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Application of a Dual-Half-Controlled-Converter in a PMSG Wind Turbine

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***Abstract*--The configuration and control of a dual-half-controlled-converter (DHCC) designed for a permanent magnet synchronous generator (PMSG) wind turbine are proposed in this paper. The system performance is analyzed using Saber simulations. The simulations results demonstrate that by using coordinated current regulation techniques, pure sinusoidal input current waveforms can be achieved and shared equally between the two half-controlled-converters (HCC). For the same amount of power throughput and the same number of switches, the current rating required for the switches is significantly lower compared to a voltage source converter (VSC), which brings down the semiconductor cost without sacrificing system performance.**

***Index Terms*--DHCC, PMSG, coordinated hysteresis current regulator, complementary configuration, harmonics**

I. INTRODUCTION

As the permanent magnet synchronous generator (PMSG) gradually gains popularity in the wind power industry, especially for direct-driven wind turbine applications, the demand for power electronic devices with higher rating at lower cost has risen. A typical configuration of a PMSG wind turbine is shown in Fig. 1 and the state of the art control strategies can be found in [1, 2]. Since all the power must go through the voltage source converter (VSC), the cost of the converters escalates as the generator reaches ever higher power rating. An alternative variable speed wind turbine with low power electronics cost is the doubly-fed-induction-generator (DFIG), in which the power that goes through the converter is typically only one third of the total generation. However, the slip rings bring in mechanical and maintenance issues. Also, additional equipment is necessary to meet the voltage sag ride through requirements; while the PMSG fed by a back-to-back VSCs provides such capability inherentlyu.

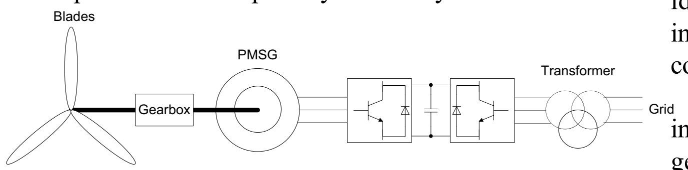

Fig. 1. System configuration of a typical PMSG wind turbine

In order to take advantage of the properties of the PMSG wind turbine system, and to minimize the power electronics cost at the same time, half-controller-converters (HCC) can be employed as a cost-effective substitution of the traditional machine-side VSC in a PMSG wind turbine system.

The topology of an HCC is shown in Fig. 2. Its concept and operating principles have been introduced in [3]. In this paper the authors reported the unidirectional power flow restriction of the HCC, and the necessary lagging power factor requirement for improved performance of the HCC in rectification operation. However, the resultant severe even harmonics make it a poor option for machine side converter since these harmonics not only saturate the windings but also induce unacceptable torque ripple.

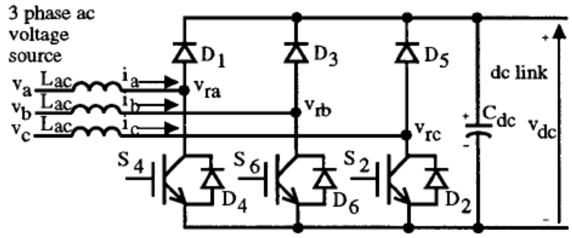

Fig. 2. Configuration of a half-controlled-converter for 3-phase boost rectification

The same authors also reported a design with two HCCs of complementary configuration which was applied to 3-phase rectification with multiple DC links [4]. In this case the even harmonics were cancelled out in such a configuration. The authors further introduced a coordinated current control technique which was capable of reducing not only the even harmonics but also non-triplen odd harmonics at the machine side. The greatest advantage of such a configuration over the traditional VSC is that the current and power throughput can be shared equally between the two HCCs so that the current and power rating of the device can be halved. The other merit is that the topology is free of shoot through.

The application of the complementary HCCs configuration in the 3-phase rectification with single DC link was reported in [5], in which the authors used identical coordinated current control technique reported in [4]. This topology can be used as the machine-side-converter with proper modifications in control techniques.

