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Series Compensated Open-Winding PM Generator Wind Generation System

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Abstract — **This paper presents a new wind power generation system utilizing an open-winding permanent magnet synchronous generator (PMSG). A diode rectifier is used for the major portion of power conversion process. In addition, the proposed system controls the generated power by using an auxiliary voltage source inverter located at the neutral of the generator. The VA rating of the auxiliary inverter is only a fraction of the system rated power. Compared to wind power systems utilizing a PWM rectifier or diode rectifier having a DC/DC boost converter, the converter cost can be considerably reduced. In addition, the generator underutilization issue in a conventional diode rectifier fed wind power system can also be solved.**

Keywords —**Wind power, PMSG, diode rectifier, series compensation, SSSC.**

I. INTRODUCTION

Synchronous generators, especially permanent magnet synchronous generators (PMSGs) are gaining increased attention in wind power applications. The PMSG is favored due to its high efficiency and power density. In addition, high pole number PMSG enables direct drive wind turbines which can eliminate the gear box and reduce the maintenance cost of wind farms. However, a full power rating converter is required to decouple the line frequency and rotor speed because the PMSG is only able to generate power at the synchronous speed. A back-to-back PWM voltage source converter (VSC) is commonly used in wind power systems utilizing PMSGs. With the machine side PWM VSC, the generator current can be controlled to maximize generator efficiency and utilization. At the grid side, the PWM inverter provides the grid with controllable real and reactive power. The power quality and system stability can be both improved. The only disadvantage of such a system is the high cost associated with the full rating active power electronics converter [1-3].

A low cost diode rectifier has been proposed to replace the generator side PWM VSI in order to reduce the cost of the overall system. In this kind of system, a DC/DC boost converter is often needed to control the generated power [1-3]. However, the DC/DC boost converter must be sized based on the full power rating of the system. In addition, a high power inductor may be required. Therefore, the cost reduction is not so attractive. Moreover, it has been reported that the generator suffers from underutilization issues when operating in a diode rectifier wind power system [4]. The generator underutilization issue of diode rectifier generating systems can be explained using a simplified non-salient PMSG model. When a diode rectifier is used, the displacement power factor of the generator is unity. The DC/DC boost converter is able to increase the generator current by reducing the terminal voltage that is applied to the generator. However, the generator power may not increase as the generator current increases. Moreover, the generator current vector will always lag the back-emf. As a result, the generator will not deliver rated power at the rated generator current and voltage. The authors of [4] proposed to use the static synchronous series compensator (SSSC) to improve the generator utilization. The issue is solved by compensating the voltage drop on the synchronous reactance of the generator in an open loop fashion. However, a coupling transformer is required for the SSSC, which leads to increase in both cost and weight of the overall system.

A similar wind power system has been proposed by Takaku et. al. [5-7]. Instead of the SSSC, a magnetic energy recovery switch (MERS) is used. Nevertheless, the system requires four active power electronics switches and one capacitor for each phase. Wiik and et. al. proposed a control method for controlling the MERS based on sensing the generator voltage [6]. It was verified experimentally that generator output power and generator utilization can be improved by series compensation in a wind power generation system which employs a synchronous generator and diode rectifier. However, in the existing literature [4-7], a DC capacitor and resistive load are used at the output of the diode rectifier for purposes of analysis. The DC bus voltage is left free to change in the study. The overall system control method was not discussed. Moreover, only non-salient synchronous generators are considered. The control methods in the previous literatures are not applicable to salient-pole generators. In addition, the authors did not mention the possibility to use series compensation to reduce the generated power when needed.

Open-winding machines have been proposed for a variety of applications including high power industrial drives [8], hybrid electric vehicles (HEVs) [9], microgrids [10], drive reliability improvement [11-12] and wind power generation [13-14]. Wang and et. al. proposed using a half-controlled converter-fed open-winding PM generator wind power system to reduce the total active switch rating. In [14], the authors proposed to use a series VSI with open-winding PMSG in a constant speed wind turbine system. One set of the three phase terminals is directly coupled to the power grid without any power electronics converter. The VSI at the neutral of the generator is used to provide damping and improve the system stability instead of controlling the generator power. There is no existing literature found utilizing open-winding configuration to improve the generator output power and to reduce the total converter rating at the same time in wind power generation systems.

In this paper, a new open-winding PMSG wind power topology is proposed. It will be shown that the generator utilization can be improved comparing to conventional diode rectifier type wind power generation systems. In addition, the generator power can be controlled without a fully rated active converter. The cost of the system can be reduced. The overall system control method is also discussed.

II. PROPOSED TOPOLOGY AND OPERATING PRINCIPLE

The proposed topology considered in this paper is shown in Figure. 1. An open-winding PMSG is used with an uncontrolled diode rectifier and an auxiliary fractional sized compensating VSI. The auxiliary inverter is used for both generator control and generator utilization improvement. The DC side of the auxiliary VSI is connected to a floating capacitor. A separate PWM VSI is used as the grid side inverter to regulate the main DC bus voltage. Gearbox can be used to increase the generator speed for higher power density.

