Performance Enhancement of PMSG Systems with Control of Generator-side Converter Using d-axis Stator Current Controller

Kitsanu Bunjongjit[*1], Non-member and **Yuttana Kumsuwan**[*2], Member

ABSTRACT

This paper presents a performance enhancement of a permanent magnet synchronous generator (PMSG) system with control of generator-side converter for a wind turbine application. This method uses zero d-axis stator current control to minimize winding losses of the generator. The electromagnetic torque of the generator is correlated with the magnitude of the q-axis stator current, while the d-axis stator current is regulated at zero, the control scheme decouples the dq-axis stator current control through a vector control for the generator-side converter. This paper also presents mathematical analysis of the active power and stator power factor, and the maximum power point tracking (MPPT) operation. Simulation results are provided to guarantee the proposed control scheme, in which the performance enhancement and efficiency are evaluated.

Keywords: Permanent-Magnet Synchronous Generator (PMSG), Wind Generation, Generator-side Control, Maximum Power Point Tracking (MPPT), D-axis Stator Current Control.

1. INTRODUCTION

Over recent years, wind energy has been considered as one of the most significant renewable energy sources. Among the existing wind power generation systems, its generators can be categorized into four main types [1], [2]: 1) the doubly fed induction generator 2) the squirrel cage induction generator 3) the wound rotor synchronous generator and 4) the permanent magnet synchronous generator. Nowadays, the wind energy industry uses PMSG for direct grid-connection because it gives higher efficiency and has no slip ring maintenance. Thus, the lightweight and low maintenance features can be obtained in this type of wind power generation system [3], [4].

The configuration of PMSG wind power generation system is shown in Fig. 1. Presently, there are a few papers examining for the generator-side wind power generation control [5]-[7]. For this reason, this paper focuses on the analysis of the generator-side converter d-axis stator current control approaches for control of PMSG wind turbines. The generator-side can be controlled with various schemes, the control schemes are separated into three control strategy types to execute different intentions; 1) zero d-axis stator current (ZDSC): control to achieve a linear relationship between the stator current and the generator torque 2) maximum torque per- ampere (MTPA): control to produce maximum generator torque with a minimum stator current and 3) unity power factor (UPF): control to maintain power factor at one. However, there are other techniques for the generator-side control presented in [5]-[6], namely, a vector control. The control strategy in the generator-side has two control loops, three PI controllers and many measured variables from the generator-side and the grid-side which leads to a seriously complicated control design. Compared with the proposed control strategy in [7], ZDSC control can provide a simple topology solution and excellent generator integration performance such as a simple control algorithm, generating maximum efficiency, and minimizing system losses. However, the major drawback of ZDSC control is not suitable for salient-pole synchronous generators and it is not optimal for the operation range over the base speed.

The main objective of this paper is to describe the generator-side performance using ZDSC control scheme. The wind turbine PMSG generation system operates in the base speed range. The dynamic model equations of the PMSG and ZDSC control schemes are analyzed in a space vector diagram and phasor diagram, respectively. The stator power factor and the generator active power are discussed. Furthermore, comparison between the generator active power and the mechanical power are studied to establish a performance enhancement for the system. Additionally, the MPPT method is implemented which can provide the optimal torque control along the whole operation range. Simulation results are shown to verify the performance of the proposed control strategy for PMSG generation system.

2. PRINCIPLES OF THE PMSG WIND ENERGY SYSTEM

The configuration of PMSG wind power generation system is shown in Fig. 1. The PMSG converts the mechanical power from the wind turbine into ac electrical power, which is then converted to dc power

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* The authors are with Department of Electrical Engineering, Faculty of Engineering, Chiangmai University, Thailand., E-mail: kaengio@gmail.com[1] and yt@eng.cmu.ac.th[2].

