A Two Stage Converter Based Special Rectifier for Wind Energy Conversion System

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Abstract-This paper proposes a control strategy for maintaining and tracking a constant voltage and frequency across loads through stand alone variable speed wind energy conversion system. The system which consists of a variable speed wind turbine coupled to a permanent magnet synchronous generator (PMSG). The output of ac supply is obtained from PWM inverter. By changing the modulation index of the PWM the inverter control can be achieved. Both the output of the rectifier and inverter are controlled through the proposed controller that follows the common control. Extracting as much wind energy as possible and feeding the load with high quality electricity are 2 main targets. Boosting DC-link voltage is enough level to realize the targets. In this paper, first studied about the topologies of 2-phase input uncontrolled rectifier are, a cost-effective, which is especially suitable for the wide range input voltage of wind generation system. To further boost DC-link voltage, by replacing some of the diodes with IGBTs and using fully the leakage inductance of specially designed PMSG, a boost-rectifier topology is presented. Both simulation and test results from a developed 10kW 2-phase wind turbine PMSG generation system well verify the presented topologies.

Keywords PMSG, VSWECS, THD, TSR, PSCAD

I. INTRODUCTION

Due to wide range of advantages, the development of direct-drive, load-connected wind turbine PMSG generation system has become one important for the R&D of wind energy application. Extracting maximum energy from wind and feeding low THD current to the load are two important R&D objectives of PMSG generation systems. In order to realize the 2 main targets, a suitable DC-link voltage of the wind Generation converter must be achieved. When the wind speed is heavy, to improve the operation safety, to reduce the stress of the power devices in the converter and the DC-link voltage should be constrained to certain level. When the wind speed is low, the input voltage of the converter is low, and in order to extract maximum wind energy andachieve the THD of converter output current, the DC-link voltage must be boosted through measurement, while to increase the DC-link voltage, employing a PMSG with higher terminal voltage seems to be one good choice. At present, usually a DC boost rectifier is employed to boost the DC-link voltage in the wind energy generation system.
This design can realize the DC-link voltage control and at the same time may realize the maximum power point tracking of the system, but additional power devices and bulky inductor are needed, and this will cause the increasing in manufacturing cost and decreasing in system efficiency. Moreover, the employment of boost rectifier may lead to acoustic noise which sometimes is

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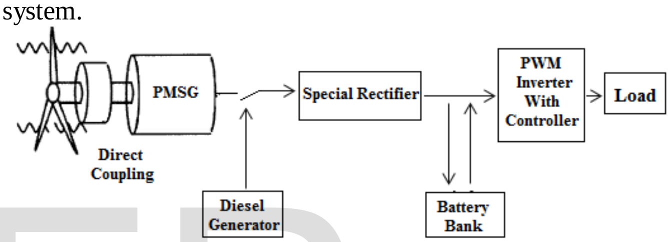

Fig.I. Schemetic diagram of converter with PMSG system.

Considering of the mechanical design restriction of PMSG used in wind energy generation system and the implementation difficulty of the converter of the 3-phase and 2-phase PMSG wind energy generation system is studied, and the topology study is carried out based on the 2-phase system. In recent years, focus has been shifted towards the non conventional energy resources Wind is a renewable energy and readily available free source of energy. The main challenge is that the wind speed is variable and so directly interfacing the wind turbine generator to the load may lead to voltage and frequency fluctuations. This problem make worse when the variable speed generators such as Permanent Magnet Synchronous Generator (PMSG) are used since they have a higher speed range which translates to variable frequency and voltage of ac output supply. However, for satisfactory, the electrical supply must meet acceptable values of voltage and frequency. It consists of power electronics components such as rectifier, Boost rectifier and PWM Inverter. Further add to the reliability of the scheme, diesel generators and battery banks will provide continuous electricity in case of very low wind speeds or unexpected system failures.

II. PROPOSED SCHEME

The proposed WECS, It consists of the PMSG, power electronic interface, controller at both the dc and ac stages, and the alternative power supplies.

