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Half-Controlled-Converter-Fed Open-Winding Permanent Magnet Synchronous Generator for Wind Applications

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Abstract – **The configuration and control of two cascaded half-controlled-converters (HCC) designed for use with an open-winding permanent magnet synchronous generator (PMSG) wind turbine are investigated in this paper. The system is modeled and simulated in Simulink with the assistance of PLECS. The simulations results demonstrate that by using speed-control-based hysteresis current regulator, pure sinusoidal phase current waveforms can be achieved in the machine windings at various power factors. Compared to an open-winding PMSG fed by two cascaded voltage source converters, the proposed system requires fewer switches but provides identical excellent performance and good fault tolerance. The proposed system is also free of shoot-through issues. Although HCC allows only unidirectional power flow, this is typically not an issue in the wind power applications.**

Index Terms — **Half-controlled-converter, open-winding PMSG, fault tolerance, speed control, current regulation**

I. INTRODUCTION

THE permanent magnet synchronous generator (PMSG) has gained increasing popularity in the wind power applications, placing higher demands and requirements on the power electronic devices. The configuration of a typical PMSG wind turbine is presented in Fig. 1. Since all the power must pass through the voltage source converters (VSC), the cost of the converters escalates as the wind generators move into every higher power range. The back-to-back VSC provides excellent protection against grid faults, but it cannot act against the faults at the machine terminals and the machine side converter (MSC). Meanwhile, the dead-time compensation must also be carefully tuned to avoid shoot-through.

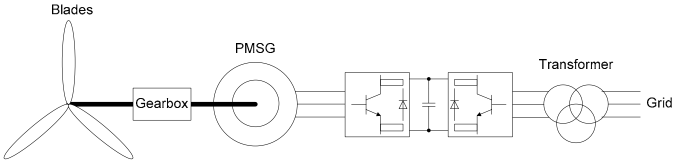

Fig. 1. System configuration of a typical PMSG wind turbine

To boost the performance and fault redundancy of the ac machine, individual phase drive units were introduced in [1] and [2], which form a cascaded inverter topology that drives an open-winding ac machine. The conceptual configuration is shown in Fig. 2. At the cost penalty of a doubled number of devices, the system shown in Fig. 2 provides better performance with lower switching frequency compared to standard VSC 3-phase inverter [1]. Since the full DC bus voltage can be directly applied to a single phase rather than across two phases, the DC bus voltage as well as the device voltage rating can be significantly lowered. Also the system provides improvements in the fault redundancy at short or open switch faults [3].

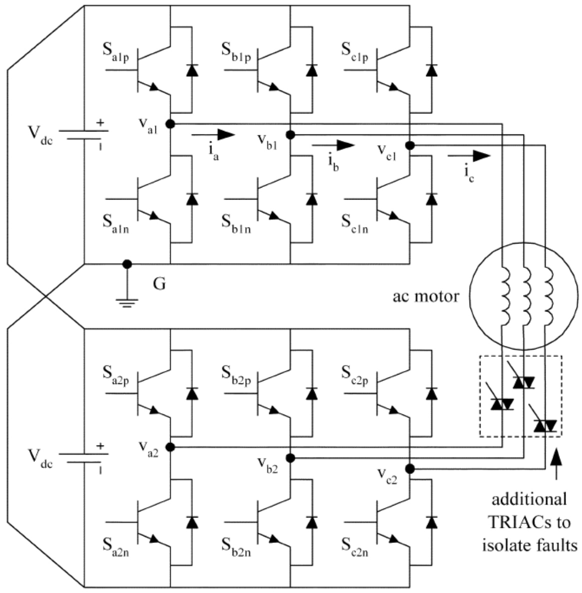

Fig. 2. Cascaded VSC feeding an open-winding ac motor [3]

In order to lower the power electronics cost and to preserve the fault redundancy with minimum sacrifice in performance, half-controlled-converters (HCC) can be substituted for the VSCs. The topology of a HCC is illustrated in Fig. 3. Its conceptual features and operating principles were introduced in [4]. The HCC costs about half that of the VSC and is free of shoot-through issues, but does not support bidirectional power flow.