Like the SSSC, the auxiliary inverter is a series compensation device. It can be controlled as a variable three-phase impedance. If the injected voltage is leading the generator current by 90 degrees, the inverter is effectively a three-phase inductor. On the contrary, the inverter is effectively a three-phase capacitor if the injected voltage is lagging the current by 90 degrees. The DC bus of the auxiliary inverter is simply a DC capacitor with no connection to a power source. The compensation DC bus voltage can be controlled by the inverter. When the injected voltage has a component that is in phase with the current, the compensation DC bus voltage will be increased. In contrast, the compensation DC bus voltage is reduced when there is a component that is 180 degrees away from the current. This component can be considered as resistance or negative resistance from the circuit point of view. If energy storage is desired, the energy storage element can be attached to the DC bus of the auxiliary inverter so that the auxiliary inverter is also used as an interface to the energy storage.

Since an open-winding machine is the same as regular Y-connected machines from an electromagnetic point of view, the mathematical model of an open-winding PMSG in the rotor reference frame can be written as:

$$\begin{cases} v_d = v_{d1} - v_{d2} \\ v_q = v_{q1} - v_{q2} \\ v_0 = v_{01} - v_{02} \end{cases} \tag{1}$$

$$\begin{cases} v_d = (r_s + pL_d)\, i_d - \omega_r L_q i_q \\ v_q = (r_s + pL_q)\, i_q + \omega_r L_d i_d + \omega_r \lambda_m \\ v_0 = (r_s + pL_{lk})\, i_0 \end{cases} \tag{2}$$

$$T_e = \frac{3P}{4}\left[\lambda_m i_q + \left(L_d - L_q\right) i_d i_q\right] \tag{3}$$

$$J\frac{2}{P} p\omega_r = T_e - T_m \tag{4}$$

Where p is the operator for differentiation with respect to time. The voltages in the three orthogonal axes are v_d, v_q and v_0. J is inertia and P is the number of poles. For a non-salient generator, the d- and q-axis inductances are the same. r_s is the generator resistance and L_{lk} is the leakage inductance.

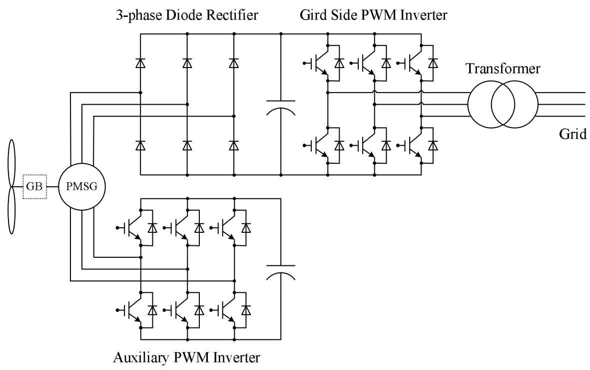


Fig. 1. Proposed series compensated diode rectifier open-winding PMSG wind power system.

In the proposed configuration shown in Fig. 1., the two DC buses of the diode rectifier and the compensation VSI are isolated. Therefore, there is no zero current path even though the three windings do not have a neutral connection. As a result, there is no need for bulky zero sequence choke or special PWM technique for the inverter.

It is convenient to first explain the operating principle by using a non-salient generator, for instance a surface permanent magnet (SPM) generator. A single-line diagram is shown in Fig. 2. E, V_{rect}, V_{com} are generator back-emf, rectifier voltage and compensation VSI voltage. The AC side voltage of the diode rectifier V_{rect} is equal to the vector sum of the generator voltage Vs and the compensation voltage V_{com}.

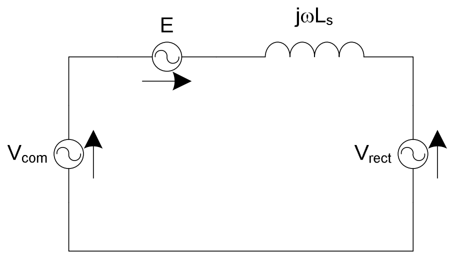
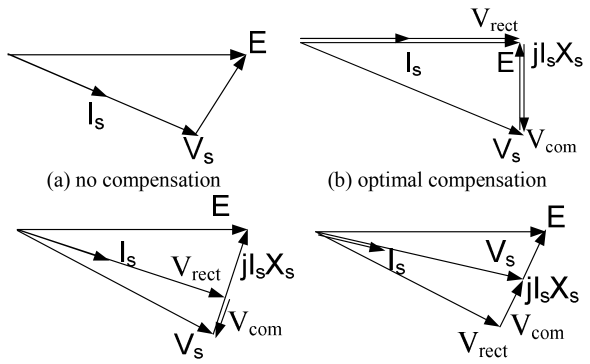


Fig. 2. Single line diagram of proposed system with non-salient PMSG

Assuming the compensation is purely reactive and ignoring the generator resistance, the power flow into the rectifier can be calculated as:

$$P_s = \frac{3V_{rect}E}{X_s} sin(\delta) + \frac{3V_{rect}V_{com}}{X_s} cos(\frac{\delta}{2}) \tag{5}$$

Where δ is the power angle defined as from the back-emf E to the rectifier voltage V_{rect}. The generated power can be controlled by varying the compensation voltage. If the current is continuous, the rectifier operates at unity displacement power factor, i.e. the current is in phase with the voltage fundamentally. The phasor diagrams of a lossless non-salient generator with and without compensation are shown in Fig. 3. When the compensation voltage completely cancels the voltage drop on the synchronous reactance, the generator operates on its maximum torque per ampere (MTPA) curve. When the compensation is capacitive, the generator power is increased and when the compensation is inductive, the generator power is reduced.