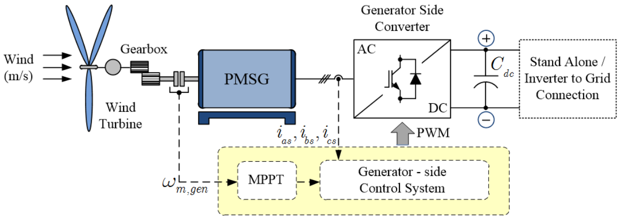

Fig.1: *Configuration of PMSG system with control of generator-side converter using d-axis stator current control scheme.*

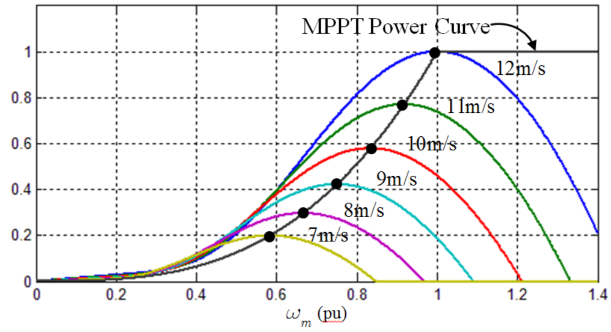

Fig.2: *Wind turbine power-speed characteristic and maximum power point tracking method operation.*

through a converter with dc link supplying either the stand-alone load or the inverter to a grid-connection. By using an additional inverter, the PMSG can supply the ac electrical power with constant voltage and frequency to the power grid. Two control functions are implemented on the generator-side: one is to extract the maximum power available from the wind turbine and the other is to optimize generator operation, which will be discussed in the following description.

2.1 Maximum Power Point Tracking (MPPT) with Optimal Torque Control

The mechanical torque T_m, which is captured by a wind turbine, can be expressed as [8]

$$T_m = \frac{1}{2}\rho A v_w^3 C_p / w_m r_T \tag{1}$$

where ρ is the air density, A is the sweep area of the wind turbine V_w, is the wind velocity, r_T is the turbine radius, w_m is the generator speed, and C_p is the power coefficient of the wind turbine.

From (1), in order to capture the maximum mechanical power from a wind turbine at different wind speeds, see the wind turbine power-speed characteristics and maximum power point operation that are shown in Fig. 2. It can be seen that the trajectory of the black circles represents a MPPT power curve, which can be expressed in the term of the mechanical torque $T_{m,MPPT}$ by the following equations

$$T_{m,MPPT} = K_{opt} w_m^2 \tag{2}$$

where K_{opt} is the coefficient for the optimal torque, which can be calculated according to the rated parameters of the generator.

2.2 Dynamic Model of PMSG

In order to get a dynamic model for the PMSG that easily allows us to define the generator-side control system. Fig. 3 shows an arbitrary dq-axis dynamic model of PMSG in the rotor field synchronous reference frame. The voltage equations of the PMSG are given by

$$v_{ds} = -\left(R_s i_{ds} + L_d \frac{di_{ds}}{dt}\right) + w_r L_q i_{qs}, \tag{3}$$

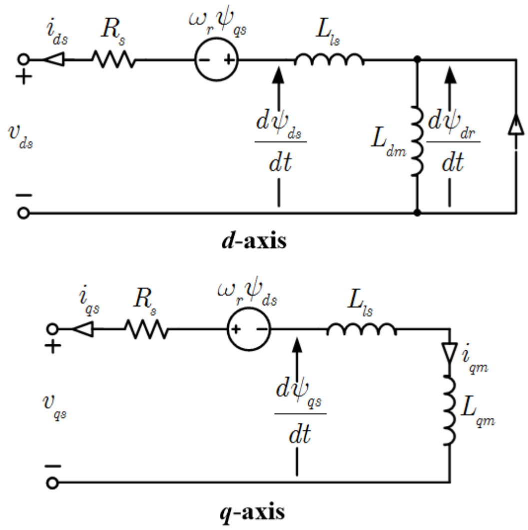

Fig.3: *Arbitrary dq-axis dynamic model of the PMSG in the rotor field synchronous reference frame (dq-axis).*

