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The Modeling and Control of a Wind Turbine using Permanent Magnet Synchronous Generator

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Abstract: This paper presents a novel control strategy for the operation of a direct-drive permanent-magnet synchronous generator-based stand-alone variable-speed wind turbine. The Control strategy for the generator-side converter with maximum power extraction is presented. The stand-alone control is featured with output voltage and frequency controller that is capable of handling variable load. The potential excess of power is dissipated in the dump-load resistor with the chopper control, and the dc-link voltage is maintained. Dynamic representation of dc bus and small-signal analysis is presented. Simulation results show that the controllers can extract maximum power and regulate the voltage and frequency under varying wind and load conditions. The controller shows very good dynamic and steady-state performance.

Keywords: Maximum Power Extraction, Permanent Magnet Synchronous Generator (PMSG), Switch-Mode Rectifier, Variable-Speed Wind Turbine, Voltage and Frequency Control.

I. INTRODUCTION

Variable-Speed wind turbines have many advantages over fixed-speed generation such as increased energy capture, operation at maximum power point, improved efficiency, and power quality. However, the presence of a gearbox that couples the wind turbine to the generator causes problems. The gearbox suffers from faults and requires regular maintenance. The reliability of the variable-speed wind turbine can be improved significantly by using a direct-drive permanent magnet synchronous generator (PMSG). PMSG has received much attention in wind-energy application because of their property of self-excitation, which allows an operation at a high-power factor and high efficiency. The use of permanent magnet in the rotor of the PMSG makes it unnecessary to supply magnetizing current through the stator for constant air-gap flux; the stator current need only to be torque producing. Hence, for the same output, the PMSG will operate at a higher power factor because of the absence of the magnetizing current and will be more efficient than other machines. To extract maximum power from the fluctuating wind, variable-speed operation of the wind-turbine generator is necessary. This requires a sophisticated control strategy for the generator. Optimum power/torque tracking is a popular control strategy, as it helps to achieve optimum wind-energy utilization. Some of these control strategies use wind velocity to obtain the desired shaft speed to vary the generator speed. However, anemometer-based control strategy increases cost and reduces the reliability of the overall system. These control strategies are not suitable or too expensive for a small-scale Wind turbine.

The magnet in the rotor of the PMSG makes it unnecessary to supply magnetizing current through the stator for constant air-gap flux; the stator current need only to be torque producing. Hence, for the same output, the PMSG will operate at a higher power factor Because of the absence of the magnetizing current and will be more efficient than other machines. To extract maximum power from the fluctuating wind, variable-speed operation of the wind-turbine generator is necessary. This requires a sophisticated control strategy for the generator. Optimum power/torque tracking is a popular control strategy, as it helps to achieve optimum wind-energy utilization. Some of these control strategies use wind velocity to obtain the desired shaft speed to vary the generator speed. However, anemometer-based control strategy increases cost and reduces the reliability of the overall system. These control strategies are not suitable or too expensive for a small-scale wind turbine. In, the current vector of an interior-type PMSG is controlled to optimize the wind-turbine operation at various wind speed, which requires six active switches to be controlled. Switch-mode rectifier has been investigated for use with automotive alternator with permanent-magnet synchronous machines. The switch-mode rectifier has also been investigated for small-scale variable-speed wind turbine; the current vector of an interior-type PMSG is controlled to optimize the wind-turbine operation at various wind speed, which requires six active switches to be controlled. Switch-mode rectifier has been investigated for use with automotive alternator with permanent-magnet synchronous machines. The switch-mode rectifier has also been investigated for small-scale variable-speed wind turbine.

A control strategy for the generator-side converter with output maximization of a PMSG-based small-scale wind turbine is developed. The generator-side switch-mode rectifier is controlled to achieve maximum power from the wind. The method requires only one active switching device [insulated gate bipolar transistor (IGBT)], which is used to control the generator torque to extract maximum power. It is simple and a low-cost solution for a small-scale wind turbine. For a stand-alone system, the output voltage of the load side converter has to be controlled in terms of amplitude and frequency. Previous publications related to PMSG-based variable-speed wind turbine are mostly concentrated on grid connected system. Much attention has not been paid for a stand-alone system. Many countries are affluent in renewable energy resources; however, they are located in remote areas where power grid is not available.

