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Open-End-Winding PMSG for Wind Energy Conversion System with Dual Boost NPC Converter

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Abstract--Commercial wind turbines have increased in size and power in the last decade, reaching 7.5MW. This has driven the development of new converter generator wind turbine configurations where permanent magnet synchronous generators (PMSG) have been at the forefront due to the higher power density, efficiency and lower maintenance, compared to the classic doubly fed induction generator (DFIG). In this paper a new WECS configuration is explored based on an open-end winding three-phase PMSG. The proposed converter configuration allows elevating the low voltage at generator side to a medium-voltage at the grid side. Each three-phase terminal of the machine is connected to a full bridge diode rectifier, followed by a dc-dc boost converter to elevate the voltage level and control the MPPT. The grid side converter is a three-level neutral point clamped (NPC) inverter operating at medium-voltage level. The performance of the proposed configuration is verified by simulation using PSIM and MATLAB/ SIMULINK platforms.

I. INTRODUCTION

Wind energy conversion systems (WECS) have been among the fastest growing renewable energy systems of the last decades, mainly due to technology development, cost reduction, environmental awareness and cost increase of fossil fuels. The technology development has been mainly driven by size and power increase and search for higher efficiency. In addition to higher power ratings, the substantial increase in penetration of wind power in the utility has also shaped technology development due to more demanding grid codes, particularly in relation to power quality and reliability requirements. This is why the latest wind turbine developments have been focused on permanent magnet synchronous generators with full scale power converters and reduction or even elimination of the mechanical gear stage. Currently state of- the-art commercial wind turbines reach up to 7.5MW, and present developments are aiming at the 10MW milestone. First configurations for WECS used squirrel-cage induction generators operating at fixed speed. Its simplicity and low investment cost where not advantageous enough for an industry growing towards larger turbines with higher energy output. As consequence, the double fed induction generator (DFIG) based WECS was introduced. The DFIG enabled variable speed operation and maximum power point tracking (MPPT), thanks to a partially rated power converter controlling the rotor currents. Therefore the DFIG became the work horse of the wind power industry. Nevertheless, cost reduction and improvements in reliability of power electronics technology, along with the more demanding grid codes made the full scale power converter a feasible solution. The search for lower maintenance and higher power rating, particularly for the growing offshore penetration, has made the gearless direct drive with large pole number synchronous generators an attractive solution. In particular, the permanent magnet synchronous generator (PMSG) due to the cost reduction of magnets, higher powers density and no need for slip rings. Most wind energy conversion systems (WECS) operate in low voltage at generator and grid side (690V), and are based on two-level back-to-back voltage source converter topologies connected in parallel to reach higher power ratings. In case of PMSG based WECS, since they do not consume reactive power, diode rectifiers at generator side followed by dc-dc boost stage and a grid tied two-level voltage source converter have also been adopted in industry as a cost effective and higher power density solution. Multiple three phase winding PMSG have also become popular in practice since they distribute the power among multiple back-to-back converters for each set of windings, instead of connecting them in parallel. In addition, multiphase machines provide a series of advantages, such as lower phase currents for the same power rating, fault tolerant operation in case of power switch or phase winding open circuit, lower MMF harmonics due to air gap cancelation, improved efficiency and higher power density. Multilevel converters have been also proposed extensively over the years for use in WECS. Nevertheless, only the neutral point clamped converter in back-to-back configuration has reached industrial application. This configuration operates in medium voltage at both generator and grid side. Although, medium voltage NPC motor drives are common in other application fields and have great advantages, the use of medium voltage generators is not a mainstream alternative in wind power industry. On the other hand open-end winding machines have been widely reported for different applications, including high power drives,

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propulsion systems and grid connected distributed generation systems, where good performance, improved power quality, high power density and efficiency have been observed. Despite this, open-end winding generator based WECS have not been extensively studied, and several generator-converter configurations can be further explored. In this work an open-end winding PMSG based WECS is proposed combining low-voltage operation at generator side with medium-voltage operation at grid side. This is achieved by combining three-phase diode bridges followed by dc-dc boost converters at the generator side to elevate voltage and perform the MPPT of the generator, and a three-level neutral point inverter at the grid side. The proposed configuration is a cost-effective solution with high power density, due to the very simple generator side converter. Medium-voltage operation with an NPC inverter at the grid side brings along several advantages such as higher efficiency, improved power quality, smaller filter and less transformer step-up effort. Simulation results are presented to provide a preliminary validation of the proposed configuration.

