

Slot-PM-Assisted Hybrid Reluctance Generator with Self-Excited DC Source for Stand-Alone Wind Power Generation

Xing Zhao, Jiang Jifu, Shuangxia Niu and Qingsong Wang

Author post-print (accepted) deposited by Coventry University's Repository

Original citation & hyperlink:

Zhao, X., Jifu, J., Niu, S. and Wang, Q., 2021. Slot-PM-Assisted Hybrid Reluctance Generator with Self-Excited DC Source for Stand-Alone Wind Power Generation. *IEEE Transactions on Magnetics*. (In Press)

<https://dx.doi.org/10.1109/TMAG.2021.3081585>

DOI [10.1109/TMAG.2021.3081585](https://dx.doi.org/10.1109/TMAG.2021.3081585)

ISSN 0018-9464

Publisher: IEEE

© 2021 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Copyright © and Moral Rights are retained by the author(s) and/ or other copyright owners. A copy can be downloaded for personal non-commercial research or study, without prior permission or charge. This item cannot be reproduced or quoted extensively from without first obtaining permission in writing from the copyright holder(s). The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the copyright holders.

This document is the author's post-print version, incorporating any revisions agreed during the peer-review process. Some differences between the published version and this version may remain and you are advised to consult the published version if you wish to cite from it.

Slot-PM-Assisted Hybrid Reluctance Generator with Self-Excited DC Source for Stand-Alone Wind Power Generation

Xing Zhao¹, Jiang Jifu¹, Shuangxia Niu¹, Qingsong Wang²

¹Department of Electrical Engineering, Hong Kong Polytechnic University, Hung Hom, Hong Kong

²School of Computing, Electronics and Mathematics, Coventry University, United Kingdom

This paper proposed a new slot-PM-assisted hybrid reluctance generator (SPMa-HRG) with self-excited DC source for stand-alone wind power generation system. By introducing PM excitation in stator slot openings, enhanced torque density due to flux modulation effect can be achieved compared to original reluctance topology. Moreover, the introduced PMs make it feasible to build a self-excited DC source to fed DC field winding without using extra power supply. In particular, a simple design of AC supply winding is proposed, by splitting a small portion of AC armature winding to provide electrical power to DC field winding through a diode rectifier and small capacity H-bridge converter. Compared to using separate DC source, the device cost is reduced, and the system reliability is improved. In this paper, the generator structure and operation principle are introduced. PM usage is optimized to obtain the optimal torque. The feasibility of the optimal design with self-excited DC source is verified by field-circuit coupled finite element analysis.

Index Terms—Slot-PM-assisted, hybrid reluctance generator, self-excited DC source, stand-alone wind power generation.

I. INTRODUCTION

Nowadays, developing renewable and green energy sources has attracted more and more attention with the increasing concerns about fossil fuel depletion and global warming issue. Wind energy is one the most important renewables, which is widely distributed in both land and offshore environment [1-2]. To provide energy supply to remote rural areas, stand-alone wind power system with battery appeals to an excellent solution with maintenance simplicity and low system cost [3]. Generator is one of the most important devices of a wind energy system. Permanent magnet (PM) wind generator has been widely used for high efficiency and high power density [4-5]. However, due to poor flux regulation ability, the PM generator usually needs a large-capacity power converter for energy conversion, which is a large shortcoming for system reliability. Besides, the rare-earth PM material is a non-renewable source, and its supply is unstable, which increases the price of PM generator.

Developing high-performance generator using less PMs has attracted much attention in literature. The switched reluctance generator (SRG) is a potential non-PM solution having a robust structure and simplified power conversion unit [6]. However, its torque ripple is severe with half-cycle-conducting operation principle [7]. DC-excited doubly salient generator (DC-DSG) is another non-PM candidate, which shares a similar structure with SRG but with extra DC field coils in stator. DC-DSG suffers from asymmetric magnetic circuit and rich even-order harmonics, making its torque ripple unacceptable [8-9]. To address this issue, variable flux reluctance generator (VFRG) is proposed, which has good symmetric magnetic characteristics and reduced torque ripple [10-11]. However, its torque density is much smaller than that of the traditional PM machines due to the poor excitation ability of DC field winding compared to that of rare-earth PMs [12-13]. Moreover, an extra power supply is needed to regulate current in DC field winding, which reduces the reliability of wind power generation system.