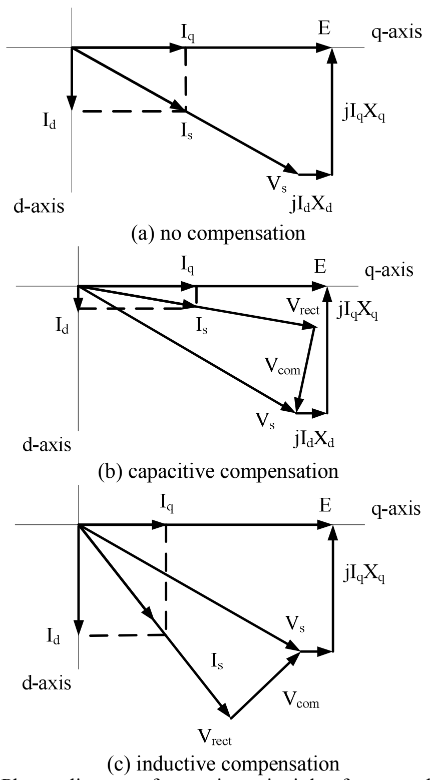


(a) no compensation (b) optimal compensation

(c) capacitive compensation (d) inductive compensation

Fig. 3. Phasor diagram of operating principle of proposed system employing non-salient synchronous generator

For a salient interior permanent (IPM) magnet generator, it is not possible to construct a simple single line diagram as for a SPM generator. However, the relationship between the compensation voltage and generator power is similar to a SPM generator. A phasor diagram can still be drawn for a salient-pole generator. Fig. 4 shows the phasor diagram for an IPM generator controlled by the proposed system. In both salient and non-salient generator cases, the compensation voltage vector is perpendicular to the current vector.



(a) no compensation

(b) capacitive compensation

(c) inductive compensation

Fig. 4. Phasor diagram of operating principle of proposed system employing salient synchronous generator

An IPM generator is used in this paper to maintain generality of the proposed topology and control method. The parameters of the generator ignoring practical details such as saturation and skin effect are listed in TABLE I.

TABLE I
PARAMETERS OF MACHINE UNDER SDUDY

Parameter	Description	Value
P_r	rated power	10 kW
V_r	rated phase voltage	115 Volts
I_r	rated current	29 Amps
f_r	rated frequency	34.5 Hz
ω_r	rated speed	216.8 elec rad/s
r_s	stator resistance	0.315 Ohm
L_d	d-axis inductance	16 mH
L_q	q-axis inductance	51 mH
λ_m	permanent flux linkage	0.75 wb
P	number of poles	4

In the steady state, the time derivative terms in (1) can be eliminated. Ignoring the losses and assume unity displacement power factor, (1) can be rearranged as (6).

$$\begin{cases} -v_{rect}\, sin(\delta) = -\omega_r\, L_q\, i_s\, cos(\delta) + v_{com}\, cos(\delta) \\ v_{rect}\, cos(\delta) = -\omega_r L_d i_s\, sin(\delta) + \omega_r \lambda_m + v_{com}\, sin(\delta) \end{cases} \quad (6)$$

The power angle and current amplitude can be obtained by solving equations (6) numerically. The main DC bus voltage is set to 200 V and the fundamental component of a six step waveform is used as the rectifier voltage. The current and power angle values from numerical calculation are then used to obtain the generator power as a function of compensation voltage. Figure 5 shows the curve of generator power versus compensation voltage at different speeds for the 10 kW lab scale IPM generator (ideal lossless model is used). It can be seen from Fig. 5 that a compensation voltage of 20 V_{pk} is sufficient to shape the generated power within a reasonable range. The compensation inverter can be sized to be less than 30% of the rated power to control the power and rotor speed of the generator. It can even be sized smaller if desired. In the situation that the compensation voltage needed to operate the generator on MTPA curve is higher than the available voltage, the inverter can be kept at its highest output voltage, the generator power and utilization can still be improved compared to a diode rectifier only system.

Unlike the systems in the existing literature, the proposed system is capable of reducing generator power in addition to improving generator power output. When the compensation is inductive, the generated power decreases. This feature enables the proposed system with the capability of maximum power point tracking (MPPT). The details of the control method will be discussed in the next section.