II. CONFIGURATION DESCRIPTION

The proposed WECS configuration is shown in fig 1. The wind turbine is coupled directly to an open-end-winding three phase PMSG, without a gearbox due to the high number of poles. The open-end winding three phase PMSG has no neutral, and both ends of each stator phase winding are available to be connected to a power converter. In this work, each set of three-phase terminals are connected to a diode full bridge rectifier. This is possible since PMSGs do not require magnetizing currents, as is the case in induction machines. The diode rectifier provides unidirectional power flow from the generator to the grid-tied inverter, with a simple and cost effective design. A second converter stage, based on dc-dc boost converters elevates the voltage while it can be used to control the power drawn from the generator, hence enabling the implementation of an MPPT scheme. Note that depending on the power level, interleaved or multichannel boost converters can be used. In case of multichannel boosts, when controlled with phase shifted carriers, the current and voltage ripples at the input and output of the dc-dc converters can be significantly reduced while increasing the power rating of the converter.

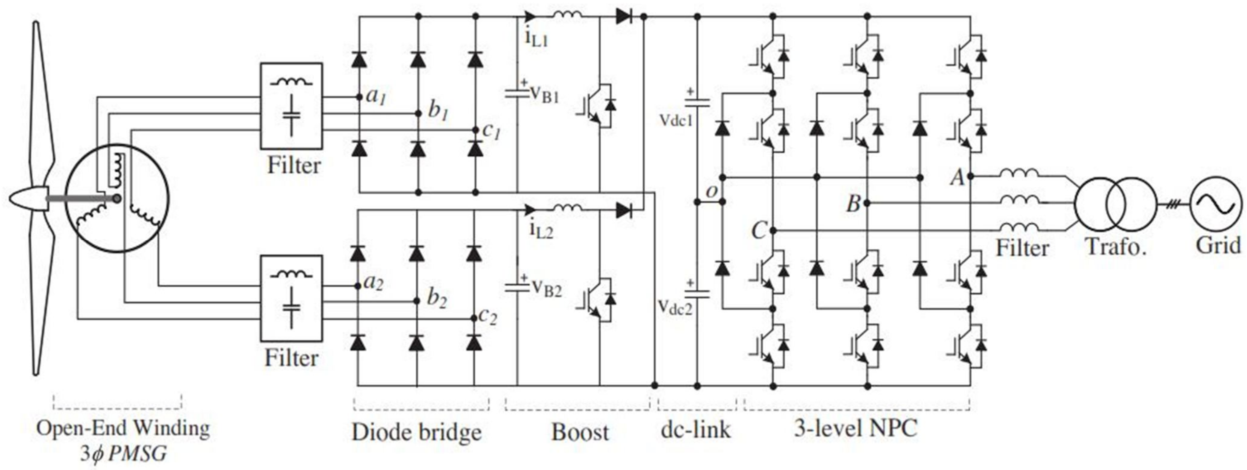

Fig 1 Open-end winding PMSG double boost NPC based WECS

The third converter stage is based on a medium-voltage NPC inverter connected to the grid. The NPC generates three output voltage levels ($V_{dc1}+V_{dc2}$, 0, $-V_{dc1}-V_{dc2}$) per phase, by connecting each output to the positive, neutral and negative potentials of the dc-link through the appropriate switching state. The NPC shown in Fig. 1 features IGCT switching devices, although high-voltage IGBT based versions are also available. The NPC is usually connected to 2.3, 3.3, 4.16 and 6.6 kV medium voltage grids, and can be found up to tens of megawatt. The proposed configuration has higher power density, and is more cost effective compared to the NPC in back-to-back configuration, mainly due to the simple generator side converter. The trade-off for such advantage is that the diode-boost generator side converter has less control degrees of freedom, and produces more distorted generator currents which can cause higher torque ripple. However, passive ac filters are often used to mitigate this effect, and torque fluctuations do not affect the system operation due to the very large inertia of the turbine.