The application of HCCs in the wind turbine was first introduced in [6], in which a doubly-fed-induction-generator (DFIG) was fed by two HCCs. However, the simulation resulted indicated that the even harmonics could not be perfectly cancelled out which could be an issue for practical applications.

In this paper, a dual-half-controlled-converter (DHCC) is used to replace the machine-side VSC in the PMSG wind turbine. The system configuration, control

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algorithm, and performance are investigated using Saber simulations.

II. System Configuration and Operating Concept

The configuration of the proposed PMSG wind turbine is presented in Fig. 3. HCC1 and HCC2 are the two component modules of the DHCC, and the grid-side-converter (GSC) is a full-controlled VSC that interfaces the grid. A transformer is used at the machine side with two secondary sides of opposite polarity, which makes the two HCCs complementary equivalent [4]. The incorporation of the transformer grants power isolation and convenient common-emitter gate drive configuration [5]. The gearbox is optional as it depends on whether or not the PMSG is direct-drive.

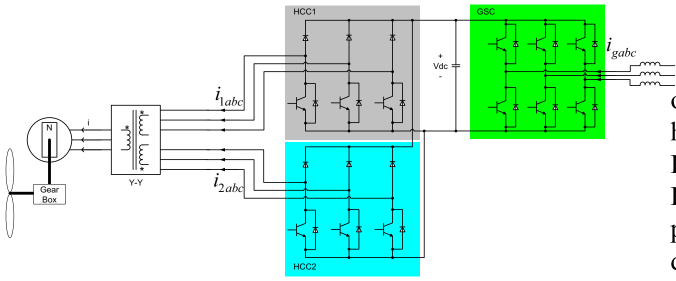

Fig. 3. System configuration of the proposed PMSG-DHCC wind turbine

Using proper control technique, the current and power through put can be shared equally between the two HCCs. Hence, for the same amount of output power and the same number of switches, the current rating of the switches in the DHCC can be reduced by half compared to a VSC, which leads to a lower cost without sacrificing much performance.

It should be mentioned that the DHCC supports only unidirectional power flow, so that the PM machine can only operate as a generator but not as a motor. Consequently, the generator is started simply by letting the wind stress drive the rotor shaft of the PMSG.

III. Controller Design

A speed-control-based current regulation algorithm is adopted for the DHCC as shown in Fig. 4. The speed command is dynamically varied to track the maximum wind power capture. The d-axis current command depends on the desired operating point. It is set to be a function of the q-axis current if the unity or lagging power factor at the machine terminal is preferred, and it can be set to zero if maximum torque per ampere performance is desired.

To achieve sinusoidal input current waveforms and minimize the harmonic content, a coordinated current control technique is implemented as shown in Fig. 4. The cross-coupling of the current commands through the low-pass-filter (LPF) is capable of eliminating not only the even harmonics but also the non-triplen odd harmonics [5]. The LPF is for filtering out switching noises. Proper limits should be set to the current commands in order to prevent over-current.

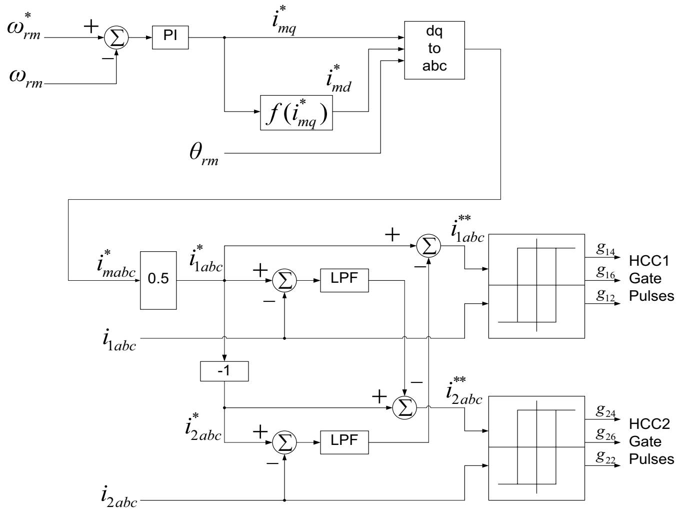

Fig. 4. PMSG-DHCC controller with coordinated current controller

The current commands for the two HCCs must be opposite polarity due to the complementary configuration, however, the voltage and current vectors of the two HCCs rotate in the same direction at same frequency. Hysteresis current regulators are used to generate gate pulses for the DHCC. A rotor position sensor is used to determine the q-axis location.