A. Wind Generator

The output power of the wind turbine is given as

$P=1/2\rho A C_p V_w^3$

where the variables are defined as follows:

C_p: Power coefficient

A: Area swept by turbine
ρ: Air density
V_w: Speed of the wind

To trap the wind power either an induction or a synchronous generator may be coupled to the wind turbine. Induction generators are more or less fixed speed generators. Hence, to have a closer speed tracking their speed is controlled by the pitch and yaw control mechanisms. However, these methods result in high mechanical losses. On the other hand, PMSG are used in conjunction with variable speed turbines as they allow the turbines to operate over a wide range of speed maintaining optimum tip speed ratio (TSR) and thus allowing maximum power conversion. The variable-speed based systems inflict lower stress on the shafts and gears compared to the constant-speed systems. In permanent-magnet Wind Generation systems, the output current and voltage are proportional to the electromagnetic torque and rotor speed, respectively. Using a permanent magnet synchronous generator also excludes the need to have a separate field circuit for excitation.

III. TWO-PHASE UNCONTROLLED RECTIFIER

A. Topologies of 2ΦInput Uncontrolled Rectifier

Two possible rectifier topologies that can be used for the 2-phase PMSG generation system as shown. In fig(2) which uses line terminal and the neutral line of the PMSG is used as well. The average output voltage of the two-phase rectifier shown in fig. which derived as $V_{dc} = 2V_1/\pi$, whereV_1 is the rms value of PMSG's line-line voltage. The average output voltage of the rectifier derived as $Vdc = (2 + \sqrt{2})V_1/\pi$.
Obviously, the utilization of the neutral line of the 2-phase PMSG increases the DC-link voltage.

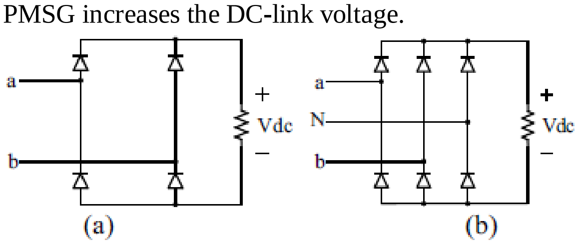

Fig. 2. Topologies of two-phase rectifier.

B. Uncontrolled "Boost Voltage" Rectifier

It has been noticed that the average output voltage of topology shown in Fig. 2(b) is higher than that of Fig. 2(a), however, an additional pair of diode is needed. the output voltage of topology shown in Fig. 2(b) can't be changed at high input voltage, i.e., when wind speed is high, therefore the topology shown in Fig. 2(b) will burden high input voltage, this may damage the rectifier.

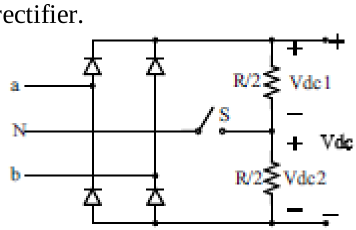

Fig. 3. "boost voltage" rectifier

In order to overcome above drawback, a 2-phase input "boost voltage" rectifier topology, as shown in Fig. 3, is presented. In the figure, when switch S is closed the voltage across the load can be derived as

$$V_{dc} = V_{dc1} + V_{dc2} = (2+\sqrt{2})/\pi * V_1 \quad (1)$$

The adding of the switch S makes it possible to limit the output voltage of the rectifier at high input voltage, i.e. when the switch S is opened, the average output voltage will be decreased to $V_{dc} = 2V_1/\pi$.

Replacing the resistors in topologies shown in Fig. with capacitors, and when the capacitance is sufficient, the DC-link voltage of the topologies shown in Fig. 2(a) and Fig. 2(b)

$$V_{dc} = 2V_m \quad (2)$$

while the DClink voltage of topology shown in Fig. 3

$$Vdc = Vdc1+Vdc2 = 2\sqrt{2}V_m \quad (3)$$

whereV_m is the phase rms voltage of PMSG. The average voltage of the presented topology shown in figure is √2times that of topologies shown in fig. (2). In practical application, the average output voltage may be slightly less than the values shown in (2) and (3).