III. OPEN-END WINDING THREE-PHASE PMSG MODEL

The open-winding three-phase permanent magnet synchronous generator has both ends of each phase winding available for connecting to the diode rectifiers. The first end of each phase (a1; b1; c1) is connected to the upper diode bridge rectifier, while the second end of each phase (a2; b2; c2) is connected to the lower diode bridge rectifier shown in fig 5.2. The machine has non salient poles and the stator windings are sinusoidal distributed. By assuming a sinusoidal magneto motive force distributed in the air gap and ignoring magnetic saturation, core losses and mutual leakage inductance, the phase model of the PMSG is described by the stator voltage matrix equation as follows.

$$v_s = R_s i_s + p.(L_s i_s) + p.\lambda_{sm}$$

where the stator voltage V_s, stator current i_s and permanent magnet flux linkage λ_{sm} are defined as the following vectors:

$$v_s = [(v_{a1} - v_{a2})(v_{b1} - v_{b2})(v_{c1} - v_{c2})]^T$$

$$i_s = [i_a\ i_b\ i_c]^T$$

$$\lambda_{sm} = \lambda_m[\cos(\theta_r)\ \cos(\theta_r - \frac{2\pi}{3})\ \cos(\theta_r + \frac{2\pi}{3})]^T$$

Where, λ_m is the flux of the permanent magnets of the generator and θ_r is the rotating angle of the magnetic field. The matrix R_s and L_s correspond to the resistance and inductance of each phase stator winding. For simplicity, the generator model can be described in synchronous coordinate's dq as follows, by applying Clark- Park vector transformation.

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

$$v_{q1} - v_{q2} = L_q \frac{di_q}{dt} + \omega\lambda_m + R_s i_q + \omega L_q i_q$$

The dynamic behavior of the rotor speed ω in terms of mechanical torque T_m and electromagnetic torque T_e is described by the following equations:

$$\frac{d\omega}{dt} = \frac{P}{J}(T_e - T_m)$$

$$T_e = \frac{3P}{2}\left(\lambda_m i_q + (L_d - L_q) i_q i_d\right)$$

The parameters of the model are the number of pole pairs P, the flux of the permanent magnets λ_m, the stator resistance R_s, the stator inductance L_s or synchronous inductances L_q and L_d, and the moment of inertia J.

IV. CONTROL

A. Generator side converter control

The diagram in Fig 2 shows the control strategy applied to the wind turbine, the permanent magnet generator and the boost converters. A PI regulator is used to control the speed V_m of the open-end winding permanent magnet generator. In order to have the optimal mechanical speed for a specific wind speed v!, its reference value m is obtained from a maximum power point tracking (MPPT) scheme, based on the optimal tip speed ratio (OTSR) method. The PI regulator gives the reference value i_L^* for the currents i_{L1} and i_{L2} through the inductor for each boost converter. The current reference value is proportional to the torque and power of the mechanical system. Since it is simple and robust, in this work the inductor currents are controlled by hysteresis comparators, which provide the switching signals SB1 and SB2 for each semiconductor.

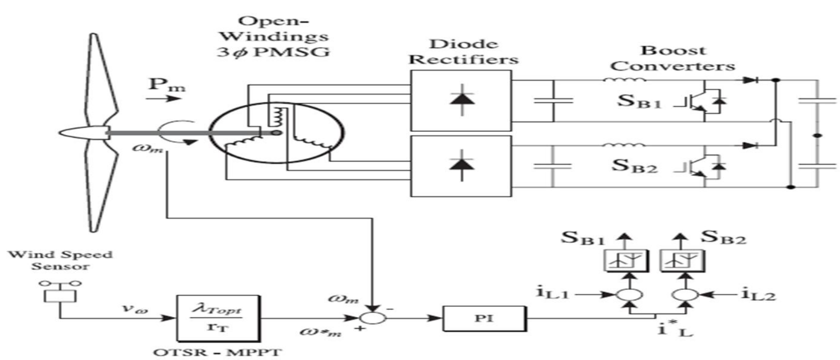

Fig 2 Generator side converter control

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B. Grid side converter control

As Fig 3 shows, the control scheme adopted for the neutral-point clamped (NPC) grid-tied inverter corresponds to the traditional voltage oriented control (VOC) .In this work the modulation method for the NPC converter is based on phase disposition PWM or level shifted PWM (LSPWM). In order to increase the dc-link usage up to 15%, a min-max zero sequence has been added to the modulation scheme. In addition, it has been included the traditional dc link voltage unbalance compensation algorithm in which an offset proportional to the unbalance is added to the voltage references.