The local small-scale standalone distributed generation system can utilize these renewable energy resources when grid connection is not feasible. In this paper, a control strategy is developed to control the load voltage in a stand-alone mode. As there is no grid in a stand-alone system, the output voltage has to be controlled in terms of amplitude and frequency. The load-side pulse width modulation (PWM) inverter is using a relatively complex vector-control scheme to control the amplitude and frequency of the inverter output voltage. The stand-alone control is featured with output voltage and frequency controller capable of handling variable load. A dump-load-resistor controller is used to dissipate excess power during fault or over generation. The excess power is dissipated in the dump-load resistor with the chopper control, and the dc-link voltage is maintained.

II. WIND TURBINE CHARACTERISTICS

The amount of power captured by the wind turbine (power delivered by the rotor) is given by

$$Pt=0.5\rho ACp\,(\lambda,\beta)\times(v_w)3=0.5\rho ACp\times(\omega_m/R\lambda)^3 \qquad (1)$$

where ρ is the air density (kilograms per cubic meter), vω is the wind speed in meters per second, A is the blades' swept area, and *Cp* is the turbine-rotor-power coefficient, which is a function of the tip-speed ratio (λ) and pitch angle (β).ω_m = rotational speed of turbine rotor in mechanical radians per second, and R = radius of the turbine. The coefficient of performance of a wind turbine is influenced by the tip-speed to wind-speed ratio, which is given by

$$TSR = \lambda = \omega_m R/v_w. \qquad (2)$$

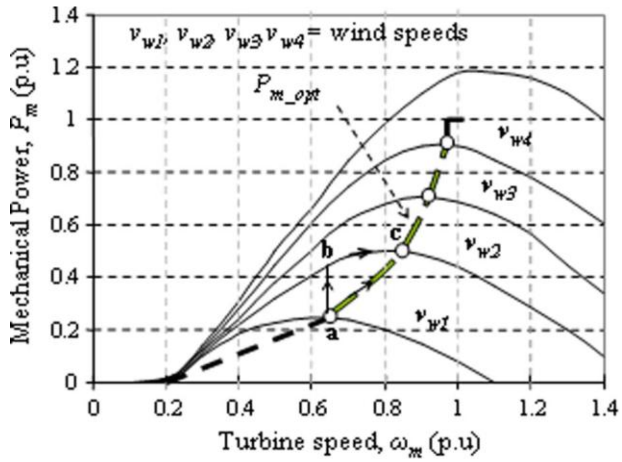


Fig.1. Mechanical power generated by the turbine as a function of the rotor speed for different wind speeds.

The wind turbine can produce maximum power when the turbine operates at maximum Cp (i.e., at Cp_opt). Therefore, it is necessary to keep the rotor speed at an optimum value of the tip-speed ratio *λ*opt. If the wind speed varies, the rotor speed should be adjusted to follow the change. The target optimum power from a wind turbine can be written as

$$Pm\_opt = 0.5\rho ACp\_opt\,(\omega_m\_optR/\lambda opt)^3 =$$

$$Kopt\,(\omega_m\_opt)3 \qquad (3)$$

Where

$$Kopt = 0.5\rho ACp\_opt(R/\lambda opt)^3 \qquad (4)$$

$$\omega m\_opt = \lambda opt/Rv_w = K_w v_w. \qquad (5)$$

Therefore, the target optimum torque can be given by

$$Tm\_opt = Kopt\,(\omega_m\_opt)2 \qquad (6)$$

The mechanical rotor power generated by the turbine as a function of the rotor speed for different wind speed is shown in Fig. 1. The optimum power is also shown in this figure. The optimum power curve (Popt) shows how maximum energy can be captured from the fluctuating wind. The function of the controller is to keep the turbine operating on this curve, as the wind velocity varies. It is observed from this figure that there is always a matching rotor speed which produces optimum power Fig.1.Mechanical power generated by the turbine as a function of the rotor speed for different wind speeds. For any wind speed, if the controller can properly follow the optimum curve, the wind turbine will produce maximum power at any speed within the allowable range. The optimum torque can be calculated from the optimum power given by (6). For the generator speed below the rated maximum speed, the generator follows (6).