IV. TWO-PHASE CONTROLLED RECTIFIER

Based on the principle of conventional boost rectifier, as there exists leakage inductance in PMSG which can be thought of the energy storage inductor, and through replacing some of the diodes in the rectifier with controllable switches, e.g., IGBTs, the rectifier will become controlled rectifier. Using suitable control strategies, the DC-link voltage may be boosted, thus this kind of rectifier can be named as boost rectifier.

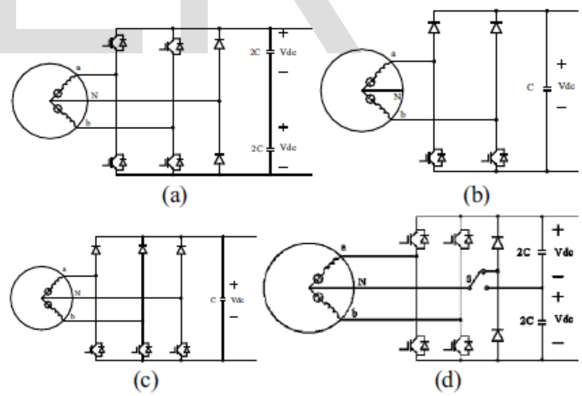

Fig. 4. Topologies of boost rectifier.

Several possible topologies which can be used as the controlled rectifier. Considering of both manufacture cost and the need of wide-range input voltage of the converter, the topology shown in Fig. 4(d) is employed to build the two-phase PMSG generation system.
When the wind speed is low, switch S is controlled so that the neutral line of the PMSG is connected to the mid-point of the DC-link capacitors, therefore, the DC-link voltage is boosted, meanwhile, the IGBTs in the lower arms of the rectifier can be controlled to further "boost" the DC-link voltage if needed. Control of both bottom and top of the arm of rectifier can realize the function of power factor adjustment of the PMSG.

V. PWM INVERTER

In this case, a PWM inverter employing double edge sinusoidal modulation is used. Such a modulation, the symmetrical 3Φ output of the inverter consists of sinusoidal modulated train of carrier pulses, both halves of which are modulated such that the average voltage difference between any two of the output three phases varies sinusoidally for one phase. Each edge of the carrier wave is modulated by a variable angle δ and can be mathematically

$\delta = m \sin(\alpha)\, \delta_{max}$ (4)

where m is the modulation index and ranges from 0 to 1, α is the angular displacement of the unmodulated edge and δ max is the maximum displacement of the edge for a chosen frequency ratio. A PWM inverter reduces harmonics in the ac output. An additional controller is used in the inverter stage to maintain constant ac supply voltage against variations in the load. The power electronics switches used at both the converter stage are IGBTs since they can operate at a high switching frequency and reduces the ON state losses.

VI. DIESEL GENERATOR AND BATTERY

To tide over situations when the wind speed falls to very low values and the generator output falls down. A Diesel Generator setting has been connected through a changeover switch in parallel with the PMSG. A battery in shunt with the dc bus is to provide uninterrupted power supply during the time taken for the Diesel Generator to start operation in the case of critical loads

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VII. PROPOSED CONTROLLER DESIGN

This system has a nonlinear dynamic behavior, and it works in switching mode. Moreover, it is exposed to significant variations which this system may take away from nominal conditions, due to changes on the load or line voltage at the input. In this paper we analyze the equations of a boost converter and design components and simulation of the converter. This work is applied to tracking the point of maximum power.

VIII METHODOLOGY

1) Conversion modes:

The DC/DC converter has operated in two modes, a Continuous Conduction Mode and Discontinuous Conduction. CCM for efficient power conversion and DCM for low power or Stand-by operation.

a) Continuous Conduction Mode:

$V_i t_{on} + (V_i - V_o) t_{off} = 0$ (1)

Where;
Vi: The input voltage, V.
Vo: The average output voltage, V.
ton: The switching ON of the IGBT's, s
toff: The switching OFF of the IGBT's, s

Dividing both sides by Ts and rearranging items yield

$V_o/V_i = T_s/t_{off} = 1/1\text{-}D$ (2)

Where;
Ts: The switching period, s.
D: The duty cycle.