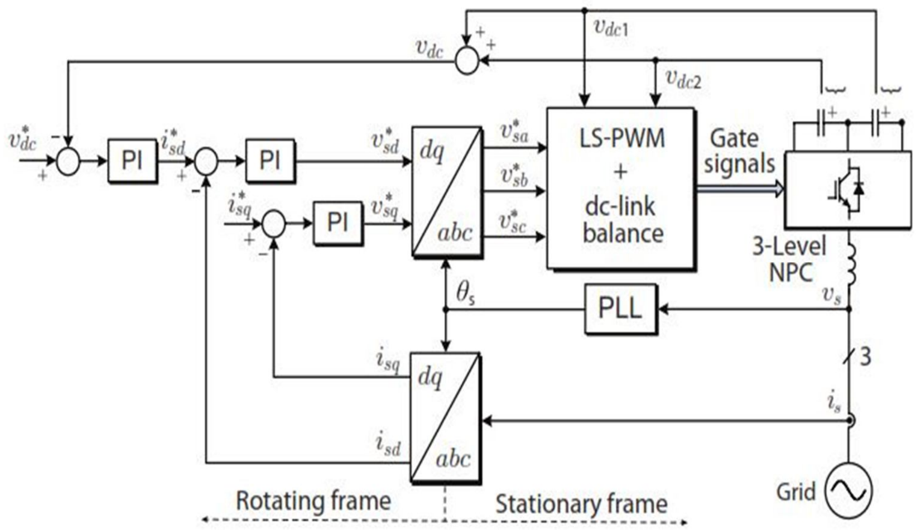


Fig 3 Grid Side Converter Control

V. RESULT

In order to explore the performance of the proposed configuration, simulations were carried out by using PSIM software for the power converters, and MatLab & Simulink for the generator model and control schemes. The parameters for the open-winding permanent magnets generator are shown in Table 1. Since the generator side works at low voltage and low frequency, the value of the capacitor right after each full diode bridge rectifier, is 45,000[μ F] (= 0.59 [pu]), and the boost converter inductor value is 10[mH] (=2.9[pu]). The average switching frequency, for each boost converter, is 2[kHz].

Parameter	Value
Rated Mechanical Power	$2[MW]$
Rated Line-to-line Voltage	$690\ [V]$
Rated Rotor Speed	$22.5\ [rpm]$
Rated Mechanical Torque	$848.826\ [KN \cdot m]$
Rated Rotor Flux Linkage	$5.8264\ [Wb]$
Stator Winding Resistance	$0.821\ [m\Omega]$
Synchronous Inductances	$1.5731\ [mH]$
Number of Pole Pairs	26
Moment of Inertia	$2.6922[MKg \cdot m^2]$

Table 1 Simulation parameters for the PMSG

At the grid side the dc-link capacitors value is 4700[μF] and the reference voltage value is 2,750[V] for each one. The average switching frequency is 1[kHz] for the NPC inverter. The parameters of the model are the number of pole pairs P, the flux of the permanent magnets λ_m, the stator resistance R_s, the stator inductance L_s or synchronous inductances L_q and L_d, and the moment of inertia J. The dynamic results are obtained by applying a step change in the wind speed from 0.9[pu] to 1[pu]. The wind speed step produces a power step change with cubic relation (0.73[pu] to 1[pu]), which generates an electrical torque step change of the same proportion. This change is equivalent to a step change in the turbine speed reference from 20.25[rpm] to 22.5[rpm] (0.9[pu] to 1[pu]).

Figure 3 shows the results at the generator side. Before the wind speed change is applied, the mechanical T_m and electric T_e torque are equal. Right after the wind speed step change is applied at time $t = 1.5$[s], the MPPT algorithm increases the generator speed reference. The control system forces to build electric torque T_e with opposite sign in order to accelerate the machine. However the electrical torque T_e producing current is saturated to zero, so no power is consumed for acceleration, instead the acceleration is produced by the mechanical torque T_m, which is provided by the wind. This can be confirmed by the generator currents (i_{ag} , i_{bg} , i_{cg}) dropping to zero. When the speed ω_m reaches the reference ω_m^*, the electric torque T_e builds up to the level of the mechanical torque T_m to leave the generator in steady state.