The so called dual-half-controlled-converter (DHCC) was previously proposed in [5] as an excellent substitution of MSC for a standard PMSG wind turbines. However, unlike the DHCC topology of [5], the system proposed in this paper requires one HCC at each side of the open-winding PMSG. The overall system is capable of achieving good speed and current regulation over a wide operating range. The need for a coupling transformer as in [5] is eliminated.

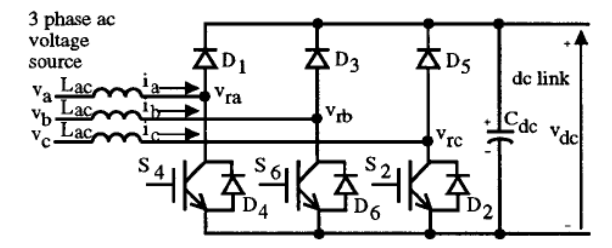

Fig. 3. Configuration of a half-controlled-converter for 3-phase boost rectification [4]

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Although a stand-alone HCC generates significant harmonics including even order harmonics [4], the cascaded topology consisting of two HCCs switching in a coordinated manner can easily manage the problem. It provides identical excellent performance and fault redundancy as the system shown in Fig. 2, but with fewer switches and without shoot-through issues.

II. System Configuration, Modeling, and Operating Principles

A. System Configuration

The proposed HCC-fed open-winding PMSG wind turbine is shown in Fig. 4, in which the TRIACs are optional for extra fault redundancy. Two HCCs, HCC1 and HCC2, are connected to the two sides of the open-winding PMSG. They share a common DC link which is connected to the grid side converter (GSC) that interfaces with the larger grid. The mechanical part of the wind turbine is omitted for simplicity. The converters can have independent DC links, which will provide an extra degree of freedom on the system, but such opportunities are not investigated in this paper.

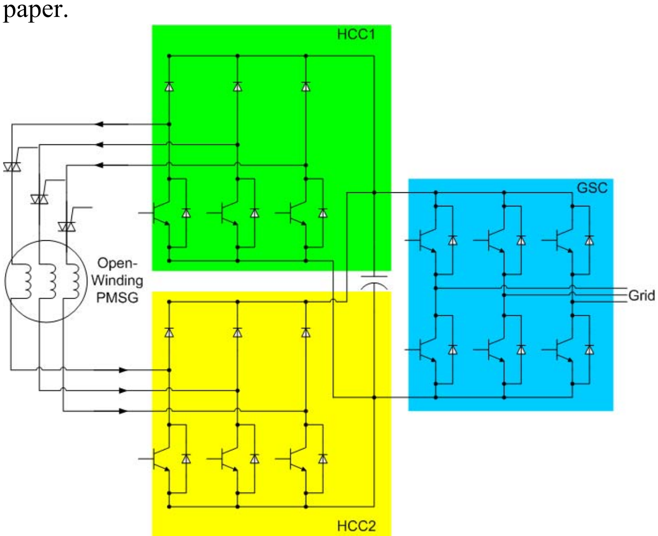


Fig. 4. Configuration of a cascaded-HCC-fed open-winding PMSG

B. Open-Winding PMSG Modeling

Unlike the standard PMSG with one end of all phase windings tied to the neutral, the open-winding PMSG has both ends of each phase winding open and accessible to external circuit. It can be modeled in the synchronous D-Q reference frame, which turns out to be not much different from the D-Q model for a standard three-phase PM machine with a floating neutral. The equivalent circuits of such a machine in the D-Q frame are presented in Fig. 5. The equations in the D-Q format can be written as:

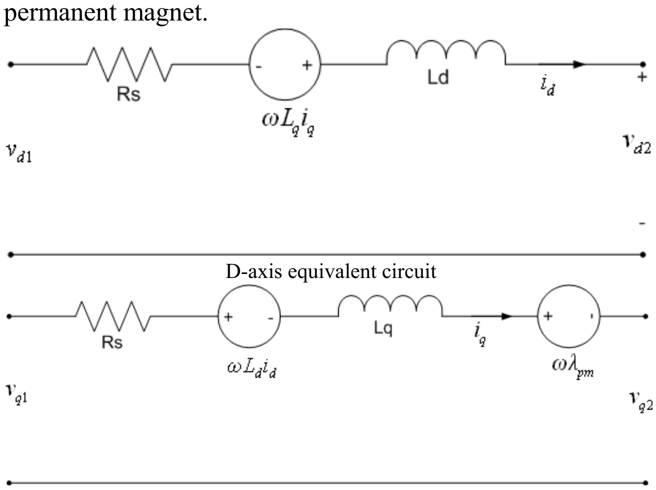
$$L_q \frac{di_q}{dt} = (v_{q1} - v_{q2} - \omega\lambda_{pm} - i_q R_s) - \omega L_d i_d \quad (1)$$

$$L_d \frac{di_d}{dt} = (v_{d1} - v_{d2} - i_d R_s) + \omega L_q i_q \quad (2)$$

$$T_e = \frac{3}{2}\frac{pole}{2}[\lambda_{pm} i_q + (L_d - L_q) i_q i_d] \quad (3)$$

$$P_e = \frac{3}{2}[(v_{d1} - v_{d2}) i_d + (v_{q1} - v_{q2}) i_q] \quad (4)$$

where v_{q1}, v_{d1} and v_{q2}, v_{d2} are Q-D voltages of HCC1 and HCC2 respective, and λ_{pm} is the flux linkage of the permanent magnet.



Q-axis equivalent circuit

Fig. 5. D-Q equivalent circuit of an open-winding PM machine

C. Operating Principles

To show the operating principle, the simplified per-phase equivalent circuit is used shown in Fig. 6. Herein, the current reference direction is also specified. For the current to flow in the specified direction, the anti-parallel diode of S2 must carry the phase current. Now if S1 is turned on, then the back-emf will force the phase current to increase; and if it is turned off then the difference between the DC voltage and the back-emf will force the current to decrease. Now if one reverses the polarity of both the current and back-emf, then it is S2 that regulates the current while the anti-parallel diode of S1 is carries the circulating current.

Since the full DC voltage can be applied to each phase winding rather than across two phases, the required DC bus voltage and therefore the voltage rating of the devices can be reduced. It should be noted that the mechanism in which the current is regulated requires that the DC voltage must be higher than the back-emf amplitude, and also that the back-emf must be large enough so as to build up the desired current.

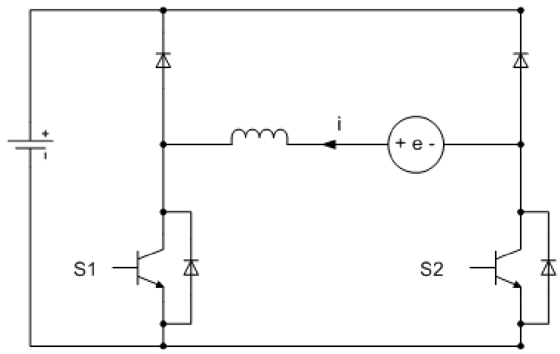


Fig. 6. Per-phase equivalent circuit

III. Controller Design

A speed-control-based current regulator is employed for the proposed system as shown in Fig. 7. The speed control mode enables maximum power point tracking for the wind turbine. The Q-axis current reference is generated through a PI regulator driven by the speed error. The D-axis current reference is set as a function of Q-axis current reference according to the desired power factor. In real applications the power factor seen from the grid is regulated by the GSC, and ideally the MSC should be operating at maximum torque per ampere mode, i.e. at unity internal power factor, so that the current capacity can be fully utilized.