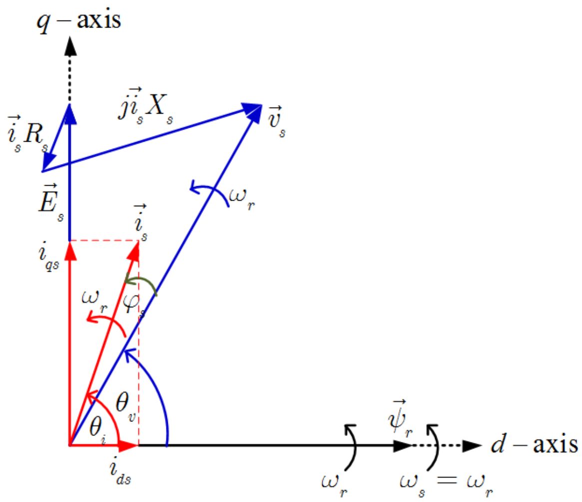

Fig.4: *A space vector diagram of the PMSG.*

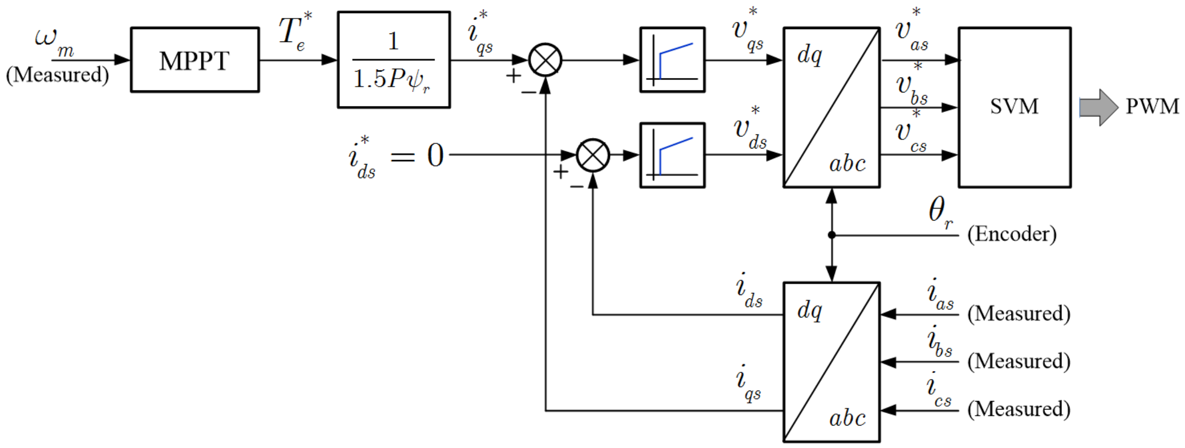

Fig.5: *Block diagram of the generator-side control algorithm based on the zero d-axis stator current control.*

$$v_{qs} = -\Big(R_s i_{qs} + L_q \frac{di_{qs}}{dt}\Big) - w_r L_d i_{ds} + w_r \overrightarrow{\psi}_r, \quad (4)$$

where R_s is the PMSG stator resistance, $\overrightarrow{\psi}_r$ is the rotor flux-linkages, L_d and L_q are the stator dq-axis self-inductances, i_{ds} and i_{qs} are the dq-axis stator currents, and w_r is rotor speed.

The generator torque T_e of the PMSG can be calculated by

$$T_e = \frac{3P_p}{2}\Big[\overrightarrow{\psi}_r i_{qs} - (L_d - L_q) i_{qs} i_{ds}\Big], \quad (5)$$

where p_p is the pole pairs.

Following the arbitrary dq-axis dynamic model of the PMSG in Fig. 3, a space vector diagram for the PMSG is expressed in Fig. 4. The space vector diagram is derived under the rotor flux-linkage which is aligned with the d-axis of the synchronous reference frame. All vectors in this diagram together with dq-axis frame rotate in space at the synchronous speed, which is also the rotor speed of the generator w_r.