Mode I ($0 < t \le ton$)
assuming a lossless circuit, Pi=Po, then

$I_i V_i = I_o V_o$ (3)

$I_i/I_o = 1\text{-}D$ (4)

Where;
Io: The average output current, Amp.
Ii: The average input current, Amp.

b) Discontinuons Conduction Mode:

Mode II ($ton < t \le Ts$)

The boost converter is said to be operating in the discontinuous conduction mode.

$V_i D T_s + (V_i - V_o) D_1 T_s = 0$ (5)

$Vo/Vi = D1+D/D1$ (6)

and

$I_o/I_i = D_1/D_1+D$ (since Pi=Po) (7)

$I_i = V_i/2L_b D T_s (D+D1)$ (8)

Using Equ. (7) in the foregoing equation yields

$I_o = (V_i T_s/2L_b) DD1$ (9)

In practice, Vo is held constant and D varies in response to variation in Vi, it is more useful to obtain the required duty cycle, D, a function of load current for various values of Vo/Vi. By using Eqns (6)and (9), we can determine that:

$D = [4Vo/27Vi\ (Vo/Vi\ \text{-}1)\ Io/Io,aver,max]^{0.5}$

Where;
Io,aver,max
The maximum average output current at the edge of continuous conduction.

2) Selection of the Semiconductor Device:
The IGBT's has been chosen in such a way that it can handle the worst case current and voltage stresses.

3). Selection of the Diode:
Based on the output voltage the diode reverse voltage rating is limited. The diode conducts when the switch is in the "OFF" state and that can be provides a current path for the inductor to the output. Similar to the IGBT's during the poor operation peak current through the diode occurs at low line input voltage and maximum load. Other considerations in selecting the diode based on its ability to block the required off–state voltage stress and have sufficient peak average current handling capability, fast switching characteristics, low reverse–recovery region, and low forward voltage drop.

IX. SYSTEM SIMULATION AND TEST

A. Simulation Model

A simulation model including the wind turbine, PMSG, rectifier, inverter. used to validate the presented topologies and examine the performance of the generation system. The simulation study is performed using PSCAD/EMTDC simulation software.

B. Simulation Results

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When the wind speed is set as 9.5m/s, the simulated waveforms of voltage and current for the 2-phase PMSG is taken if the neutral line of PMSG connected to the diode and capacitor as shown in fig. 5(a) and (b) respectively.

From the two cases in Fig. 5, it can be found that the second operation mode will lead to a more symmetric output voltage/current of the PMSG. Simulation results also show that with "boost-voltage", the output power is increased from 6.9 kW to 7.2 kW, the current THD is decreased from 4.6% to 3.2%, and the speed of the PMSG is changed from about 190r/min to 142r/min, the DC-link voltage Vdc is increased from 350V to 355V even though the speed of the PMSG is decreased.

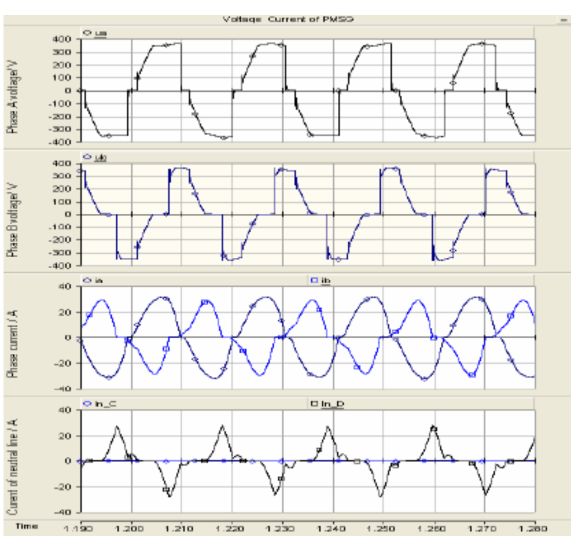
Fig. 6, gives the simulated output power, PMSG speed, voltage and current of the generation system. The boost rectifier is enabled since t=0.9sec, i.e., Switch S4 and S6 in Fig. 4 are controlled. It can be found that when boost rectifier is used, more power can be extracted.