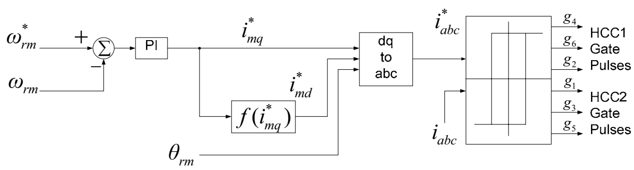


Fig. 7. Speed-control-based hysteresis current regulator

In this paper, a hysteresis regulator is adopted for its simplicity and robustness. To take full advantage of the topology, only three comparators are needed to drive the two HCCs. In fact, the switches in the lower half of HCC2, i.e. S24, S26, and S22, can be considered as the equivalent switches at the upper half of HCC1, i.e. S11, S13, and S15 respectively. Therefore, the switching of two converters can be easily coordinated as if they are one single converter, even without worrying about dead-time compensation. A simple switching table, as shown in TABLE I can be used.

TABLE I
HCC SWITCHING TABLE

Current Error	S (HCC1)	S (HCC2)
> hysteresis band	OFF	ON
< - hysteresis band	ON	OFF

To simplify the simulation and focus on the characteristics of the HCCs, the GSC is not modeled in the simulation. Instead, an equivalent constant DC source is used to represent the GSC in the simulation.

IV. SIMULATION STUDIES

The system parameters used for simulations are tabulated in TABLE II.

TABLE II
PARAMETERS OF THE SIMULATED SYSTEM

PMSG machine parameters	
Rated power	200 kW
Nominal line-to-line voltage	110 V
Nominal line current	1000 A
Pole number	4
D-axis inductance	0.1 mH
Q-axis inductance	0.1 mH
Magnet peak flux linkage	0.3 Webers
Stator resistance	0.01 Ω
Rotor inertia	1 kg m^2
DC link voltage	400 V

The d-axis current reference is set to zero for maximum torque per ampere operation. The steady state speed command is 0.8 pu. The results of steady state operation are shown below.

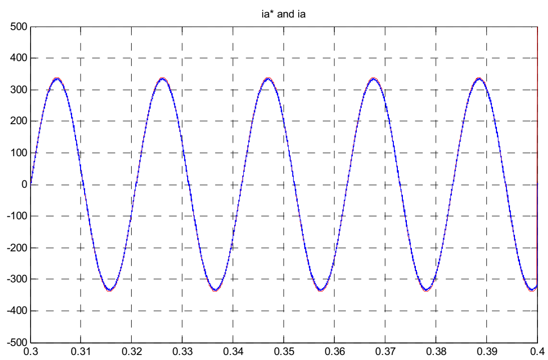


Fig. 8. Commanded (red) and measured (blue) phase current

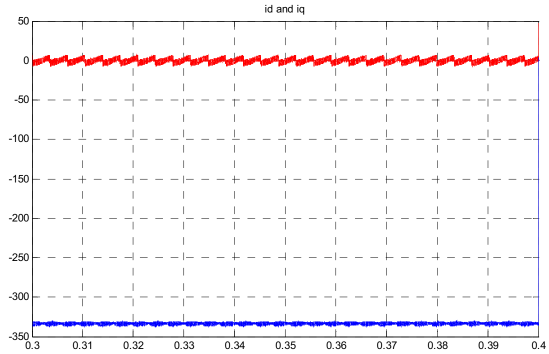


Fig. 9. D-axis (red) and Q-axis (blue) current

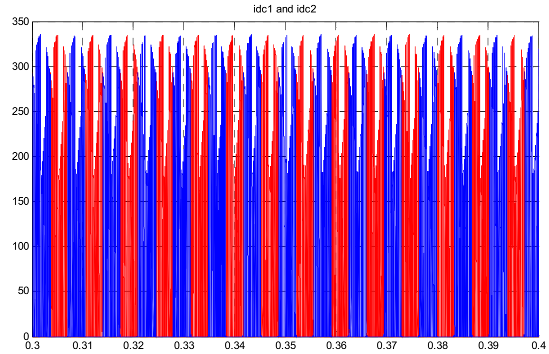


Fig. 10. DC link current of HCC1 (red) and HCC2 (blue)

It is observed that the measured current follows the reference almost ideally so that the currents in the D-Q frame as well as the developed torque have minimal significant harmonics. It should be noted again that the operating speed of the PMSG must be carefully chosen so that the back-emf is sufficiently large to build up the commanded current.