Manuscript received March 16, 2021; Revised April 14, 2021; Corresponding author: Jifu Jiang (20032118r@connect.polyu.hk).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

This paper proposes a slot-PM-assisted hybrid reluctance generator with self-excited DC source for the stand-alone wind power generation system, which has enhanced torque density, simplified power conversion unit for DC field supply, and thus improved system reliability. The generation structure, operation principle, and design considerations are expanded in this paper. Further, the feasibility of the proposed wind power generation system is verified by field-circuit coupled simulation.

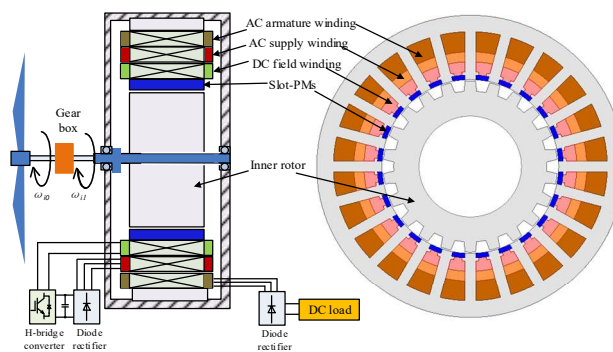


Fig. 1. Wind power generation system based on the proposed SPMa-HRG.

II. GENERATOR CONFIGURATION AND OPERATION PRINCIPLE

A. Generator Configuration

Fig. 1 presents the detail configuration of the proposed novel slot-PM-assisted hybrid reluctance generator (SPMa-HRG) with self-excited DC source, which has three sets of windings in stator, namely, DC field winding, AC armature winding and AC supply winding. Radial magnetized PMs are placed in the slot opening of stator to enhance the torque density. The rotor consists of only iron core and thus has mechanical robustness. The current produced by AC supply winding passes through the diode rectifier and H-bridge converter, and further provides the excitation current for DC field winding.

The advantages of proposed generator are listed as following.

(a) Since all excitation sources are placed in the stator side and the rotor comprises only iron core, there is no need of brush and slip rings, which provides mechanical robustness.

(b) Radial magnetized PMs in the slot openings contribute to enhanced torque density compared to the traditional reluctance topology, and meanwhile avoiding demagnetization risk as the flux linkage of windings does not pass through slot PMs.

(d) Output voltage of AC armature winding can be controlled through regulating DC field excitation, thus a variable-speed constant-voltage generation operation can be realized.

(e) A small portion of AC armature winding are split out and function as AC supply winding to provide excitation current to DC field winding through an uncontrollable diode rectifier and H-bridge converter. In this way, no extra DC source is needed, which can reduce the device cost and improve the independent characteristic of the wind power generation system.

B. Flux Modulation Principle

The slot PM excitation in the proposed SPMA-HRG operates based on flux modulation principle. The magnetomotive force (MMF) of slot PM excitation of an be denoted as

$$F = F_a \cos(P_s \theta) \quad (1)$$

where F_a , P_s , and θ represent the amplitude of fundamental slot PM MMF, number of stator teeth, and the rotor mechanical angle, respectively. The rotor permeance can be expressed as

$$\Lambda = \Lambda_0 + \Lambda_a \cos[P_r(\theta - \omega t)] \quad (2)$$

where Λ_0 , Λ_a , P_r , ω , and t represents average permeance, amplitude of fundamental permeance, number of rotor salient pole, rotor mechanical angular velocity, as well as time.