3. CONTROL OF THE GENERATOR-SIDE CONVERTER

3.1 Zero d-axis Stator Current (ZDSC) Control

The proposed generator-side control scheme is shown in Fig. 5. MPPT and ZDSC controls are implemented on the generator-side. The generator torque reference T_e^* is generated by the MPPT method in agreement with the measured generator speed w_m. The generator torque reference produces q-axis stator current reference i_{qs}^*. The d-axis generator current reference i_{ds}^* is set according to the generator operation requirements. The measurement of the three-phase stator currents i_{as}, i_{bs}, i_{cs} are transformed into dq-axis stator currents i_{ds},i_{qs} according to the measured rotor flux angle θ_r. The measured dq-axis stator currents are subtracted with their current reference. The errors are sent to PI controllers which lead to obtaining the dq-axis reference voltages v_{ds}^*, v_{qs}^* for the converter. The dq-axis reference voltage v_{ds}^*, v_{qs}^* are transformed into three-phase reference voltages $v_{as}^*, v_{bs}^*, v_{cs}^*$ and sent to the PWM generation block using SVM modulation. The proposed generator-side control will be discussed in more detail in the following.

Zero d-axis stator current control is applied to improve the efficiency of the machine. With this control, the d-axis stator current component i_{ds} is then controlled to be zero ($i_{ds} = 0$) to minimize the generator current and thereby reduce the winding losses. With the d-axis stator current kept at zero, the stator current is equal to its q-axis component i_{qs} is

$$i_s = \sqrt{(i_{ds})^2 + (i_q s)^2} = i_{qs}. \quad (6)$$

According to the ZDSC Control scheme, the generator torque T_e from (5) can be simplified to

$$T_e = \frac{3}{2} p_p \psi_r i_q s = \frac{3}{2} p_p \psi_r i_s. \quad (7)$$

Thus, the q-axis stator current reference i_{qs}^* can be determined as the following

$$i_{qs}^* = \frac{T_e^*}{1.5 p_p \psi_r} \quad (8)$$

Considering the relation stated on (7) and (8), the generator torque generated by the q-axis stator current reference and the generator torque can also be controlled directly by the q-axis stator current. Furthermore, the dq-axis reference voltages for the converter can be derived from (3) and (4) as

$$v_{ds}^* = v'_{ds} + w_r L_q i_{qs}, \quad (9)$$

$$v_{qs}^* = v'_{qs} - w_r L_d i_{ds} + w_r \overrightarrow{\psi}_r. \quad (10)$$

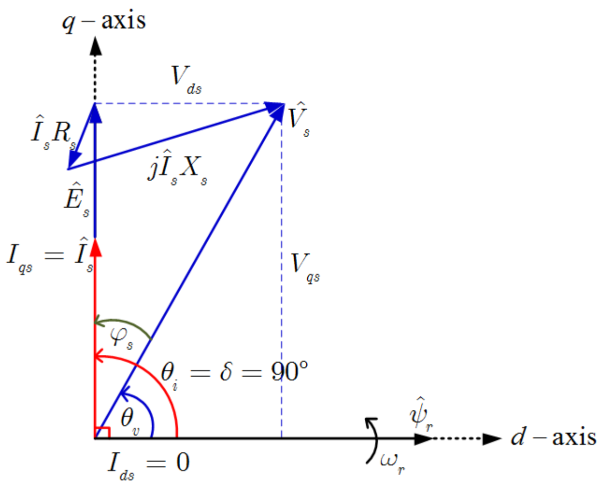

Fig.6: *A phasor diagram of the PMSG with ZDSC control.*

3.2 ZDSC Control Performance Analysis

In order to analyse the performance of the ZDSC control, the control strategy was discussed based on the steady state condition, from (3) and (4), the steady-state voltage equations of the PMSG can be expressed as the following

$$V_{ds} = -R_s I_{qs} - w_r L_q I_{qs}, \tag{11}$$

$$V_{qs} = -R_s I_{qs} - w_r L_d I_{ds} + w_r \hat{\psi}_r. \tag{12}$$

From (11) and (12), they can be analysed into the phasor diagram to provide the control strategy analysis. Fig. 6 gives the ZDSC control phasor diagram in the synchronous reference frame, the stator power factor angle φ_s is defined by

$$\varphi_s = \theta_i - \theta_v, \tag{13}$$

where θ_v and θ_i are the stator voltage angle and the stator current angle, respectively.