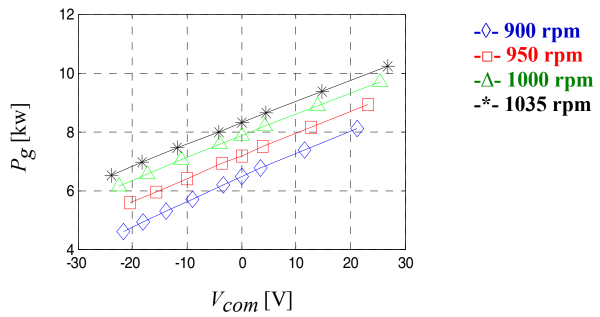


Fig. 5. Power vs. compensation voltage plot of proposed system with IPM generator

III. Control Method

In the proposed system, the control of the grid side converter is the same as other topology utilizing standard active front end configurations. The diode rectifier is not controllable. Therefore, only the control of the generator compensation VSI is discussed here.

In the existing literature [4-7], series compensation devices are used to counter the voltage drop on the synchronous reactance of the generator. The series compensation devices are controlled in the impedance mode. Series compensation is commonly used as a scheme for power flow control in flexible alternating current transmission systems (FACTS) [15]. The proposed control method employs this concept and uses the estimated generator power as the control variable. This method is suitable for both constant and variable speed turbine systems.

A. Constant Speed Turbine

In some wind power applications, pitch control and gear boxes are used so that the generator rotor speed is nearly constant. The block diagram of the controller for constant speed operation is shown in Fig. 6.

The controller of the compensation VSI is in the synchronous frame that is tied to the generator current, which means the q-axis is aligned with the peak of phase-A current. The two orthogonal components of the compensation inverter voltage v_{qi}, v_{di} control the real and the reactive power of the compensation VSI. The real components of the VSI voltage v_{qi} is used to control the floating capacitor voltage. A simple proportional-integral (PI) controller is used in the capacitor voltage controller. As shown in Fig. 5, the reactive compensation voltage has a roughly linear relation with the generator power assuming constant rotor speed and rectifier AC side voltage. Another PI controller is used to control the generator power by varying the reactive component of the VSI voltage. The generator power is estimated using measured current and main DC bus voltage.

The generator current can be highly nonlinear due to the diode rectifier. To obtain a smooth current vector angle for compensation VSI control, a current phase locked loop (PLL) is used as the current phase detector. Another advantage of using a current PLL is that the controller does not require position sensors because the control of generator power is only based on current vector angle.

B. Variable Speed Turbine

The maximum power that can be extracted from a wind turbine is loosely in a cubic relationship to the wind speed. In the proposed system, generator power is used as the control variable. As shown in Fig. 7 (a), the most straightforward method for MPPT control will be using a look-up table extracted from the turbine design. The power command can be determined using the measured wind speed.

In other cases, the turbine speed can be controlled by the rectifier to match the optimal tip speed ratio (TSR). In the proposed topology, the speed of the generator rotor speed can be controlled by varying the generator power. At a certain speed and torque level, the turbine speed can be increased by decreasing the generator power. In contrast, increasing generator power will decrease the speed. Therefore, an outer speed loop can be added to the constant speed turbine controller. As shown in Fig. 7 (b), the speed controller will generate the generator power command that is sent to the inner power loop.

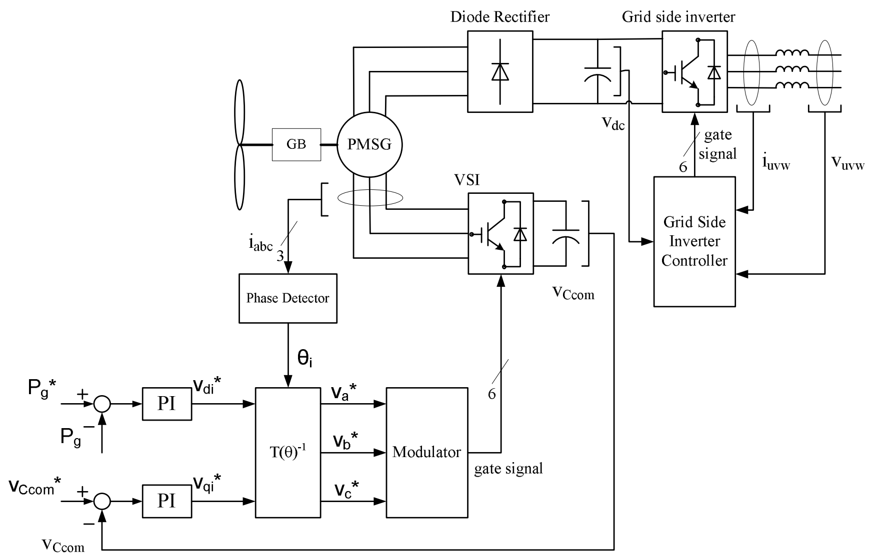
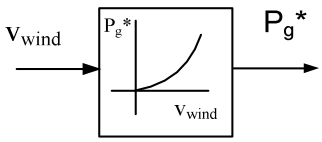
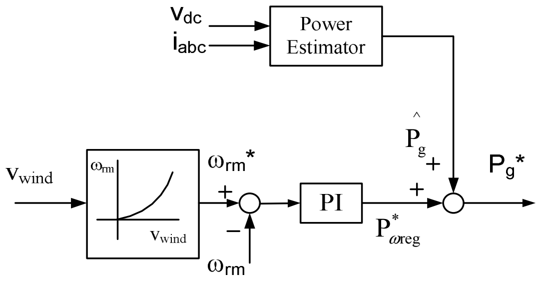