By multiply equation (1) and (2), the airgap flux density after modulation can be expressed as

$$\begin{aligned} B &= F \times \Lambda \\ &= F_a \cos(P_s \theta) \times \{ \Lambda_0 + \Lambda_a \cos[P_r(\theta - \omega t)] \} \\ &= F_a \Lambda_0 \cos(P_s \theta) + \frac{1}{2} F_a \Lambda_a \cos((P_s + P_r)\theta - P_r \omega t) + \quad (3) \\ &\quad \frac{1}{2} F_a \Lambda_a \cos((P_s - P_r)\theta + P_r \omega t) \end{aligned}$$

It can be seen the flux density excited by slot PMs has three dominant harmonic components after the rotor modulation, as shown in Table I. The amplitude of component II is equal to component III, which is half of that of component I. When the rotor rotates, component I is stationary and thus cannot produce effective voltage in the armature terminal. The component II and III rotates in the opposite direction, the one having positive rotating direction generates electromagnetic energy conversion, while the other produce core loss and heat only.

TABLE I
SPECIFICATIONS OF THREE HARMONIC COMPONENTS

Item	I	II	III
Pole pair number	P_s	$P_s + P_r$	$ P_s - P_r $
Amplitude	$F_a \Lambda_0$	$F_a \Lambda_a / 2$	$F_a \Lambda_a / 2$
Electrical velocity	0	$P_s \omega$	$P_r \omega$
Mechanical velocity	0	$P_s \omega / (P_s + P_r)$	$P_s \omega / (P_s - P_r)$
Rotating direction	/	Positive	Negative

III. DESIGN CONSIDERATION

Two important parameters of the proposed SPMA-HRG, are analyzed in the section, including the usage of slot PMs and coil

turns of AC supply winding. The general dimension parameters of the proposed generator are listed in Table II.

A. Optimal Usage of Slot PMs

Considering the pool excitation ability of DC field excitation, slot PMs are introduced to enhance the flux linkage, back-EMF, and steady torque of the original reluctance topology. The usage of slot PMs is a key design parameter for the proposed machine. On one hand, PMs are arranged in the slot openings and thus occupy part of the slot area for DC field winding, AC armature winding and AC supply winding, leading to the reduction of electric load and torque density. On the other hand, too much slot-PM usage will cause stator core saturation, which degrades the torque generation and increase core loss at the same time. Moreover, it is necessary to design an electric machine with less PM usage considering its high material cost.

By using finite element analysis, the torque performance of SPMA-HRG with different PM usage are evaluated, considering the effect of armature current density. Some initial dimension parameters are listed in Table II. The result is shown in Fig. 2, it can be seen, under the same current density, the steady torque firstly increases to a peak value, then reduces with the increase of slot-PM usage. This is because the stator core is saturated with slot-PM usage larger than 2mm. When the current density is above 12 A/mm², the increment in torque is not significant. In this paper, the rated working point of the proposed machine is selected as 12 A/mm² current density, in which the maximum torque is obtained under 2mm slot-PM usage.

TABLE II
INITIAL DIMENSION PARAMETERS OF PROPOSED SPMA-HRG

Symbol	Parameter	Unit	Value
R_{so}	Outer radius of stator	mm	60
R_{si}	Inner radius of stator	mm	34.5
R_{ro}	Outer radius of rotor	mm	34
R_{ri}	Inner radius of rotor	mm	20
h_{ry}	Height of rotor yoke	mm	10
h_{sy}	Height of stator yoke	mm	6.5
l	Stack length	mm	50
δ_{airgap}	Airgap length	mm	0.5
h_{PM}	Height of slot PMs	mm	Variable
θ_s	Arc of stator tooth	rad	0.1238
θ_r	Arc of rotor tooth	rad	0.1186
N_{ac}	Coil turns of ac armature winding	/	70
N_{dc}	Coil turns of DC field winding	/	30
N_{sup}	Coil turns of ac supply winding	/	10
n	Rated speed	rpm	600

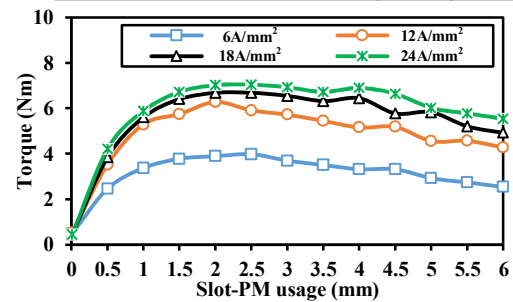


Fig. 2. Torque variation with slot-PM usage under different current density.