III. SYSTEM OVERVIEW

Fig. 2 shows the control structure of a PMSG-based standalone variable-speed wind turbine which includes a wind turbine, PMSG, single-switch three-phase switch-mode rectifier, and a vector-controlled PWM voltage-source inverter. The output of a variable-speed PMSG is not suitable for use as it varies in amplitude and frequency due to fluctuating wind. A constant dc voltage is required for direct use, storage, or Conversion to ac via an inverter. In this paper, a single-switch three-phase switch-mode rectifier is used to convert the ac output voltage of the generator to a constant conversion to ac voltage via an inverter. The single-switch three-phase switch-mode rectifier consists of a three-phase diode bridge rectifier and a dc to dc converter. The output of the switch-mode rectifier can be controlled by controlling the duty cycle of an active switch (such as IGBT) at any wind speed to extract maximum power from the wind turbine and to supply the loads. A vector-controlled IGBT inverter is used to regulate the output voltage and frequency during load or wind variations. Voltage drop due to sudden fall in wind speed can be compensated by the energy-storage system. During wind gust, the dump-load controller will be activated to regulate the dc-link voltage to maintain the output load voltage at the desired value.

IV. CONTROL OF SWITCH-MODE RECTIFIER WITH MAXIMUM POWER EXTRACTION

The structure of the proposed control strategy of the switch mode rectifier is shown in Fig. 3. The control objective is to control the duty cycle of the switch ***S*** in Fig. 2 to extract maximum power from the variable-speed wind turbine and transfer the power to the load. The control algorithm includes the following steps.

1. Measure generator speed ω_g.
2. Determine the reference torque (Fig. 4) using the following equation:

$$T^*g = Kopt(\omega_g)2 \quad (7)$$

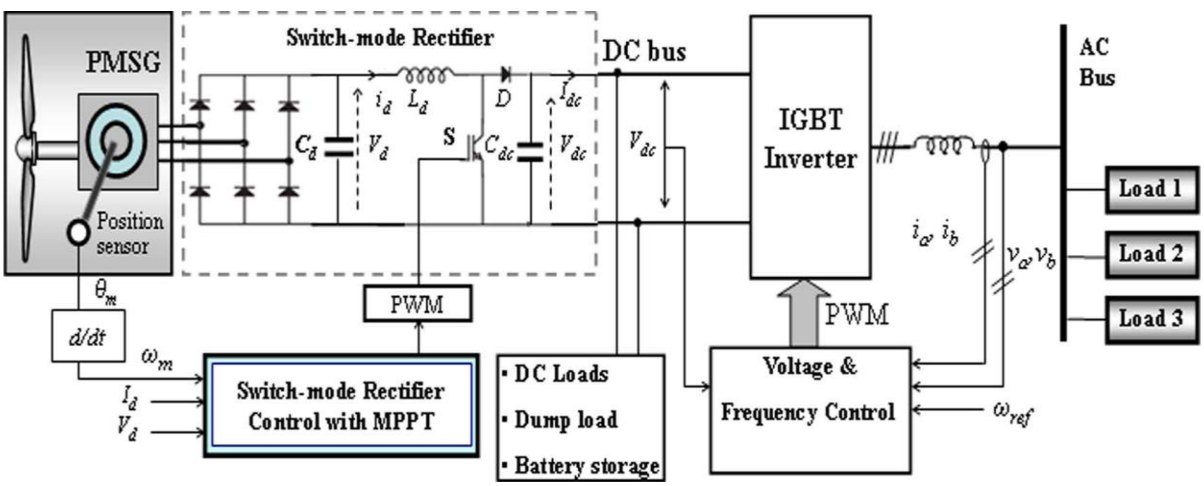


Fig. 2. Control structure of a PMSG-based stand-alone variable-speed wind turbine.

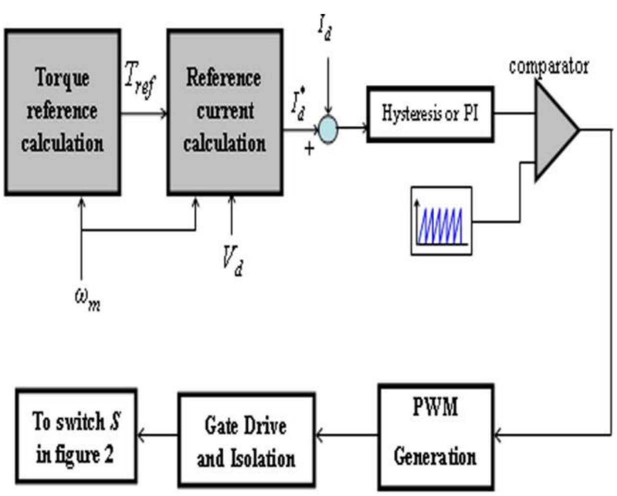


Fig. 3. Control strategy of the switch-mode rectifier.