The GSC model is presented in Fig. 5 [7] with its state equations given in (1) - (3). Based on the mathematical model, the controller for the GSC has been designed as shown in Fig. 6. A multi-loop control algorithm is employed for the GSC. The d-axis current command depends on the desired power factor. Decoupling terms are incorporated to improve the dynamic performance of GSC [8].

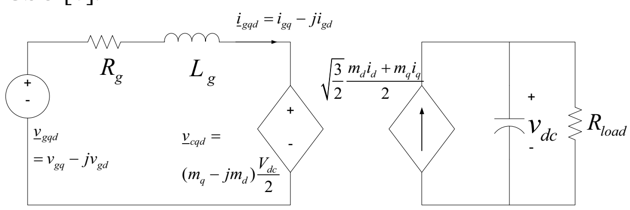

Fig. 5. Equivalent circuit model of GSC

$$L_g \frac{di_{gq}}{dt} = v_{gq} - \frac{m_q}{2} v_{dc} - i_{gq} R_g - \omega L_g i_{gd} \quad (1)$$

$$L_g \frac{di_{gd}}{dt} = v_{gd} - \frac{m_q}{2} v_{dc} - i_{gd} R_g + \omega L_g i_{gq} \quad (2)$$

$$C_{dc} \frac{dv_{dc}}{dt} = -\frac{v_{dc}}{R_{load}} + \sqrt{\frac{3}{2}}(m_d i_{gd} + m_q i_{gq}) \quad (3)$$

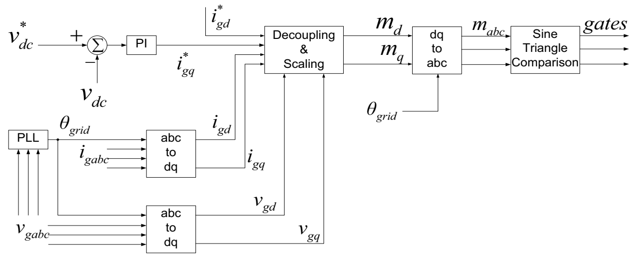

Fig. 6. Diagram of GSC controller

IV. Simulation Studies

The system parameters used for the SABER simulations are tabulated in TABLE I.

TABLE I
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
Converter side parameters	
DC link capacitor	1000 µF
Nominal DC link voltage	300 V

The operation of the PMSG-DHCC system is investigated at different power factors (viewed from the load) with and without the cross-coupling of the current commands. At every operating point with certain rotor speed and torque production, the variation of the power factor is realized by changing the d-axis current command function. Generally, at a certain level of q-axis current, decreasing d-axis current results in less lagging power factor at the PMSG terminal.

A. Simulation results of the PMSG-DHCC system without cross-coupling current commands

Fig. 7 to Fig. 9 show the simulation results of the PMSG-DHCC system without the coordinated current regulator, i.e. without cross-coupling the current commands. The signals from top to bottom are the torque production, rotor mechanical speed, commanded and measured machine phase currents, and measured currents of two HCCs. The harmonic information of the current is tabulated in TABLE II.

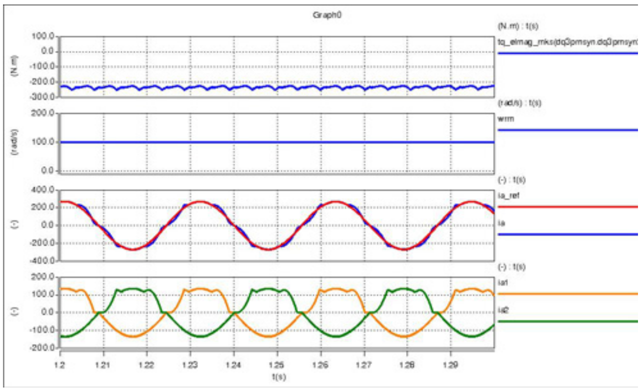

Fig. 7. Simulation results of the PMSG-DHCC system without coordinated current regulator at 10 degrees lagging power factor angle, rotor mechanical speed command = 100 rad/sec