B. Coil Turns of AC Supply Winding

The AC supply winding is an innovative design element in the proposed SPMA-HRG, aiming to give an integrated power supply to DC field winding through a diode. In this paper, a portion of AC armature winding is split out to function as AC supply winding. Further, the turn number of AC supply winding needs to be determined. The design principle is, in the steady status, the rectifier voltage of AC supply winding should be larger than the resistance voltage on DC field winding.

The resistance voltage on DC field winding can be written as

$$V_{dc} = I \times R \quad (4)$$

where I is the steady current passing through DC field winding, R is the resistance, which can be calculated as

$$R = \rho \frac{l}{S} \quad (5)$$

where ρ is the resistance coefficient, l is the overall wire length, S is the cross-sectional area of a single conductor.

The rectifier voltage of AC supply winding should satisfy

$$\begin{cases} V_{sup} > V_{dc} \\ V_{sup} = N_{sup} * V_{tur} * C_{rec} \end{cases} \quad (6)$$

Where N_{sup} is the turn number of AC supply winding, V_{tur} is the minimum root-mean-square (RMS) value of voltage per coil turn of AC supply winding, which can be calculated as 0.0625V in this initial design. C_{rec} is the rectification coefficient of 2.34. By substituting data from Table II into Equ. (6), the minimum turn number of AC supply winding can be selected as 10.

IV. PERFORMANCE EVALUATION

A. Static Electromagnetic Performance

Fig. 3 shows the no-load magnetic field distribution under different status. With only DC field excitation, the flux starts from the stator tooth, passes through the airgap and rotor, and comes back to two adjacent stator teeth, as denoted in Fig. 3(a). Due to the poor excitation ability of DC current, the maximum flux density of the stator core and rotor core is lower than 1.5T, which means the core is far from full utilization. With only slot PMs, there are significant flux linkage passing from the air gap as shown in Fig. 3(b), and the flux density in the stator core and rotor core are basically balanced, which verifies the feasibility of such a unique slot PM configuration. Further, with DC field excitation and slot PMs both active, as presented in Fig. 3(c), the flux density of stator core and rotor core are enhanced.

The air gap flux density with two different excitation sources is calculated and presented in Fig. 4 (a), along with harmonics distribution which is obtained by Fast Fourier analysis. With only DC field excitation, the main working harmonics are the 10th, 12th and 34th components. With only slot PMs excitation, the main harmonics are 2nd, 24th, and 46th, which is consistent with the previous analysis of flux modulation effect of slot PMs. Further, Fig. 4(b) shows the airgap flux density and harmonics distribution of AC armature winding, it can be seen, although the harmonics of dual excitation sources are entirely different, the armature field can effectively interact with both excitation sources, benefiting from the harmonics diversity arising from the single-layer concentrated winding connection.

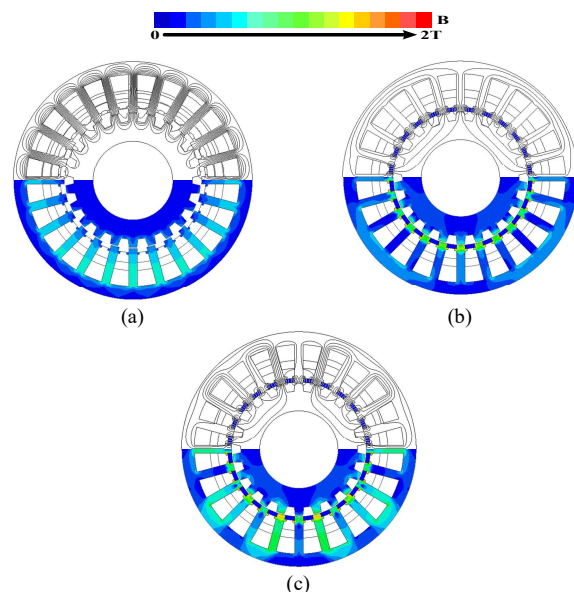


Fig. 3. No-load magnetic field distribution. (a) DC field excitation only. (b) Slot PMs excitation only. (c) Both DC field and slot PMs excitation.