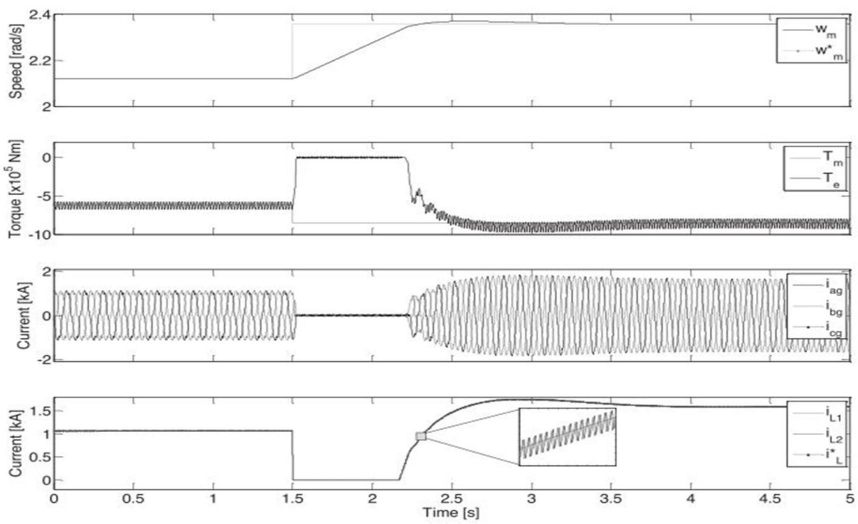


Fig 3 Generator side dynamic response during wind speed step change

Figure 3 also shows the boost converter current through each inductor i_{L1}, i_{L2} and the reference i_L^*. As it was explained in the previous section, the generator speed PI regulator returns the reference value i_L^* for the currents i_{L1} and i_{L2}, which is proportional to the power and electrical torque T_e .The high dynamic performance of the hysteresis regulators can be clearly appreciated. The main drawback of the proposed configuration is the higher distortion of the generator currents due to the diode rectifier, which in turn causes more torque ripple than other configurations. However, since the inertia of wind turbines is very high, this drawback does not affect the speed regulation and MPPT. In addition this effect can be mitigated using ac filters if needed.

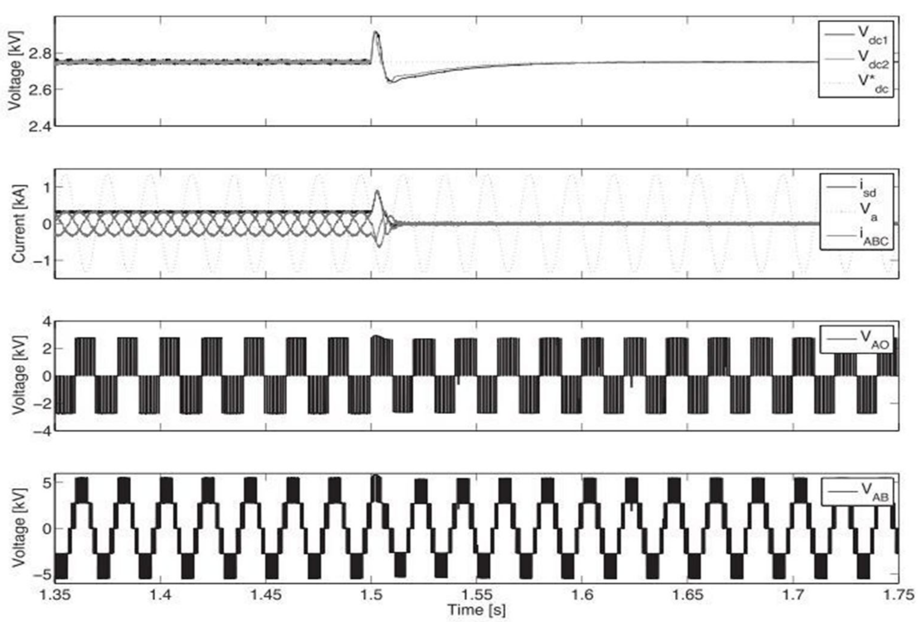


Fig 4 Grid-tied 3L-NPC inverter dynamic response before during a wind speed step change

The grid side results are shown in Fig 4. Since the machine works at low speed (due to high pole number), the time scale for the grid signals is different than Fig 3. Figure 4 shows the results before and during the wind speed step change is applied, while Figure 5 shows the behavior after. In addition, the steady state 1.75–2.15[s] has been deleted for better appreciation. It can be observed that the dc-link voltages V_{dc1} and V_{dc2} are controlled and balanced following the reference V_{dc}*. When the turbine is accelerated, the power transferred to the grid becomes zero, to allow all mechanical torque to accelerate the turbine. During this transient the active power is adjusted by the controllers. When the generator reaches the reference speed, electric torque builds up and power is transferred to the grid, causing a voltage swell in the dc-link voltages before it's compensated by the controller.