As shown in Fig. 6, the ZDSC controls the stator current vector, which should always be kept aligned with the back EMF and perpendicular to the rotor flux-linkage of the PMSG. i.e, the stator current angle θ_i or torque angle δ should be set as 90°.

$$\theta_i = \delta = 90°. \tag{14}$$

The stator voltage angle θ_v can be defined from Fig. 5. It can be explained by using the steady-state voltage equations from (11) and (12) as

$$\begin{aligned} \theta_v &= \sin^{-1}\left(\frac{V_{qs}}{\sqrt{(V_{ds}^2 + (V_{qs}^2)}}\right) \\ &= \sin^- 1\frac{1}{\sqrt{1 + \frac{(L_q \hat{I}_s/\hat{\psi}_r)^2}{(1+R_s\hat{I}_s/w_r\hat{\psi}_r)^2}}} \end{aligned} \tag{15}$$

Substituting (14) and (15) into (13), the stator power factor angle φ_s equation with ZDSC control can be expressed as

$$\psi_s = 90° - \sin^{-1}\frac{1}{\sqrt{1 + \frac{(L_q \hat{I}_s/\hat{\psi}_r)^2}{(1+R_s\hat{I}_s/w_r\hat{\psi}_r)^2}}} \tag{16}$$

Based on (16), when the stator inductance, resistance and rotor flux-linkage of PMSG are constant, the stator power factor angle φ_s under ZDSC control decomposes increasing the stator current $\hat{I}_s$ and the rotor speed w_r respectively. Consequently, when the stator power factor PF_s is low, the performance of the PMSG drive will be reduced by the increased apparent power S for producing the generator torque T_e and increasing the winding losses.

Considering the generator active power P_s of the PMSG under ZDSC control, it is expressed as

$$\begin{aligned} P_s &= 3 \cdot \frac{\sqrt{V_{ds}^2 + V_{qs}^2}}{\sqrt{2}} \cdot \frac{\sqrt{I_{ds}^2 + I_{qs}^2}}{\sqrt{2}} \cdot PF_s \\ &= 3 \cdot V_s \cdot I_s \cdot \cos(\psi_s), \end{aligned} \tag{17}$$

where V_s and I_s are the rms voltage and phase current. Stator power factor angle φ_s can be calculated by (16) with the PMSG parameters.

From (17), the relationship between the generator active power P_s and the stator power factor PF_s can be obtained. The generator active power is reduced when the stator power factor is deteriorated.

4. SIMULATION RESULTS

The performance enhancement of PMSG systems with the control of the generator-side converter using d-axis stator current control strategy (Fig. 1) was simulated in the Matlab/Simulink software for a wind generation system. The PMSG parameters are given in Table I. The simulation results are shown in Figs. 7 to 9.

In order to simulate the transient response of the proposed control system, Fig. 7 shows the simulated waveforms during the start-up of the PMSG wind turbine system. Generator speed w_m is assumed to have a ramp start-up from 0 pu at 0.1s to base speed at 1s as shown in Fig. 7(a). The transient waveforms of the stator voltage (phase a) v_{as}, stator currents i_s and dq-axis stator currents i_{ds}, i_{qs} are shown in Fig. 7(b) and (c), respectively, connected to the stand alone resistive load, the waveforms of stator voltage becoming the switching pulse due to the switching effect of the inverter. In contrast, the waveform of the stator currents have been filtered through the inverter impedance and according to the high switching frequency of the inverter, stator currents are smoothing sinusoidal. The generator torque T_e starts to ramp up and follows to the optimal reference torque T_e^* for MPPT up to the base value, and the kept constant is

Table 1: *Permanent magnet synchronous generator parameters*

Permanent Magnet Synchronous Generator Parameters				
	Real	Base		Per-unit
Rated Mechanical Power	2.448	2.448	MW	1.0
Rated Apparent Power	3.419	3.419	MVA	1.0
Rated Phase Voltage	2309.4	2309.4	V	1.0
Rated Stator Current	490	490	A	1.0
Rated Stator Frequency	53.33	53.33	Hz	1.0
Rated Rotor Speed	400	400	rpm	1.0
Number of Pole Pairs	8			
Rated Mechanical Torque	58.459	58.459	kN.m	1.0
Rated Rotor Flux-Linkage	4.971	6.891	Wb	0.7213
Stator Winding Resistance	24.21	4655.7	mΩ	0.0052
d-Axis Stator Inductance	9.816	13.965	mH	0.7029
q-Axis Stator Inductance	9.816	13.965	mH	0.7029