Fig. 6. Control method of proposed system with constant speed turbine



(a) Look-up table



(b) Speed control

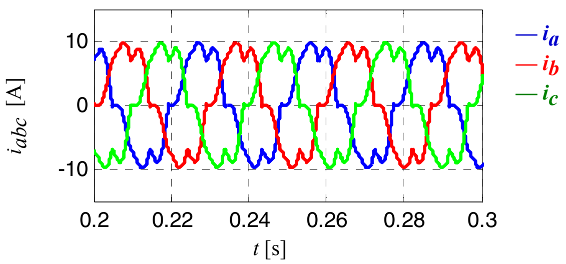
Fig. 7. Variable speed turbine control method

IV. SIMULATION STUDY

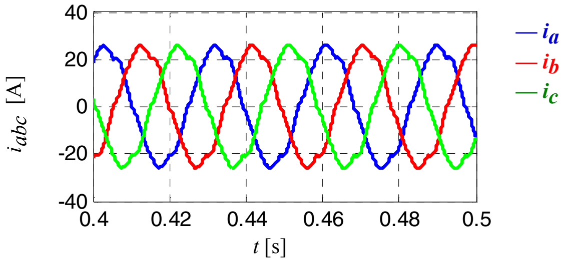
The lab scale open-winding generator is modeled together with two power electronics converters for the simulation study. For system level study, ideal models are used. No saturation or parasitic effects have been modeled. The simulation tools used are Matlab/Simulink® and PLECS®.

A. *Constant Speed Turbine*

The constant speed turbine case is first simulated. Figure 8 compares the generator current waveform in steady state with and without series compensation. A 6.5 kw generator power is used as the power command for the compensated case. It is apparent that the generator current is increased with the compensation. It should also be noted that the current is smoother which will lead to reduced torque ripple. The spectra of the current waveforms shown in Fig. 8 are compared in Fig. 9. The current total harmonic distortion (THD) is reduced from 16.3% to 5.4 %.



(a) phase current, uncompensated



(b) phase current, compensated

Fig. 8. Comparison of current in steady state

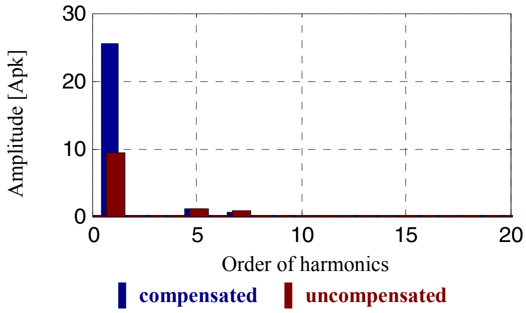


Fig. 9. Impact on Harmonics.

The transient simulation results before and after the power controller is enabled is given in Fig. 10. It can be clearly seen that the generator output power is increased from about 2 kw to 6.5 kw by applying 20 Vpk compensation voltage for the generator under study. The compensation DC capacitor voltage can be well regulated as illustrated in Fig. 10.

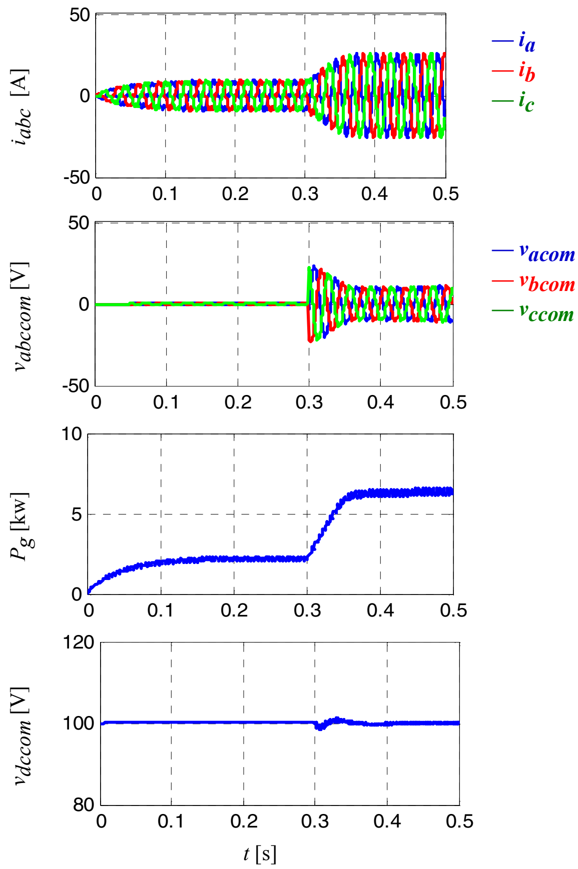


Fig. 10. Transient before and after power controller is enabled

B. *Variable Speed Turbine*

In a variable speed turbine, a constant torque is applied to the shaft of the generator. A step change in speed is commanded and the simulation results are shown in Fig. 11. The rotor speed is controlled by varying the generator power. The generator torque is the same before and after the change of speed. Again, the compensation DC capacitor voltage can be well regulated during the transient.