C. Test Results

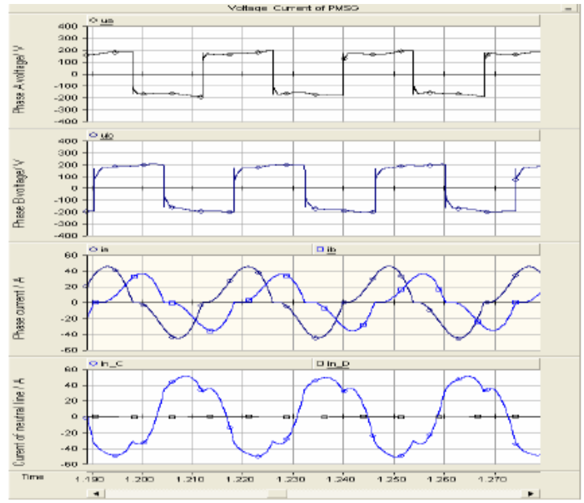
Under different operating conditions, Fig. 6, gives the phase voltage and current of the two-phase PMSG system. When neutral line of PMSG is connected to diode (condition a) and connected to capacitor bank (condition b). In the figures, from top to bottom, the curves indicate respectively voltage of phase A and phase B, current of phase A and phase B. tested results of above two conditions are listed in Table I. Table I, n is the PMSG speed in r/min, Uab is the line- line rms voltage of PMSG, Gen P is the output power of PMSG, load P is the power fed to load, and THD is the total harmonic distortion of the current fed to the load. Results show that when the speed of PMSG is low which means that when the wind speed is light, the "boost-voltage" operation makes it possible to extract more power from wind.

TABLE I. TEST RESULT OF THE PMSG SYSTEM

	n (r/min)	U_{ab} V	P_{gen} kW	P_l kW	THD %
Condition(a)	140	269.7	4.48	4.09	50.8
Condition(b)	140	237	10.9	9.91	1.6



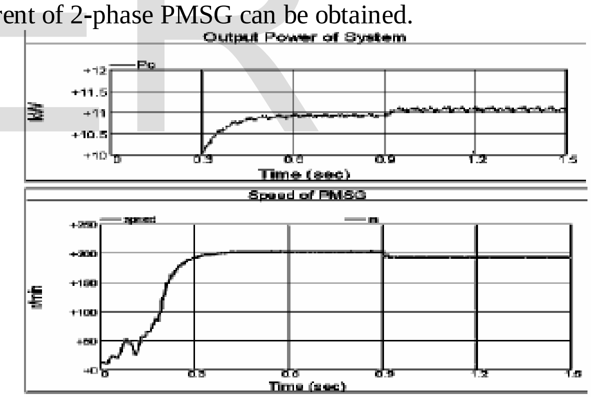
Neutral line is connected to diode



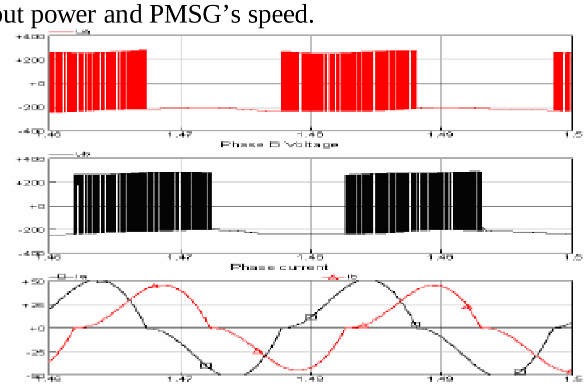
Neutral line is connected to capacitor bank.
Fig. 5. Voltage and current of the PMSG.

X.CONCLUSION

From the above simulation results, the rectifier topologies are studied through theoretical and simulations, that, at low wind speed, the power extracted from wind can be significantly increased when the presented topology works as an uncontrolled rectifier. Also it can be seen that the THD of current fed to the load is also greatly improved. So by incorporating the special rectifier, a much improved symmetrical output voltage and current of 2-phase PMSG can be obtained.



Output power and PMSG's speed.



Phase voltage and current of PMSG.
Fig. 6. Simulation results.

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