3. This torque reference is then used to calculate the dc current reference by measuring the rectifier output voltage V_d as given by

$$I^*d = (T^*g \times \omega g)/V_d \quad (8)$$

4. The error between the reference dc current and measured dc current is used to vary the duty cycle of the switch to regulate the output of the switch-mode rectifier and the generator torque through a proportional–integral (PI) controller.

The generator torque is controlled in the optimum torque curve as shown in Fig. 4 according to the generator speed. The acceleration or deceleration of the generator is determined by the difference of the turbine torque Tm and generator torque Tg. If the generator speed is less than the optimal speed, the turbine torque is larger than the generator torque, and the generator will be accelerated. The generator will be decelerated if the generator speed is higher than the optimal speed. Therefore, the turbine and generator torques settle down to the optimum torque point Tm opt at any wind speed, and the wind turbine is operated at the maximum power point. For example

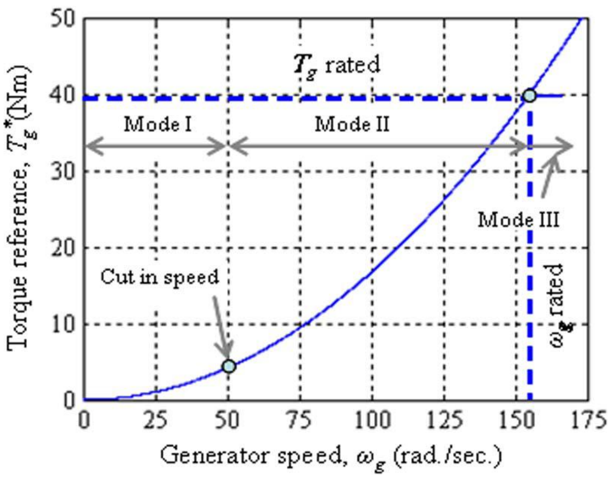


Fig. 4. Generator torque reference versus speed

(Considering Fig. 1), if the PMSG is operating at point "**a**" and the wind speed increases from v_w1 to v_w2 (point "**b**"), the additional power and, hence, torque causes the PMSG to accelerate. The accelerating torque is the difference between the turbine mechanical torque and the torque given by the optimum curve. Finally, the generator will reach the point "**c**" where the accelerating torque is zero. A similar situation occurs when the wind velocity decreases. In the proposed method, the wind speed is not required to be monitored, and, therefore, it is a simple output-maximization control method without wind-speed sensor (anemometer).

V. CONTROL OF LOAD-SIDE INVERTER

The objective of the supply-side converter is to regulate the voltage and frequency. The output voltages have to be controlled in terms of amplitude and frequency as no grid exists in a stand-alone system. The control structure for standalone control mode consists of output-voltage controller, dc link voltage controller, dump-load-resistance controller, and current controller. The output-voltage controller is used to control the output voltage during load transients or wind variation. The dc-link voltage controller is used to stabilize the dc-link voltage. The dc voltage PI controller maintains the dc voltage to the reference value. The PI controllers are used to regulate the output voltage and currents in the inner control loops and the dc voltage controller in the outer loop. To compensate for the cross-coupling effect due to the output filter in therotating reference frame, compensation terms are added as shown in Fig. 5. All the PI controllers are tuned using the Ziegler–Nichols tu ning method [13]. The vector-control scheme used is based on a synchronously rotating reference frame as shown in Fig. 6. The angular velocity of the rotating axis system ω is set in the controller and defines the electrical frequency at the load.where L_f and R_f are the filter inductance and resistance, respectively. v_{a1}, v_b1, and v_{c1} represent the voltages at the inverter output. *ia*, *ib*, and *ic* are the line currents. The vector representation of a balanced three-phase system and their equivalent vectors in a rotating dq reference frame is shown in Fig. 6. Here, transforming the voltage equations using dq transformation in the rotating reference frame.