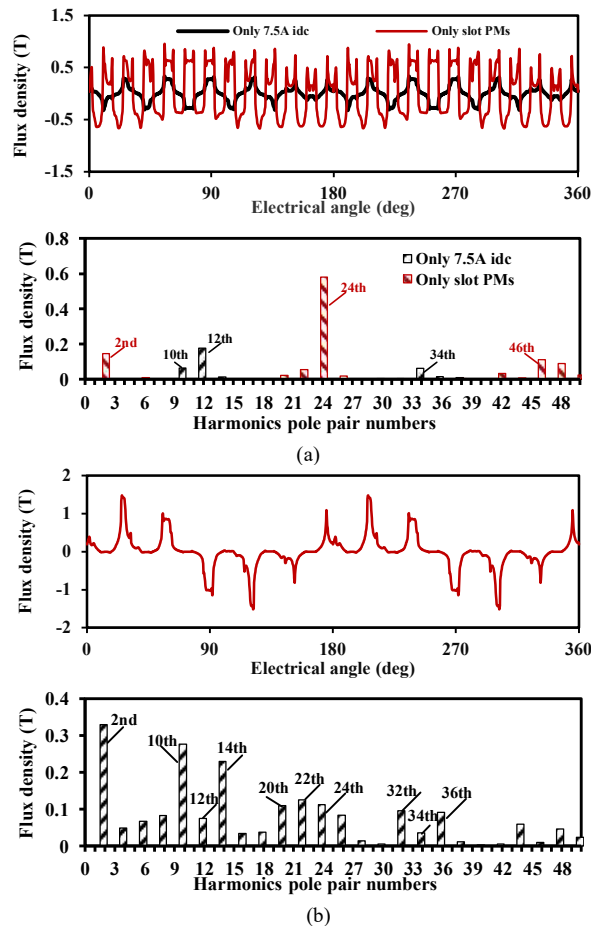


Fig. 4. Air gap flux density waveforms and harmonics distribution. (a) DC field or slot PMs excitation. (b) Armature excitation.

Fig. 5 and Fig.6 show the no-load flux linkage and back-EMF of AC armature winding under different excitation status. It can be seen, both the DC field excitation and slot PMs can generate effective flux linkage and back-EMF, and they are in the same

phase and can be overlapped together. Therefore, with slot PMs assistance, the flux linkage and back-EMF can be enhanced.

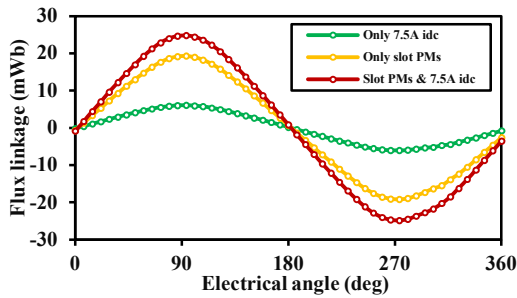


Fig. 5. No-load phase flux linkage under different excitation status.

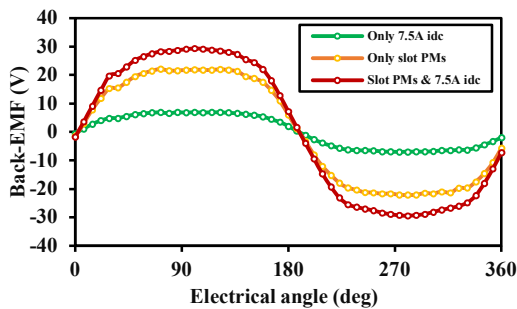


Fig. 6. No-load back-EMF under different excitation status.

