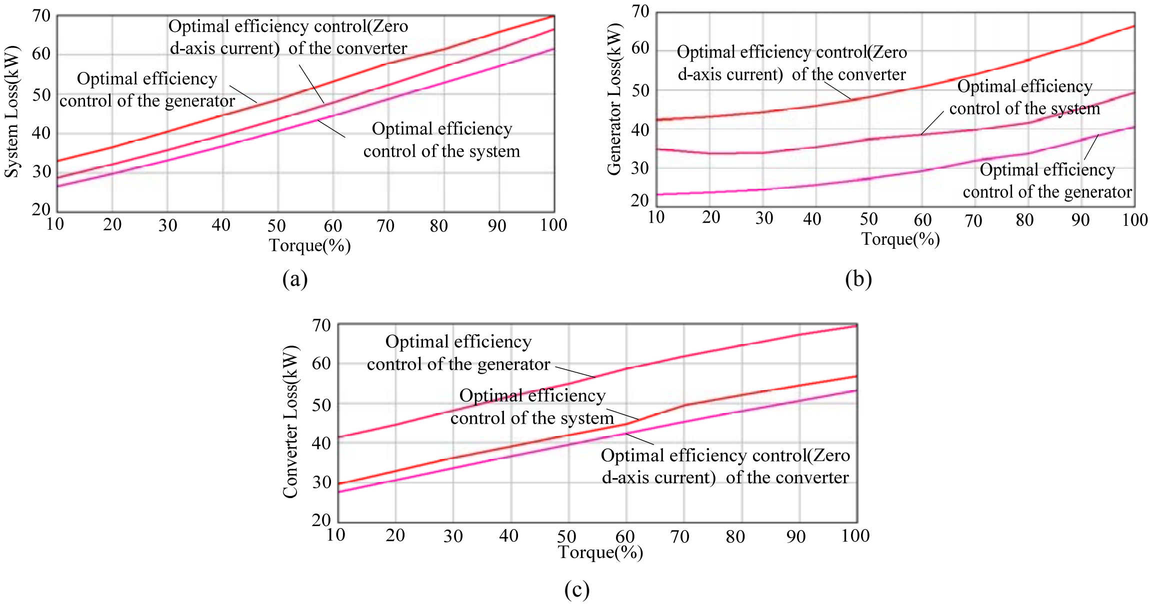


Fig. 7. Loss comparsion with different optimal efficiency control: (a) system loss;(b) generator loss;(c) converter loss.

5. Conclusion

The paper established the loss model of the direct-drive wind generation system which includes generator loss and converter loss. The generator loss is analysed with copper loss and iron loss. The converter loss model bases on the neutral point clamping three-level converter. According to the loss model, the generators and converters, optimal efficiency analytic expressions of direct current are obtained under given torque and speed with the voltage, current limit, then the optimal efficiency solution of the whole system is got. The significance of the optimal method not only reflects the wind generation system efficiency improving but also can reduce the generator or converter losses when the ability of heat sink weakens to keep the thermal equilibrium. Simulation analysis and experimental results have shown that the proposed optimal efficiency control significantly minimizes the system losses and greatly improves the efficiency compared with the conventional control method.

References

[1] Polinder H, de Haan SWR, Dubois M R, *et al*. Basic operation principles and electrical conversion system of wind turbines. *Energy and Power Engineering*, 2005; 15(4):43-50.

[2] Li H, Chen Z. Overview of different wind generator systems and their comparisons. *IET Renewable Power Generation*, 2008; 2(2):123-138.

[3] Xue Y, Han L, Li H. Overview on direct-drive permanent magnet synchronous generator for wind power. *Electric Machines & Control Application*, 2008; 35(4):1-5, 21.

[4] Song SH, Kim SI, Hahm NK. Implementation and control of grid connected AC-DC-AC power converter for variable speed wind energy conversion system. In: *Proc. of the 18th Annual IEEE Applied Power Electronics Conference and Exposition,* 2003:154-158.

[5] Yao C. *Research on Full-scale Grid-connected Power Conversion Technology for Direct-driven Wind Generation System*. Bei Jing: The University of Beijing Jiao Tong.

[6] Bianchi N, Bolognani S. Parameters and volt-ampere ratings of a synchronous motor drive for flux-weakening applications. *IEEE Trans. on Power Electronics*, 1997; 12(5):895-523.

[7] Bae BH, Schulz PN, *et al*. New field weakening technique for high saliency interior permanent magnet motor. In: *Proc. of Industry Applications Conference*, 2003:898-905.

[8] Di Tommaso AO, Miceli R, Galluzzo GR, *et al*. Efficiency control for permanent magnet synchronous generators. In: *Proc. of IEEE International Conference on Industrial Technology*, 2006:2079-2084.

[9] Duan J, Zhao K, Sun L. Optimal efficiency joint control for permanent magnet synchronous generators. *Proceedings of the CSEE*, 2012; 27(3):49-55.

[10] Lee J, Nam K, Choi S, *et al*. Loss minimizing control of PMSM with the use of polynomial approximations. *IEEE Transactions on Power Electronics*, 2009; 24(4):1071-1082.

[11] Jing W, Tan G, Ye Z. Losses calculation and heat dissipation analysis of high-power three-level converters. *IEEE Transactions on Power Electronics*, 2011; 26(2):134-140.

[12] Du Y, Liao M. Losses calculation of IGBT module and heat dissipation system design of inverters. *Electric Drive Automation*, 2011; 33(1): 42-46.

[13] Wang J, Chen Q, Jiang W. Analysis of conduction losses in neutral-point-clamped three-level inverter. *Transactions of China Electrotechnical Society*, 2007; 22(3):66-71.

[14] He Y, Wen Y, XU J. High-power permanent magnet flux-weakening strategy based on multi mode svpwm. *Proceedings of the CSEE*, 2012; 27(3):92-99.