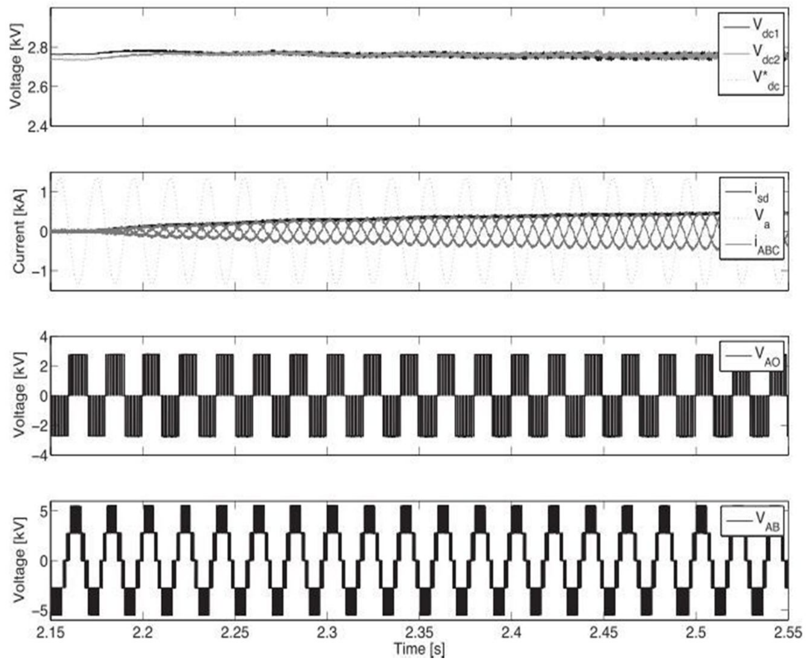


Fig 5 Grid-tied 3L-NPC inverter dynamic response after during a wind speed step change

The grid three phases currents i_A , i_B and i_C increase their amplitude as expected due to higher wind speed that generates more power. The d-axis current is enveloping the ac currents, and has been included to show the dynamics of the current control loop described in the previous section. The grid phase a voltage waveform is shown also in order to highlight the correct synchronization with the grid. Additionally, Fig 4 shows the three-level output voltage V_{AO}, and the five-level line-to-line voltage V_{AB} waveforms of the NPC inverter.