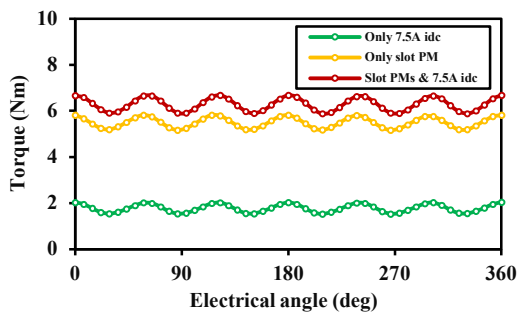


Fig. 7. Steady torque under different excitation status.

Fig. 7 presents the calculated steady torque under different excitation status. It can be found that the average torque value is 1.73 Nm with only DC field excitation, 5.39 Nm with only slot PMs excitation, 6.48 Nm with both DC field and slot PMs excitation. It can be concluded, with the introducing of slot PMs, the steady torque can be enhanced significantly.

B. Dynamic Generation Performance

Fig. 8 shows the field-circuit coupled model of the proposed SPMa-HRG based wind power generation system. Three sets of windings of the generator are exported from Ansys Maxwell software to the circuit in Ansys Simpler software, to realize configuration of self-excited DC source for generation control. The current starts from AC supply winding and enters DC field winding through the diode rectifier and H-bridge converter. The controller receives detection signals from generator output side, to control the pulse width modulation of H-bridge converter and regulate DC= current. Fig. 9 and Fig. 10 shows the flux linkage and back-EMF of AC armature winding with DC current value of negative 0.75 A, 0 A and positive 0.75 A respectively. It can be concluded, the flux linkage and back-EMF can be effectively

weakened and enhanced in a certain range, which verifies the flux regulation ability of the proposed SPMa-HRG.

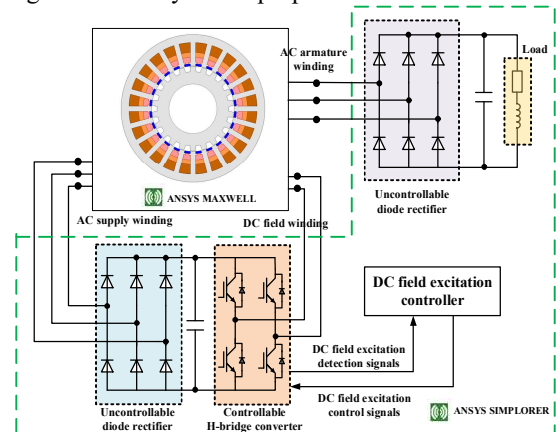


Fig. 8. Field-circuit coupled model for the proposed SPMa-HRG.

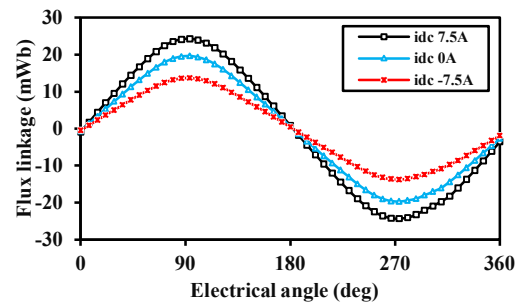


Fig. 9. Phase flux linkage with bidirectional DC field current.

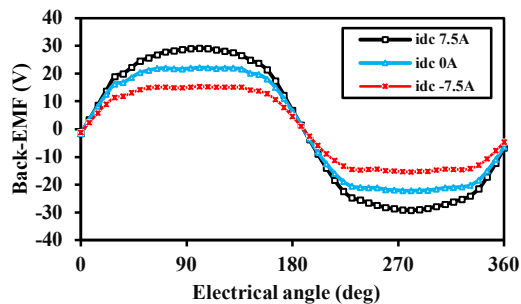


Fig. 10. Back-EMF waveforms with bidirectional DC field current.