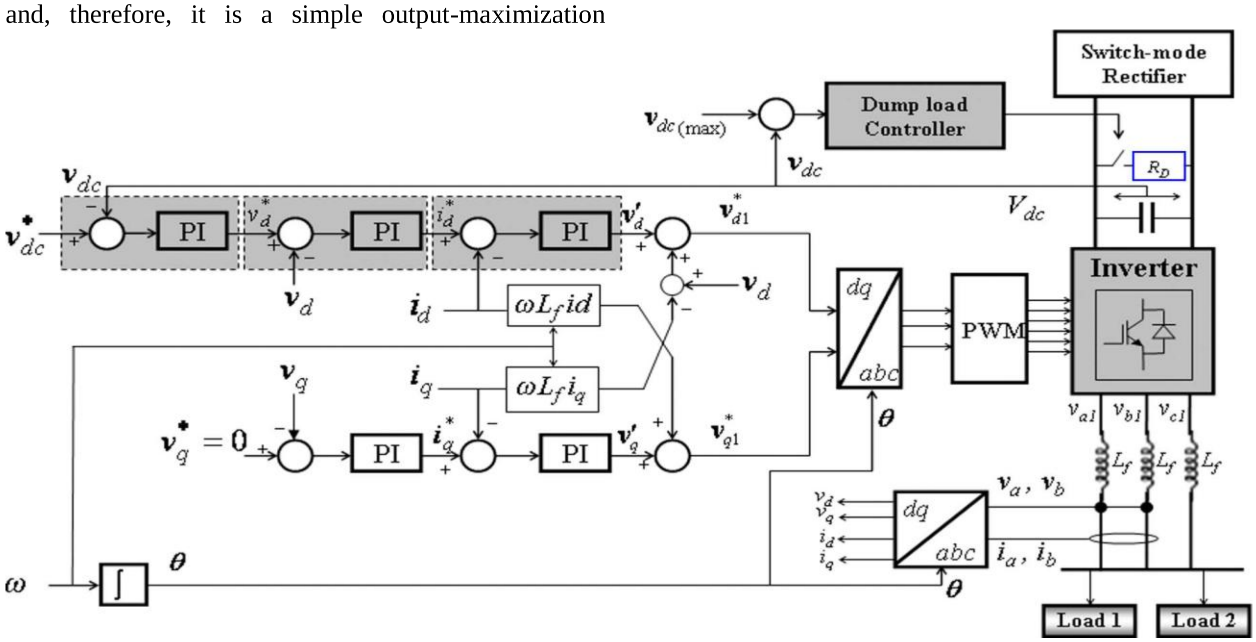


Fig. 5. Vector-control structure for stand-alone mode of operation

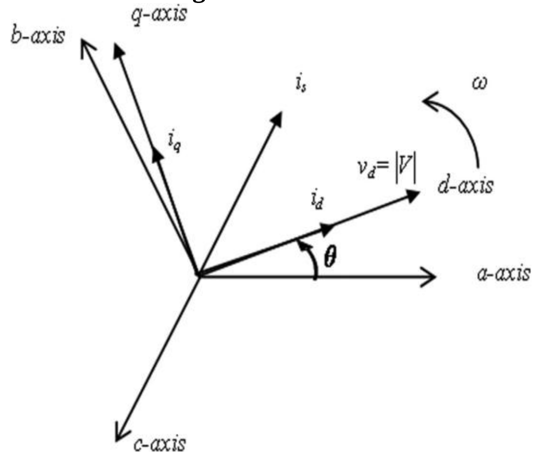


Fig. 6. abc and the rotating reference frame

$$v_d = v_{d1} - R_f\, i_d - L_f\,(di_d/dt) + \omega L_f\, i_q \qquad (10)$$

$$v_q = v_q 1 - R_f\, i_q - L_f(di_q/dt) - \omega L_f\, i_d \qquad (11)$$

The instantaneous power in a three-phase system is given by

$$P(t) = v_a i_a + v_b i_b + v_c i_c = [v_a\ v_b\ v_c]\ [i_a\ i_b\ i_c] \qquad (12)$$

Using *dq* transformation, the active and reactive power is given by

$$P = 3/2(v_d i_d + v_q i_q) \qquad (13)$$

$$Q = 3/2(v_d i_q + v_q i_d) \qquad (14)$$

If the reference frame is as vq = 0 and vd = |V |, the equations for the active and reactive power will be

$$P = 3/2(vdid) = 3/2|V|id \qquad (15)$$

$$Q = /32(vdiq) = /32|V|iq \qquad (16)$$

Therefore, the active and reactive power can be controlled by controlling the direct and quadrature current components, respectively.