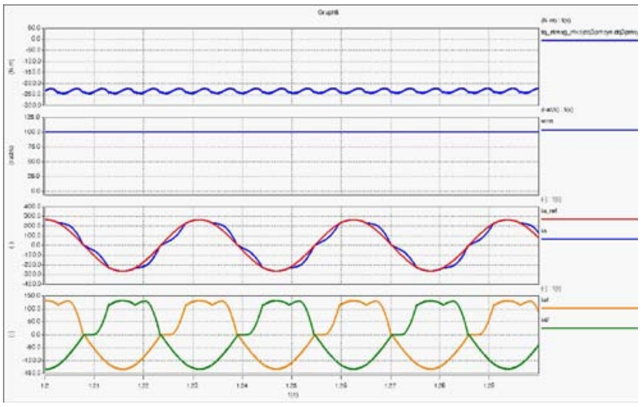
Fig. 8. Simulation results of PMSG-DHCC without coordinated current regulator at unity power factor, rotor mechanical speed command = 100 rad/sec

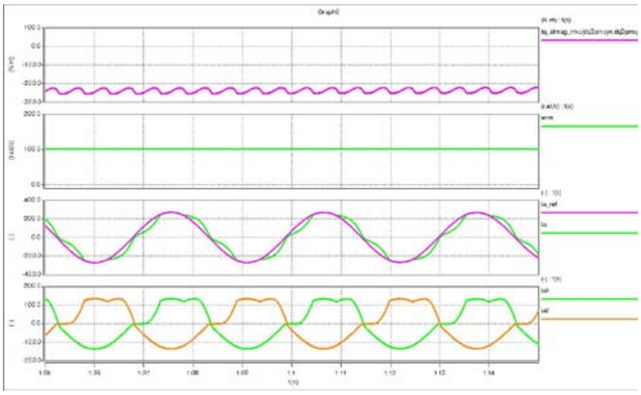
Fig. 9. Simulation results of PMSG-DHCC without coordinated current regulator with zero d-axis current command (5 degrees leading power factor angle), rotor mechanical speed command = 100 rad/sec

TABLE II
HARMONICS OF THE CURRENTS IN PMSG-DHCC SYSTEM WITHOUT COORDINATED CURRENT REGULATOR

P.F. Angle	11° lagging			unity			5° leading		
	ia	ia1	ia2	ia	ia1	ia2	ia	ia1	ia2
1st [A]	275.7	137.8	137.8	266.7	133.7	133.0	271.5	136.8	134.7
2nd [A]	1.6	6.5	7.4	1.8	17.3	18.9	5.7	24.4	27.5
4th [A]	0.7	9.0	8.4	0.4	13.6	13.5	23.0	18.3	15.8
5th [A]	16.6	8.0	8.7	20.8	10.4	10.5	23.0	10.5	12.6
7th [A]	14.4	7.6	6.8	10.4	5.1	5.2	9.7	4.7	5.0
THD [%]	8.2	12.5	12.6	8.9	18.9	19.8	9.9	24.1	25.8

B. Simulation results of the PMSG-DHCC system with cross-coupling current commands

Fig. 10 to Fig. 12 show the simulation results of the PMSG-DHCC system with the coordinated current regulator. The signals from top to bottom are the torque production, rotor mechanical speed, commanded and measured machine phase currents, and measured currents of two HCCs. The harmonic information of the current is tabulated in TABLE III.