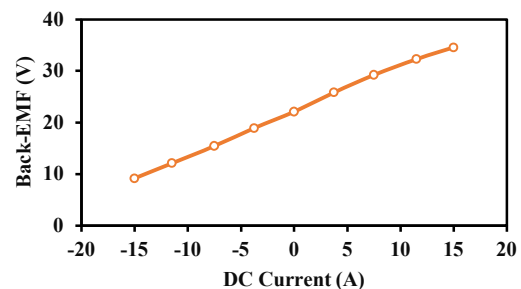


Fig. 11. Back-EMF amplitude curve against different DC field current.

Fig. 11 presents the curve of back-EMF amplitude against different DC excitation current. It can be seen, when the DC currents changes from -15 A to 15 A, the back-EMF amplitude changes from 9.2 V to 34.6 V, which verifies the back-EMF can be adjusted in a large range through bidirectional DC current. This good flux regulation ability of the proposed SPMa-HRG is suitable for wind power generation system to achieve constant

voltage generation under variable wind speeds.

Fig. 12 shows the three-phase current in AC supply winding, which passes through uncontrollable diode rectifier, H-bridge converter, and finally enters DC field winding. Because of the time constant of DC field winding, the current shows a rising process at the beginning and then comes into a steady status. Fig. 13 shows the rectified voltage and current from the diode rectifier and H-bridge converter. As denoted in Fig. 14, output voltage of the AC armature winding appears to be stable when the rectified voltage and current arrive a stable value. Besides, with different DC excitation currents, the output voltage can be flexibly changed, which verifies the feasibility and advantages of the proposed novel SPMA-HRG based wind energy system. It should be mentioned, because of the strong nonlinearity of the external circuit and load, the phase voltage of AC armature winding under load conditions cannot be so sinusoidal. There are two methods to improve the output power quality. Firstly, as we can replace the output diode rectifier with active rectifier. With the pulse width modulation of switching devices, the voltage and current harmonics in the generator side can be reduced. Secondly, we can make use of multiphase generator design and rectification, which can reduce harmonic impact by increasing the commutation frequency of wind generator.

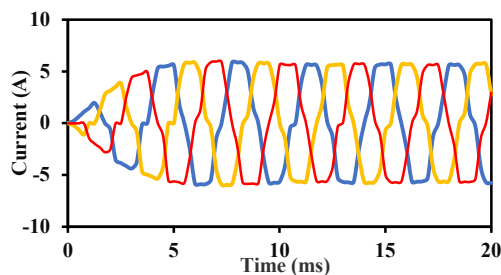


Fig. 12. Three-phase current in AC supply winding.

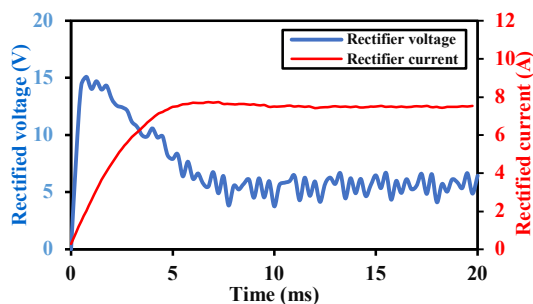


Fig. 13. Rectified voltage and current in DC field winding.

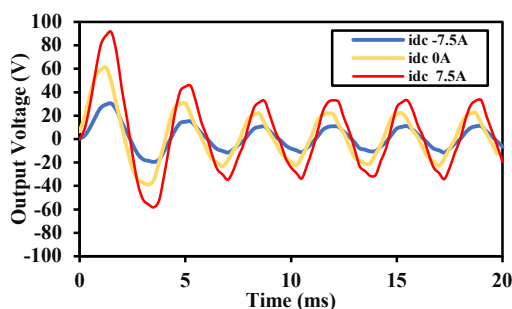


Fig. 14. Output phase voltage of AC armature winding.