VI. DC-BUS DYNAMICS AND PROTECTION

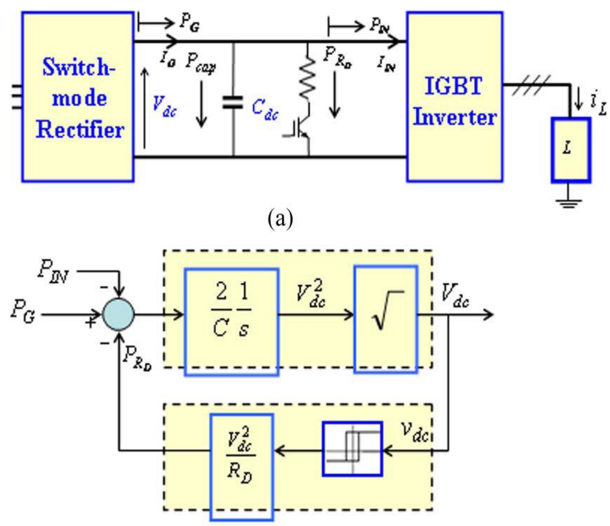
A dump-resistor controller is used to dissipate excess power during fault or over generation. The potential excess of power will be dissipated in the dump-load resistor with the chopper control, and the dc-link voltage will be maintained. The control is linear and increases the duty cycle as a function of the overvoltage amount. If the dc-link voltage exceeds the maximum limit, the dc link will be short-circuited through the resistor R_D as shown in Fig. 7. Using the power-balance principle, the dynamic behavior of the dc-bus voltage V_{dc} is given by

$$d\,(1/2CV^2dc/dt) = PG - (V^2dc/R_D) - P_{IN} \qquad (17)$$

$$d(V_{2dc})dt = 2/C(P_G - (V^2_{dc}/R_D) - P_{IN} \qquad (18)$$

Where,

PG = Power from the generator,
(V^2dc/RD) = power dissipated in the dump-load resistor (RD), and
PIN = power at the input of the inverter.



(a)

(b)

Fig. 7. Dynamic representation of a dc bus and protection. (a) Power flow in the dc link. (b) DC-bus dynamics and protection

VII. SMALL-SIGNAL ANALYSIS

Considering that the load power factor is close to unity, the reactive power supplied by the converter will be negligible. Therefore, the quadrature component of the load current will be zero. For an *RL* load, the d − q equations for the load side of Fig. 7(a) are

$$I_{IN} \approx V_d i_{Dl}/V_{dc} \qquad (19)$$

$$v_d = i_{dL} R_L \qquad (20)$$

Where vd and idL are the direct component of the load voltage and current, respectively. The dc-link voltage Vdc is given by

$$V_{dc} = (I_G - I_{IN})/sCdc \qquad (21)$$

Where C_{dc} is the dc-link capacitance. Using (19)–(21), the block diagram of Fig. 8(a) can be obtained. In Fig. 8(a), $G_{dc}(s)$ is the dc-link voltage controller, as shown in Fig. 5, and *G*ac(*s*) is the controller of the ac load voltage. The control system of fig. 8(a) is nonlinear with a coupling between the dclink voltage control loop and load voltage control loop. Linearizing around a quiescent point (Vdc0, vd0, idL0, IG0, IIN0) gives