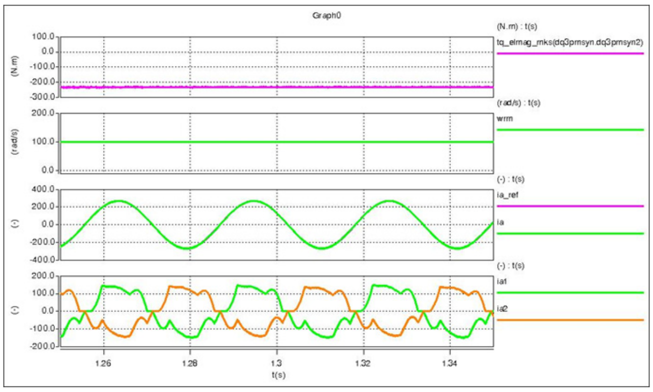

Fig. 10. Simulation results of the PMSG-DHCC system with coordinated current regulator at 10 degrees lagging power factor angle, rotor mechanical speed command = 100 rad/sec

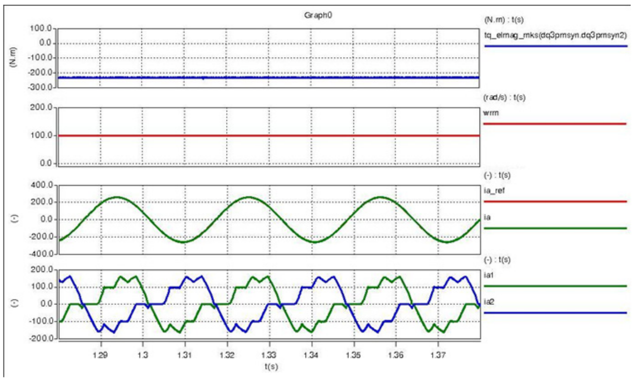

Fig. 11. Simulation results of PMSG-DHCC with coordinated current regulator at unity power factor, rotor mechanical speed command = 100 rad/sec

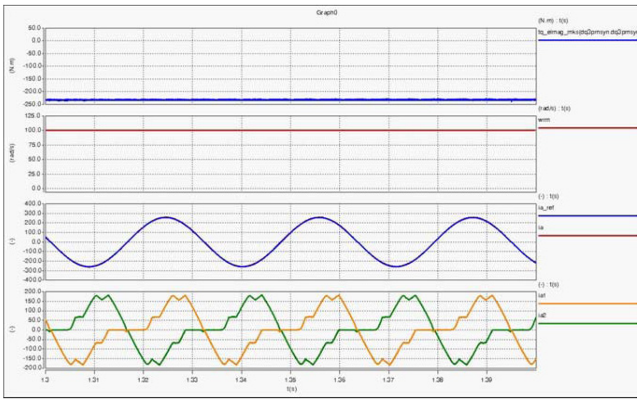

Fig. 12. Simulation results of PMSG-DHCC without coordinated current regulator with zero d-axis current command (5 degrees leading power factor angle), rotor mechanical speed command = 100 rad/sec

TABLE III
HARMONICS OF THE CURRENTS IN PMSG-DHCC SYSTEM WITH COORDINATED CURRENT REGULATOR

P. F. Angle	11° lagging			unity			5° leading		
	ia	ia1	ia2	ia	ia1	ia2	ia	ia1	ia2
1st [A]	268.0	139.6	128.4	260.4	130.1	130.3	257.7	128.9	128.9
2nd [A]	1.4	8.3	8.5	1.1	53.7	53.8	0.8	74.6	74.8
4th [A]	0.6	25.1	24.6	0.4	15.4	15.2	0.2	1.5	1.7
5th [A]	0.5	1.8	1.8	0.6	0.9	0.3	0.3	0.4	0.5
7th [A]	0.6	1.1	1.6	0.6	0.8	1.1	0.4	0.6	0.5
THD [%]	0.9	22.7	24.5	0.8	45.0	45.0	0.6	58.8	58.9

Fig. 13 and Fig. 14 show the system response to the step change of speed command and the slope change of turbine driving torque.