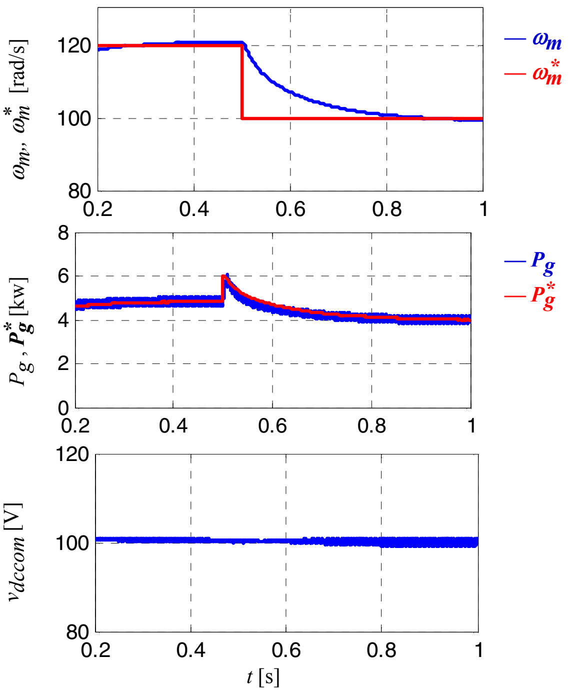


Fig. 11. Simulation results for variable speed turbine in speed control mode

V. Experimental Studies

A commercial 10 kw IPM generator has been modified as an open-winding generator for experiment studies. An inverter and a rectifier are built in the lab. For easy verification, a DC chopper and a load resistor is used to control the rectifier DC bus voltage at 200 V. The experimental set up is shown in Fig. 12.

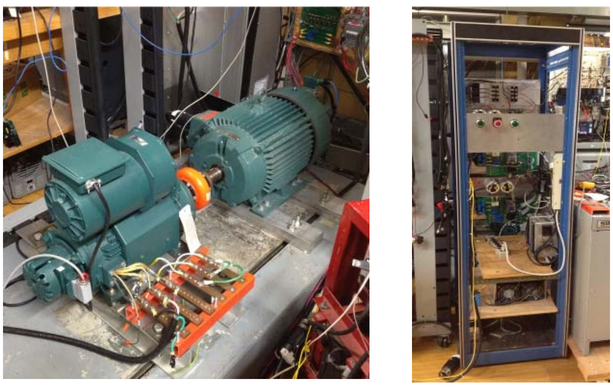


Fig. 12. Experimental set up.

The power versus compensation voltage curve in steady state is obtained experimentally and plotted in Fig. 13. The relationship between power and compensation voltage is not as linear as theoretical prediction. However, a similar monotonically increasing trend can be observed.

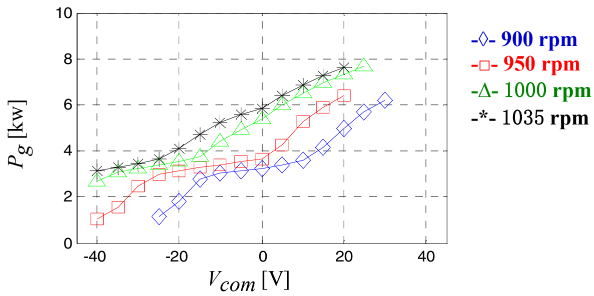
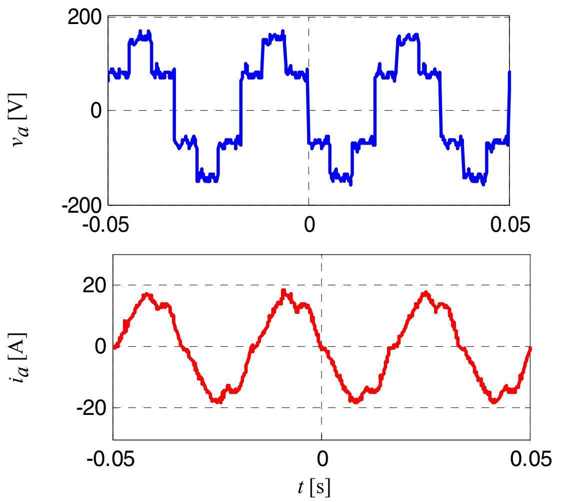
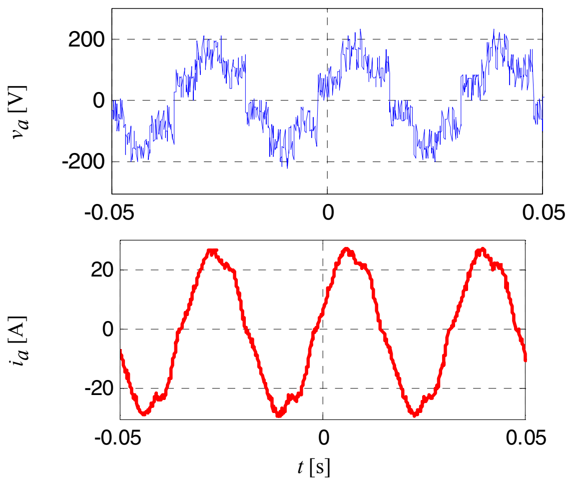