The system response to a step change in the speed command is presented in Figures 11-13. At time 0.4 second, the speed command changes from 0.8 pu to 0.9 pu. It is observed that the currents decrease to zero as the machine starts to accelerate towards the new commanded speed. This is because that the proposed system supports only unidirectional power flow, i.e. generating mode only. Consequently, to achieve a higher speed, the maximum acceleration the machine can obtain is via wind thrust, and the best that the converter can do to assist acceleration is to cut off the current so that there is no torque developed to counteract the acceleration.

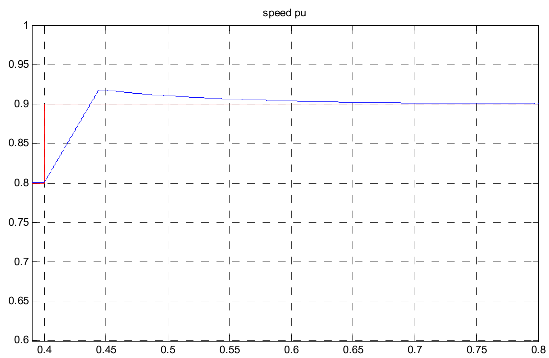


Fig. 11. Commanded (red) and measured (blue) rotor speed in per unit at a step change of speed command

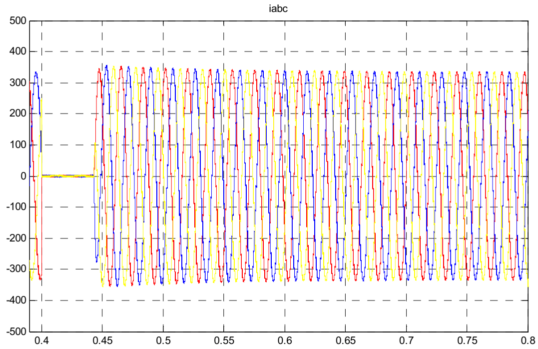


Fig. 12. Three-phase currents at a step change of speed command

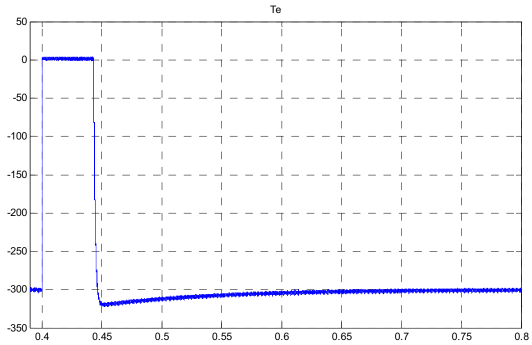


Fig. 13. Developed torque at the step change of speed command

The system response to a steep load torque change is also studied in Figure 14-16. The applied load torque has a step change at 0.8 second, from 300 Nm to 350 Nm. It can be seen that the current and torque responses are fast enough so that the speed deviation is minimum.

It should be noted that the maximum available torque is limited by the maximum achievable current, which then depends on the back-emf amplitude, and the back-emf is determined by the rotor speed. Hence, a feasible operating range, i.e. the optimal speed and torque, has to be carefully chosen.