V. CONCLUSION

This paper proposes a slot-PM-assisted hybrid reluctance generator (SPMa-HRG) with a self-excited DC source for wind power generation. The innovation of this topology is related to using slot PMs to improve generator torque density, meanwhile, introducing a unique AC supply winding that is split from AC armature winding with small turns to provide electricity to DC field winding through an uncontrollable diode rectifier as well as H-bridge converter. This self-excited DC source reduces the device cost and improves the independent characteristic of the wind power system. In this paper, the generator configuration and operation principle are illustrated. The design consideration of the slot PM usage and coil turns of AC supply winding are provided. Using the field-circuit coupled modeling and analysis, the generator electromagnetic performance, and the feasibility of using self-excited DC source are verified.

ACKNOWLEDGMENT

This work was supported by a grant from the NSFC of China under Project No. 51707171 and in part by grants from the Hong Kong Research Grants Council, Hong Kong SAR, China, under The Hong Kong Polytechnic University Project No. 152143/18E and 152109/20E.

REFERENCES

- [1] Kc A, Whale J, and T, Urmee "Urban wind conditions and small wind turbines in the built environment: a review". *Renewable Energy*, vol. 13 pp. 1268-1283, Feb. 2019
- [2] H. Polinder, F. F. A. Pijl, G. de Vilder and P. J. Tavner, "Comparison of direct-drive and geared generator concepts for wind turbines," *IEEE Trans. Energy Convers.* vol. 21, no. 3, pp. 725-733, Sept. 2006
- [3] Z. Zhou, C. Wang and L. Ge, "Operation of stand-alone microgrids considering the load following of biomass power plants and the power curtailment control optimization of wind turbines," *IEEE Access*, vol. 7, pp. 186115-186125, 2019.
- [4] X. Zhao, S. Niu and W. Fu, "Sensitivity analysis and design optimization of a new hybrid-excited dual-PM generator with relieving-DC-saturation structure for stand-alone wind power generation," *IEEE Trans. Magn.*, vol. 56, no. 1, pp. 1-5, Jan. 2020
- [5] O. Beik and N. Schofield, "An offshore wind generation scheme with a high-voltage hybrid generator, HVDC interconnection and transmission," *IEEE Trans. Power Del.*, vol. 31, no. 2, pp. 867-877, Apr. 2016
- [6] M. Lu, P. Zhou and C. Liaw, "Wind switched-reluctance generator based microgrid with integrated plug-in energy support mechanism," *IEEE Trans. Power Electron.*, vol. 36, no. 5, pp. 5496-5511, May. 2021.
- [7] Y. Jin, B. Bilgin, and A. Emadi, "An extended-speed low-ripple torque control of switched reluctance motor drives," *IEEE Trans. Power Electron.*, vol. 30, pp. 1457-1470, 2015
- [8] Z. Chen, and Y. Yan, "A doubly salient starter/generator with two-section twisted-rotor structure for potential future aerospace application," *IEEE Trans. Ind. Electron.*, vol. 59, no. 9, pp. 3588-3595, Sept. 2012.
- [9] Y. Wang, Z. Zhang, and Y. Yan, "Torque density improvement of doubly salient electromagnetic machine with asymmetric current Control," *IEEE Trans. Ind. Electron.*, vol. 63, no. 12, pp. 7434-7443, Dec. 2016.
- [10] X. Liu and Z. Q. Zhu, "Comparative study of novel variable flux reluctance machines with doubly fed doubly salient machines," *IEEE Trans. Magn.*, vol. 49, no. 7, pp. 3838-3841, July 2013.
- [11] X. Zhao and S. Niu, "Design and optimization of a novel slot-PM-assisted variable flux reluctance generator for hybrid electric vehicles," *IEEE Trans. Ener. Convers.*, vol. 33, no. 4, pp. 2102-2111, Dec. 2018.
- [12] J. Feng, L. Huang, "Torque density enhancement of 6/4 variable flux reluctance machine with second-harmonic current injection," *IEEE Trans. Energy Convers.*, vol. 34, no. 2, pp. 1135-1145, June 2019.
- [13] X. Zhao, S. Niu, and W. Fu, "Design of a new relieving-DC-saturation hybrid reluctance machine for fault-tolerant in-wheel direct drive," *IEEE Trans. Ind. Electron.*, vol. 67, no. 11, pp. 9571-9581, Nov. 2020.