Fig. 13. Power vs. compensation voltage plot of proposed system with IPM generator obtained by experiment

The voltage and current waveforms in steady state are shown in Fig. 14. The generator speed is kept at 900 rpm by the dynamometer. Fig. 14 (a) shows the waveforms for the uncompensated case. The phase voltage is a 6-step waveform. In Fig. 14 (b), the compensated phase voltage has a PWM component on top of the 6-step waveform. The power command is 6 kw for the compensated case. The current amplitude is increased compared to the uncompensated case. As a result, the power output of the generator is improved.



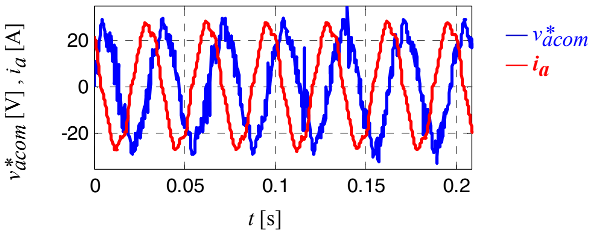
(a) uncompensated



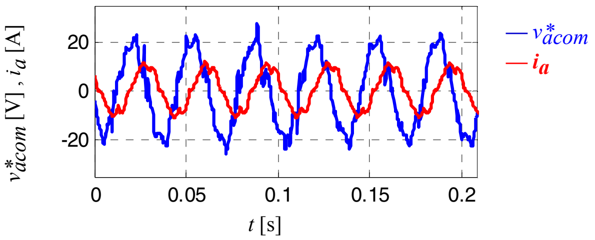
(b) compensated

Fig. 14 Comparison of uncompensated and compensated voltage and current waveform in steady state

The compensation voltage command and current for phase-A are compared in Fig. 15 for capacitive and inductive compensation. For capacitive compensation, the compensation voltage is lagging the current by 90 degrees. In contrast, the compensation voltage is leading the generator current by 90 degrees for inductive compensation. The current amplitude is much lower when inductive compensation is applied. Assuming a constant diode rectifier voltage, the generator power can be reduced.



(a) Capacitive compensation



(b) Inductive compensation

Fig. 15. compensation voltage vs. generator current, experiment

The transient results before and after the power controller is enabled is shown in Fig. 16. The generator is operated at 900 rpm. The power controller is enabled at 1.25 sec. The power output of the generator is regulated to its reference value 6 kw. The compensation DC bus voltage is well regulated during the transient.

A load step down test is also carried out as well. The results are shown in Fig. 17. The power command is changed from 6 kw to 2 kw at 1.25 sec. The generator power is controlled to be less than without compensation. The controller is able to regulate the generator power during the transient. The current amplitude is rapidly reduced. The compensation DC bus voltage is kept at its nominal value throughout the transient test.

VI. Conclusion

This paper has proposed a new open-winding PMSG wind power system. The proposed topology is capable of reducing the active power converter size while maintaining good generator utilization compared to common wind power systems. In the proposed system, the generator power can be controlled by an active converter whose size is only a fraction of the system power rating. It has also been shown that the proposed control method is applicable to both salient and non-salient generator, constant speed and variable speed turbines. The validity of the proposed topology and control method is verified by simulation and experiment studies. The proposed topology shows some attractive potential when compared to existing technologies.

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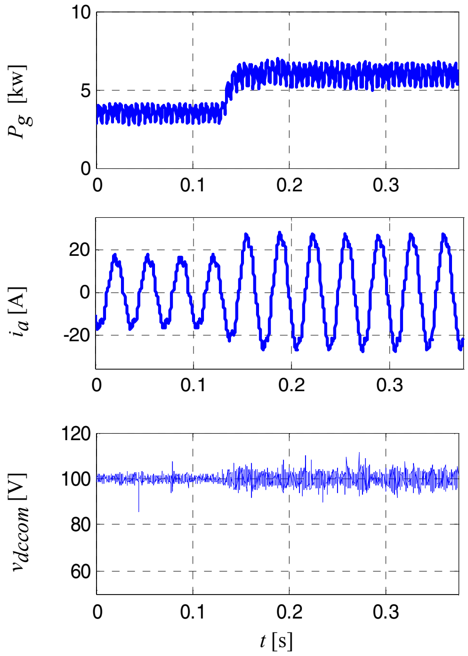