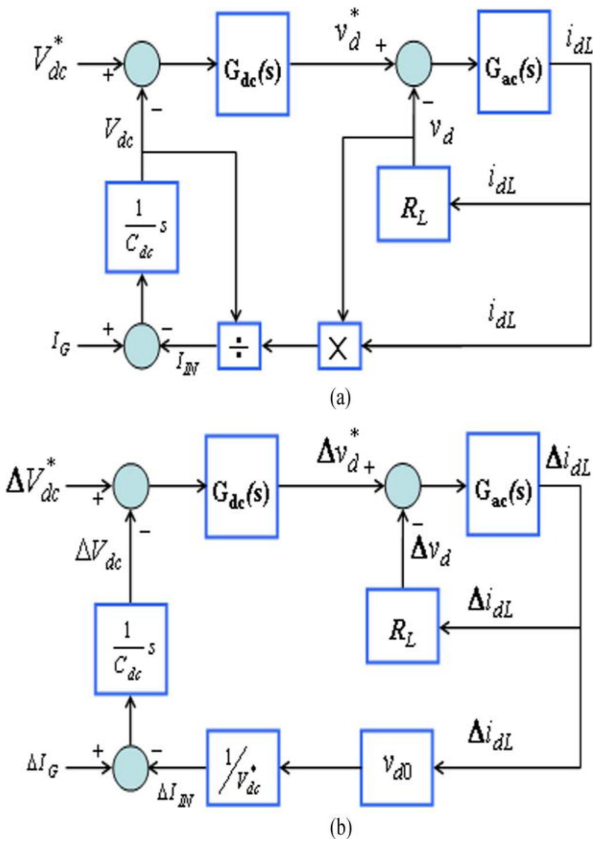


Fig. 8. Block diagram of the proposed control system. (a) Control system.(b) Small-signal model.

$$\Delta I_{IN} = ((\Delta v_d i_{dL0} + \Delta i_{dL} v_{d0})/V_{dc0}) - ((v_{d0} i_{dL0}/V^2_{dc0})\Delta V_{dc} \quad (22)$$

$$\Delta V_{dc} = \Delta I_G - (\Delta I_{IN}/sC_{dc}) \quad (23)$$

Under normal operation, the small-signal model can be simplified by considering that the variation in the dc-link voltage and direct-axis component of the load voltage is small compared with the variation in load currents. Therefore

$$(V_{d0}/V_{dc0})\Delta i_{dL} >> (i_{dL0}/V_{dc0})\Delta v_d - (V_{d0} i_{dG0}/V^2 dc0)\Delta V_{dc} \quad (24)$$

Using (22)–(24), the small-signal model of Fig. 8(b) is obtained. There is still some coupling between the dc-link voltage and the load-voltage control loops in Fig. 8(b). However, because of the high inertia of the wind turbine [14], the current will vary slowly compared with the natural frequency of the load-voltage control loop. Therefore, the load voltage can be considered almost constant for the dc-link voltage control loop, and the open-loop transfer function ΔVdc/ΔidL is obtained as

$$(\Delta V_{dc}/\Delta i_{dl}) \approx (vd0/sCdcV\ {*}dc) \quad (25)$$

VIII. RESULTS AND DISCUSSION

The model of the PMSG-based variable-speed wind-turbine system of Fig. 2 is built using Mat lab/Imposer dynamic system simulation software. The simulation model is developed based on a Kollmorgen 6-kW industrial permanent-magnet synchronous machine. The parameters of the turbine and PMSG used are given in Table I. The power converter and the control algorithm are also implemented and included in the model. The sampling time used for the simulation is 20 μs.

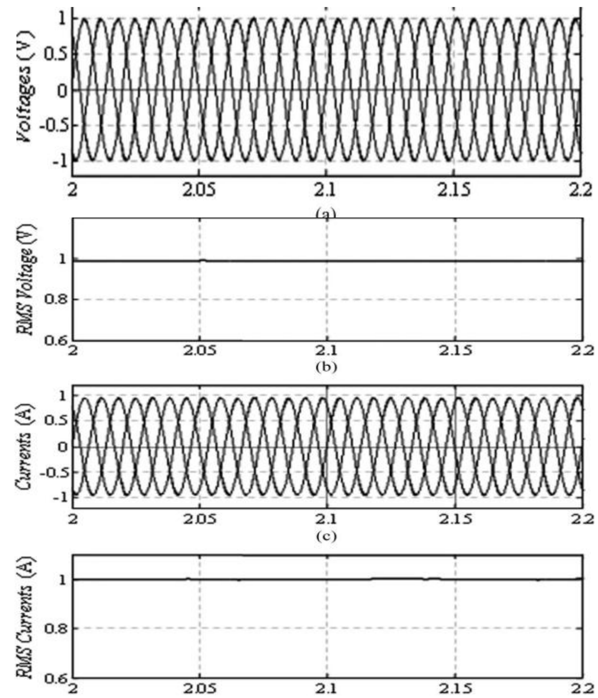


Fig. 9. Instantaneous and rms voltage and currents at a constant load (full load). (a)Instantaneous load voltages. (b) RMS line voltage. (c) Instantaneous line currents. (d) RMS line current.