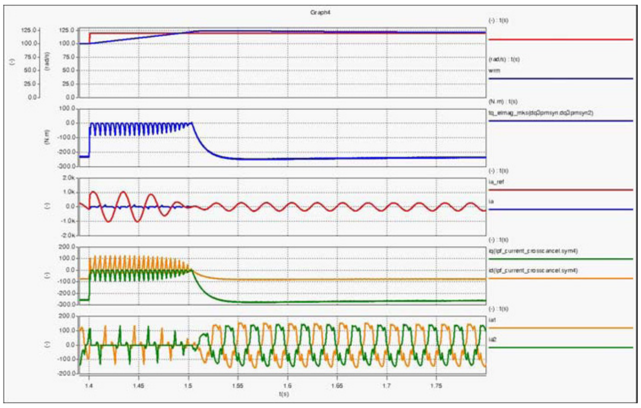

Fig. 13. Simulation results of PMSG-DHCC with coordinated current regulator at a speed command step change from 100 rad/sec to 120 rad/sec. Traces are: Commanded and real rotor mechanical speed, torque production, commanded and measured machine phase currents, measured phase current in d-q coordinate, measured currents of two HCCs.

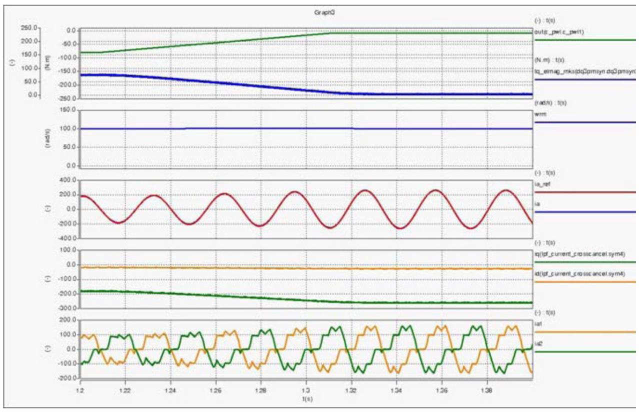

Fig. 14. Simulation results of PMSG-DHCC with CHCR controller at a driving torque slope change from 160 Nm to 230 Nm, rotor mechanical speed command = 100 rad/sec. Traces are: Applied driving torque and torque production, rotor mechanical speed, commanded and measured machine phase currents, measured phase current in d-q coordinate, measured currents of two HCCs.

V. DISCUSSIONS AND CONCLUSIONS

The simulation results show in Figures 7 to 14 demonstrate that the DHCC alone cannot guarantee sinusoidal current at the machine terminal. Although the even harmonics are well cancelled out by the complementary configuration, the rest of the harmonics are still significant. These harmonics not only saturate the machine but also induce the torque ripples that are detrimental to the gearbox. The variation of power factor does place an impact on the harmonic contents and current waveforms. As the power factor becomes less lagging, the current waveforms at the machine terminal degrade; especially the even harmonics tend to increase dramatically as the power factor becomes leading.

It is shown that the system performance is significantly boosted by the incorporation of the coordinated current regulator. This technique is capable of eliminating not only the even harmonics but also the non-triplen odd harmonics, so that a pure sinusoidal current waveform can be produced. This technique also enables the DHCC to work at unity and even certain leading power without degraded performance and THD. It is especially meaningful that the system can work at the maximum torque per ampere operating point, i.e. zero d-axis current, so that the generation capacity is maximized with the same amount of current.

However, as the power factor becomes less lagging and then leading, the "zero current period" in each HCC becomes longer. In order to compensate for the heavier current distortion in each HCC, the current peak in the complementary HCC increases, which requires a higher peak current rating for the switching devices. In the mean time, the current sharing between the two HCCs becomes more balanced, and the THD also drops, which are signs of better performance to a certain extent. Therefore, the choice of operating condition is generally a compromise, i.e. a lagging power factor mode is preferable if a minimum peak current rating of the device is desired; zero d-axis current mode should be chosen if the maximum torque per ampere is of concern; and the unity power factor mode is a compromise of the two above mentioned cases.

In conclusion, the coordinated current regulation technique must be applied in the proposed PMSG-DHCC system for satisfactory performances. The proposed control technique eliminates not only the even harmonics but also the non-triplen odd harmonics. It extends the operating region of the PMSG-DHCC system without degraded performance, so that the preferable maximum torque per ampere operating point is achievable.

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