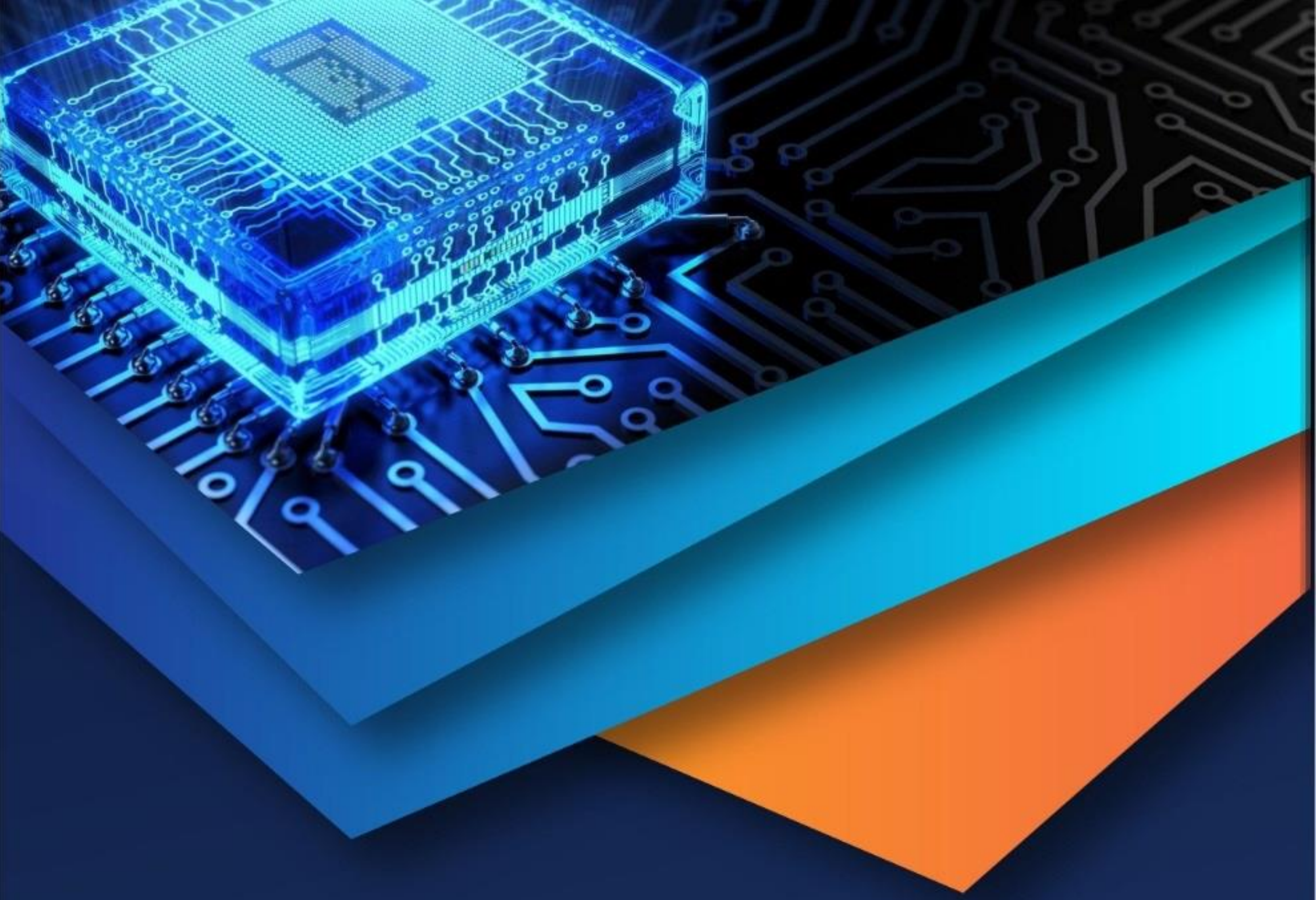
VI. CONCLUSION

In this work, a new open-end winding PMSG based configuration for wind energy conversion systems has been studied. The PMSG along with the proposed generator side converter offers a higher power density, reliable and cost-effective solution, scalable to multi megawatt turbines. The NPC grid side inverter offers medium-voltage operation at grid side, with high power quality and efficiency. Traditional control schemes can be used to control the proposed configuration. Simulations results have shown a good performance of the system for both steady state and dynamic response. Although low order harmonic current distortion is introduced at the generator side because of the diode rectifiers, it does not affect the operation of the turbine due to the large inertia, while this effect an also be mitigated using ac filters.

REFERENCES

[1] REN21 - Renewable Energy Policy Network for the 21st Century, "Renewables 2012 - Global Status Report", available online at http://www.ren21.net
[2] "Grid code - high and extra high voltage," E.ON Netz Gmbh, April 2006.
[3] B. Wu, Y. Lang, N. Zargari, and S. Kouro, Power Conversion and Control of Wind Energy Systems, 1st ed. Wiley-IEEE Press, July 2011.
[4] Ke. Ma, F. Blaabjerg and Xu. Dehong , " Power devices loading in multilevel converters for 10 MW wind turbines," IEEE International Symposium on Industrial Electronics (ISIE), pp. 340–346, 2011.
[5] S. Muller, M. Deicke, and R. D. Doncker, "Doubly fed induction generator systems for wind turbines," IEEE Ind. Appl. Mag., vol. 8, no. 3, pp. 26–33, May/Jun 2002.