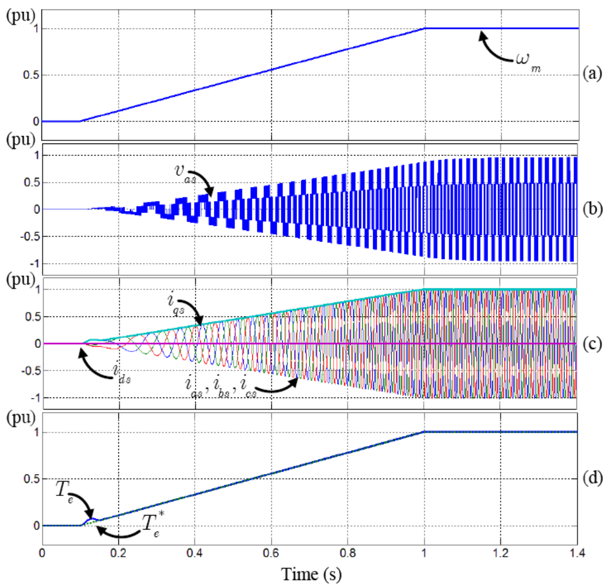

Fig. 7: *Simulation results of the PMSG with ZDSC control schemes under ramp-startup conditions. (a) generator speed, (b) phase stator voltage, (c) dq-axis stator currents and phase stator currents, and (d) generator torque.*

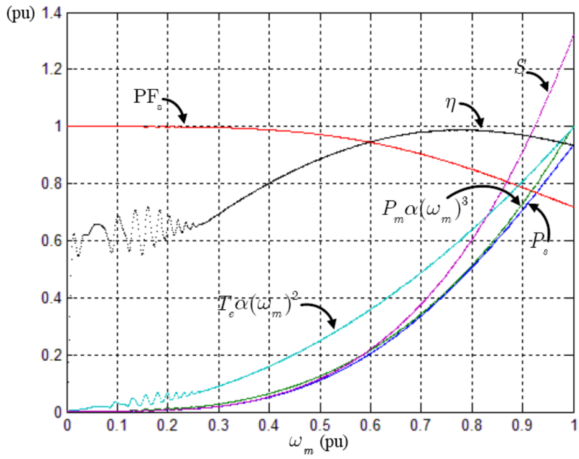

Fig. 8: *Performance of the PMSG with ZDSC control scheme under start-up conditions.*

shown in Fig. 7(d). With the ZDSC control scheme, the d-axis stator current is kept at zero and the response of the q-axis stator current doesn't affect the d-axis stator current response. In addition, the q-axis stator current is proportional to the generator torque.

Fig. 8 shows the performance of the PMSG with the purposed control scheme under the start-up conditions. When the generator speed w_m increases to 0.8 pu, the PMSG reaches 0.99 pu efficiency η and slightly fail to 0.95 pu whilst the generator speed increases to the base speed. In contrast, the stator power factor PF_s showed different changes by decreasing steadily from 1 pu to 0.71 pu. According to the increase of the appearance power S to compensate the generator torque T_e and active power P_s around the base speed range, reduction of the PMSG efficiency is occurring at the same time.

Fig.9 shows the simulated waveforms of the PMSG during the wind speed v_w step change. Wind speed is assumed to have a stepped-up from 3.6 m/s to 12 m/s at 0.1s and fell sharply to 6 m/s at 0.5sec and then rose slightly reaching around 7.8 m/s at 0.9s. Lastly, wind speed decreased steadily to 4.8 m/s at 1s then remained stable as shown in Fig. 9(a). On the other hand, the wind speed is proportional to the generator speed according to a gearbox ratio Fig. 9(b) and (c) shows the transient waveforms of the stator voltage (phase a), stator currents and dq-axis stator currents, respectively. Fig. 9(d) shows the optimal reference torque for MPPT and the generator torque. The generator torque follows the optimal reference torque excellently in transient and steady states.