Fig. 16. Transient before and after the controller is enabled, experiment

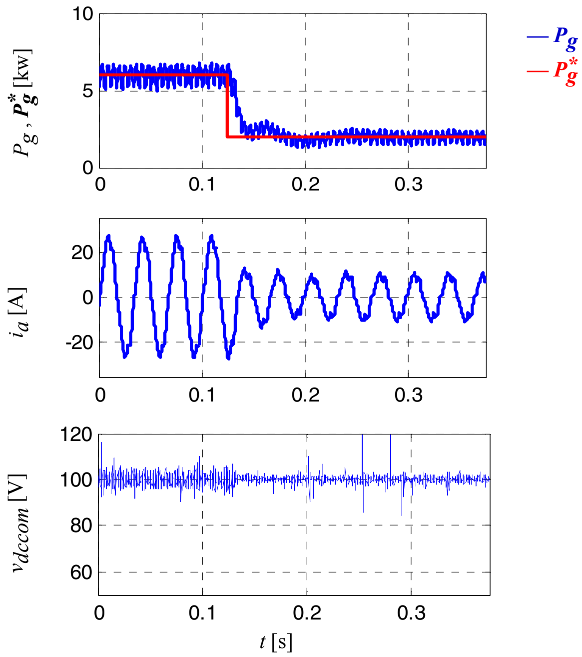

Fig. 17. Power step down transient, experiment

REFERENCES

[1] Wu B.,Lang, Y, Zargari N, and Kouro, S., *"Power Conversion and Control of Wind Energy Systems"*, Wiley-IEEE Press, Hoboken,New Jersey, 2011, 453 pages,ISBN-13: 978-0-470-59365-3.

[2] Chen, Z; Guerrero, J.M.; Blaabjerg, F.; "A Review of the State of the Art of Power Electronics for Wind Turbines," *Power Electronics, IEEE Transactions on* , vol.24, no.8, pp.1859-1875, Aug. 2009

[3] Baroudi, J.A.; Dinavahi, V.; Knight, A.M.; "A review of power converter topologies for wind generators," *Electric Machines and Drives, 2005 IEEE International Conference on*., pp.458-465, 15-15 May 2005

[4] Singer, A., Hofmann, W.;"Static synchronous series compensation applied to small wind energy conversion system," *Power Electronics and Applications, 2007 European Conference on* , pp.1-9, 2-5 Sept. 2007

[5] Takaku, T.; Homma, G.; Isober, T.; Igarashi, S.; Uchida, Y.; Shimada, R.; "Improved wind power conversion system using magnetic energy recovery switch (MERS)," *Industry Applications Conference, 2005. Fourtieth IAS Annual Meeting. Conference Record of the 2005* , vol.3, , pp. 2007- 2012 Vol. 3, 2-6 Oct. 2005

[6] Wiik, J.A.; Kulka, A.; Isobe, T.; Usuki, K.; Molinas, M.; Takaku, T.; Undeland, T.; Shimada, R.; "Control design and experimental verification of a series compensated 50 kW permanent magnet wind power generator," *Power Electronics Specialists Conference, 2008. PESC 2008. IEEE*, pp. 4525-4531, 15-19 June 2008

[7] Wiik, J.A.; Wijaya, F.D.; Shimada, R.; "Characteristics of the Magnetic Energy Recovery Switch (MERS) as a Series FACTS Controller," *Power Delivery, IEEE Transactions on* , vol.24, no.2, pp.828-836, April 2009

[8] Stemmler, H.; Guggenbach, P.; "Configurations of high-power voltage source inverter drives," *Power Electronics and Applications, 1993., Fifth European Conference on*, pp.7-14, vol.5, 13-16 Sept. 1993.

[9] Welchko, B.A.; "A double-ended inverter system for the combined propulsion and energy management functions in hybrid vehicles with energy storage," *Industrial Electronics Society, 2005. IECON 2005. 31st Annual Conference of IEEE* , 6 pp.6, Nov. 2005

[10] Mu-Shin Kwak; Seung-Ki Sul; "Control of an Open-Winding Machine in a Grid-Connected Distributed Generation System," *Industry Applications, IEEE Transactions on* , vol.44, no.4, pp.1259-1267, July-Aug. 2008

[11] Welchko, B.A.; Jahns, T.M.; Lipo, T.A.; "Fault interrupting methods and topologies for interior PM machine drives," *Power Electronics Letters, IEEE* , vol.2, no.4, pp. 139- 143, Dec. 2004

[12] Wang, Y.; Lipo, T.A.; Pan, D.; "Robust operation of double-output AC machine drive," *Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference on* , vol., no., pp.140-144, May 30 2011-June 3 2011

[13] Yang Wang; Lipo, T.A..; Di Pan; "Half-controlled-converter-fed open-winding permanent magnet synchronous generator for wind applications," *Power Electronics and Motion Control Conference (EPE/PEMC), 2010 14th International* , vol., no., pp.T4-123-T4-126, 6-8 Sept. 2010

[14] Grabic, S.; Celanovic, N.; Katic, V.A.; "Permanent Magnet Synchronous Generator Cascade for Wind Turbine Application," *Power Electronics, IEEE Transactions on* , vol.23, no.3, pp.1136-1142, May 2008

[15] Gyugyi, L.; Schauder, C.D.; Sen, K.K.; "Static synchronous series compensator: a solid-state approach to the series compensation of transmission lines," *Power Delivery, IEEE Transactions on* , vol.12, no.1, pp.406-417, Jan. 1997