The simulation results demonstrate that the controller works very well and shows very good dynamic and steady-state performance. The control algorithm can be used to extract maximum power from the variable-speed wind turbine under fluctuating wind. Fig. 12 shows the load voltage and current responses at a constant load. Fig. 9(a) and (b) shows the instantaneous and rms load voltages, and Fig. 9(c) and (d) shows the instantaneous and rms currents at a constant load. Fig. 10 shows the instantaneous and rms load voltages and currents when the load changes from 100% to 50% and then from 50% to 100%. Fig. 10(a) and (b) shows the instantaneous and rms voltages, and Fig. 10(c) and (d) shows the instantaneous and rms currents when the load is reduced to 50% at *t* = 3 s and remains at this value until *t* = 4 s. It is observed that the voltage is well maintained despite the variation of loads. The load current is changing with the load variations as expected.

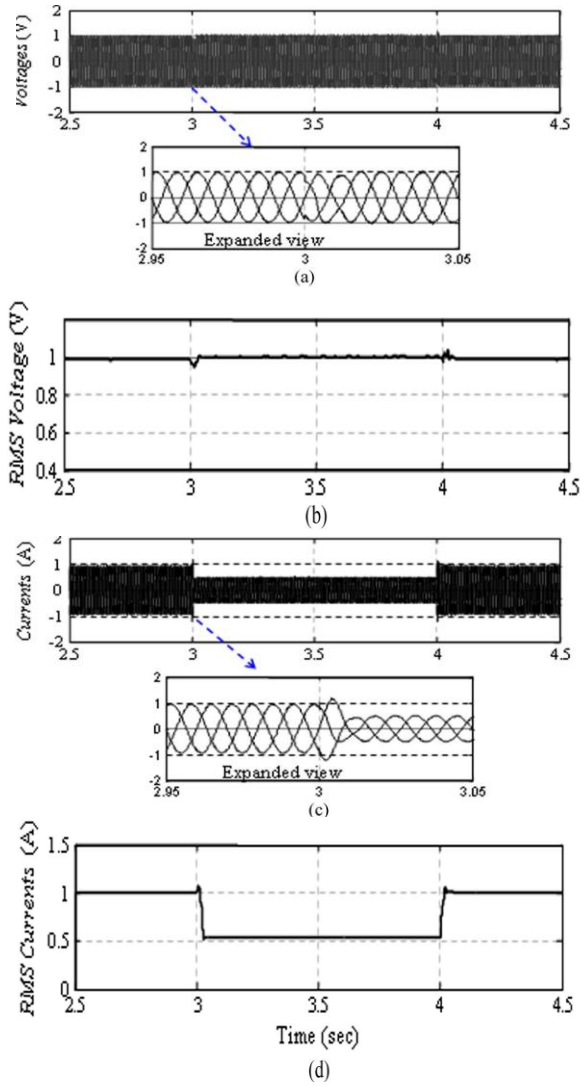


Fig. 10. Instantaneous and rms voltage and current responses when the load changes from 100% to 50% and from 50% to 100%. (a) Instantaneous load voltages. (b) RMS line voltage. (c) Instantaneous line currents. (d) RMS line current.

IX. CONCLUSION

A control strategy for a direct-drive stand-alone variable speed wind turbine with a PMSG has been presented in this paper. A simple control strategy for the generator-side converter to extract maximum power is discussed and implemented using Simpower dynamic-system simulation software. The controller is capable of maximizing output of the variable-speed wind turbine under fluctuating wind. The load-side PWM inverter is controlled using vector-control scheme to maintain the amplitude and frequency of the inverter output voltage. It is seen that the controller can maintain the load voltage and frequency quite well at constant load and under varying load condition. The generating system with the proposed control strategy is suitable for a small-scale stand-alone variable-speed wind-turbine installation for remote-area power supply. The simulation results demonstrate that the controller works very well and shows very good dynamic and steady-state performance.

X. ACKNOWLEDGMENT

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