The transient of the mechanical power P_m and generator active power P_s are shown in Fig. 9(e).

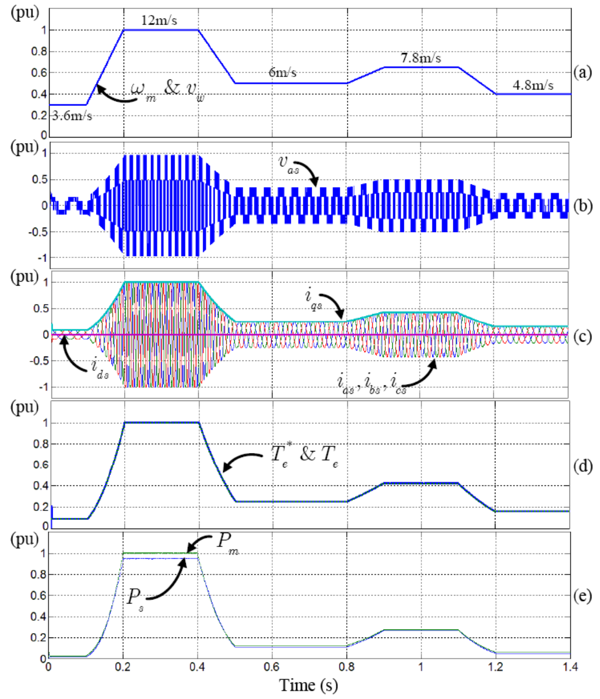

Fig.9: *Simulation results of the PMSG with ZDSC control scheme under wind speed step changes condition. (a) wind and rotor speed, (b) phase stator voltage, (c) dq-axis stator currents and phase stator currents, (d) generator torque, and (e) generator active power and mechanical power.*

At the instant time when the wind speed steps up, the MPPT operation gives the demand for generator torque to increase. The increase of generator torque leads to a higher mechanical power output. As the speed rises up to the base speed, the generator's active power increases, as well. The generator's active power reaches a high point at 0.95 pu. It's winding loss show a 5% (0.05 pu) reduction in power. In contrast, during the wind speed step down transient, the generator torque is first reduced. At the speed slowdown from a base speed of 7 m/s at 0.4s, the generator's active power fail, accordingly and kept constant at a steady state of operation. The mechanical power and the generator's active power almost have the same value, due to a very small winding loss in the machine. Consequently, it is verified that the proposed control scheme can realize high efficiency performance from 0 pu to base speed range, especially in the mid-operational range.

5. CONCLUSIONS

In this paper, a performance enhancement of PMSG systems with control of the generator-side converter using d-axis stator current controller was proposed and its performance was analysed. The control strategy was developed for the optimized generator operation whilst extracting the maximum power from wind. The proposed control system decouples the d-axis and q-axis stator current control through vector control for the generator-side converter. Particularly, the generator current was minimized to reduce the machine winding losses for the achievement of maximum overall performance and efficiency. The operating principles and theoretical analysis were verified using simulation results that exhibited improved high performance and high efficiency.

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Kitsanu Bunjongjit received a B.Eng. degree in Electrical engineering from Chiang Mai University, Chiang Mai, Thailand, in 2012, where he is currently studying toward the M.Eng. degree, with a scholarship from the faculty of engineering, Chiang Mai University. His research is focused on electrical drives and renewable energy systems.

Yuttana Kumsuwan received a M.Eng. degree in Electrical engineering from King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand, in 2000 and a Ph.D. degree in Electrical engineering from Chiang Mai University, Chiang Mai, Thailand, in 2007. Since 2011, he has been an Assistant Professor in the Department of Electrical Engineering, Chiang Mai University. He was a visiting professor at Texas A& M University, College Station, United States, from October 2007 to May 2008, and at Ryerson University, Toronto, ON, Canada from March to May 2010. His research interests include power electronics, energy conversion systems, and electrical drives.