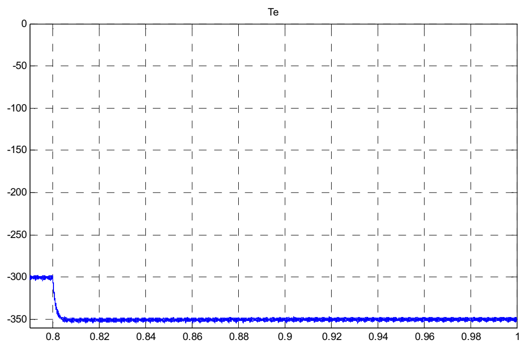


Fig. 14. Developed torque at a steep load torque change

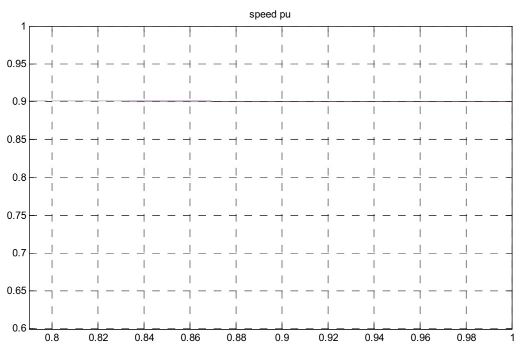


Fig. 15. Commanded (red) and measured (blue) speed at the steep load torque change

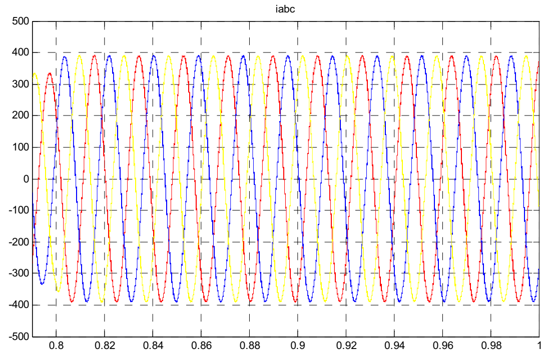


Fig. 16. Three-phase currents at the steep load torque change

V. Discussion and Conclusions

The simulation results demonstrate that the proposed system is capable of generating sinusoidal phase currents in the open machine windings. Compared to the three-terminal PMSG fed by standard VSC, the proposed system requires lower DC voltage so that the rating of the devices can be reduced. Although the cascaded HCC uses more devices than VSC, the diodes are relatively cheap, and the system provides significantly improved fault tolerance. Compared to the cascaded VSC case, the proposed system requires only six IGBTs instead of 12, which is a substantial cut in the cost; and identical performance and fault redundancy are preserved. While the switch rating of the HCC is the same as a single VSC, the circuit completely avoids the possibility of shoot-through.

It is true that the proposed system cannot support bidirectional power flow. However, this is not a serious issue for the wind applications since motoring operation is generally required. If desired, a small pony motor could be attached to the shaft to provide the brief boost in acceleration needed to reach a speed where the wind can provide the remainder of the accelerating power.

The coordinated speed-control-based hysteresis current regulator is simple and effective. The good speed regulation enables the PMSG to track the maximum power point with maximum torque per ampere. Other advanced switching techniques are currently under investigation.

VI. References

[1] K. A. Corzine, S. D. Sudhoff, and C. A. Whitcomb, “Performance characteristics of a cascaded two-level converter,” IEEE Trans. Energy Conv., vol. 14, pp. 433–439, Sept. 1999.

[2] N. Ertugrul, W. Soong, G. Dostal, and D. Saxon, “Fault tolerant motor drive system with redundancy for critical applications,” in Conf. Rec. IEEE Power Electronics Specialists Conf., vol. 3, 2002, pp. 1457–1462.

[3] Brian A. Welchko, Thomas A. Lipo, Thomas M. Jahns, and Steven E. Schulz, "Fault Tolerant Three-Phase AC Motor Drive Topologies: A Comparison of Features, Cost, and Limitations", IEEE Trans. Power Electronics, vol. 19, No. 4, July 2004.

[4] Jun Kikuchi, Madhav D. Manjrekar, Thomas A. Lipo, "Performance improvement of half controlled three phase pwm boost rectifier", Proceeding of IEEE Power Electronic Specialist Conferance, pp.319-324, vol.1, Jan. 1999.

[5] Y. Wang, T. A .Lipo, D. Panda, " The Application of Dual-Half-Controlled-Converter in a PMSG Wind Turbine," International Symposium on Power Electronics, Electrical Drives, Automation and Motion Control (SPEEDAM), Pisa, Italy, 2010.