[6] J. Carrasco, L. Franquelo, J. Bialasiewicz, E. Galvan, R. Portillo, M. Prats, J. Leon, and N. Moreno-Alfonso, "Power-Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey," IEEE Trans. Ind. Electron., vol. 53, no. 4, pp. 1002–1016, August 2006.
[7] X. Xiong, H. Xin, "Research on multiple boost converter based on MW-level wind energy conversion system," Proceedings of the Eighth International Conference on Electrical Machines and Systems (ICEMS), vol. 2, pp. 1046–1049, 2005.
[8] J. Birk, B. Andresen, "Parallel-connected converters for optimizing efficiency, reliability and grid harmonics in a wind turbine." European Conference on Power Electronics and Applications (EPE), pp. 1-7, 2007.
[9] E. Levi, "Multiphase electric machines for variable-speed applications," IEEE Trans. Ind. Electron., vol. 55, no. 5, pp. 1893–1909, May 2008.
[10] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. G. Fran quelo, B. Wu, J. Rodriguez, M. Perez, and J. I. Leon, "Recent advances and industrial applications of multilevel converters," IEEE Trans. Ind. Electron., vol. 57, no. 8, pp. 2553–2580, August 2010.
[11] Zhe Chen, J. M. Guerrero, F. Blaabjerg, "A Review of the State of the Art of Power Electronics for Wind Turbines," IEEE Transactions on Power Electronics, vol.24, no.8, pp.1859–1875, Aug. 2009.
[12] Yaramasu, V.; Bin Wu; "Three-level boost converter based medium voltage megawatt PMSG wind energy conversion systems," 2011 IEEE Energy Conversion Congress and Exposition (ECCE) , vol., no., pp.561–567, 17-22 Sept. 2011.
[13] S. Alepuz, S. Busquets Monge, J. Bordonau, J. Gago, D. Gonzalez, and J. Balcells, "Interfacing renewable energy sources to the utility grid using a three-level inverter," IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1504-1511, Oct. 2006.
[14] M. Malinowski, S. Stynski, W. Kolomyjski, and M. P.Kazmierkowski, "Control of three-level PWM converter applied to variable-speed type turbines," IEEE Trans. Ind. Electron., vol. 56, no. 1, pp. 69-77, Jan. 2009.
[15] ABB, "Medium voltage for wind power - PCS 6000 brochure," available at www.ABB.com.
[16] M. Winkelnkemper, F. Wildner, and P. K. Steimer,"6 MVA five-level hybrid converter for windpower," in Proc. IEEE Power Electron. Spec. Conf., pp. 4532–4538, Jun. 15-19, 2008.
[17] F. Blaabjerg, M. Liserre and Ke. Ma, "Power Electronics Converters for Wind Turbine Systems" IEEE Transactions on Industrial Applications., vol. 48, no. 2, pp. 708–719, March/April 2012
[18] M. Duran, S. Kouro, B. Wu, E. Levi, F. Barrero, S. Alepuz, "Six-phase PMSG wind energy conversion system based on medium-voltage multilevel converter," 14th European Conference on Power Electronics and Applications (EPE 2011), Birmingham, UK, 30 August - 1 September, 2011.
[19] P.P.. Rajeevan, K. Sivakumar, C. Patel, K. Gopakumar and A.R. Haitham , " A hybrid nine-level inverter for IM drive " IEEE International Symposium on Industrial Electronics (ISIE)., pp. 65–70, 2011.
[20] J. Wei, B. Zhou, C. Han, Q. Deng, M. Shi and Y. Liu , "The implementation of a novel open-winding permanent magnetic starter generator" 4th International Conference on Power Electronics Systems and Applications (PESA), pp. 1–6, 2011.
[21] E. Levi, I.N.W. Satiawan, N. Bodo, and M. Jones , "A Space- Vector Modulation Scheme for Multilevel Open-End Winding Five-Phase Drives" IEEE Transactions on Energy Conversion, vol. 27, no. 1, pp. 1–10, March 2012.
[22] Y. Kawabata, M. Nasu, T. Nomoto, E. C. Ejiogu, and T. Kawabata, "High efficiency and low acoustic noise drive system using open-winding AC motor and two space-vector-modulated inverters", IEEE Transactions on Industrial Electronics, vol. 49, no. 4, pp. 783–789, August. 2002.
[23] G. Grandi, C. Rossi, D. Ostojic, and D. Casadei, "A New Multi- level Conversion Structure for Grid-Connected PV Applications", IEEE Transactions on Industrial Electronics, vol. 56, no. 11, pp. 4416–4426, November. 2009.
[24] M. Kwak, and S. Sul, "Control of an Open-Winding Machine in a Grid-Connected Distributed Generation System", IEEE Transactions on Industry Applications, vol. 44, no. 4, pp. 1259–1267, July/August. 2002.
[25] Y. Wang, T.A. Lipo and D. Pan, "Half Controlled Converter Fed Open-Winding Permanent Magnet Synchronous Generator for Wind Applications," 14th International Power Electronics and Motion Control Conference, EPE-PEMC 2010.
[26] S. Kouro, J. Rodriguez, B. Wu, S. Bernet, M. Perez, "Powering the Future of Industry: High-Power Adjustable Speed Drive Topologies," Industry Applications Magazine, IEEE , vol.18, no.4, pp.26-39, July-Aug. 2012.
[27] Nahome, A.A., Zaimeddine, R., Bing L., Undeland, T., Vector Control of Direct Drive Six Phase Permanent Magnet Synchronous Generators. Power Tech, 2011 IEEE Trondheim, vol. 55, pp. 1 - 7, 2011.
[28] M. Malinowski, M. P. Kazmierkowski, and A. M. Trzynad lowski, "A comparative study of control techniques for pwm rectifiers in ac adjustable speed drives," IEEE Trans. on Power Electron., vol. 18, no. 6, pp. 1390–1396, Nov. 2003.
[29] N. Celanovic and D. Boroyevich, "A comprehensive study of neutral-point voltage balancing problem in three-level neutral-point clamped voltage source PWM inverters," IEEE Transactions on Power Electronics, vol.15, no.2, pp. 242–249, Mar 2000.



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